Plant-Powered Diet: Inseparable from Health and ESG

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This book describes my experiences as a vegan and brings together the research on the benefits of a vegan diet for both health and environmental protection. To me, a vegan diet is inseparable from health and ESG.

More research is still needed to advance the knowledge in these areas. In this regard, I have some proposals in this book that will be of interest to governments, international bodies, and medical schools on research projects related to the vegan diet.

I have kept the technical details on the science of global warming, pollution, and medical research related to a vegan diet to a minimum. Readers interested in technical details can refer to Chapters 15.5, 16.2, 16.3, and the appendices.

I hope this book inspires more people to explore and conduct detailed research on a vegan diet. Someone considering a vegan diet should also consider behavioral and psychological factors, such as having a smaller social circle and the potential non-acceptance of a vegan diet by their spouse, dating partner, or family members. Making this decision is not easy.

I wish to thank all the authors of the various articles on the links between a vegan diet and health, and global warming. The medical researchers have contributed enormously to our understanding of how adopting a vegan diet can lower the likelihood of developing certain chronic illnesses compared to a meat-based diet. The researchers in climate science have led us to a better understanding of global warming and the importance of a vegan diet. The contributions of all researchers are immeasurable. I have gained a lot from their work.

Feel free to share this book with anyone interested in adopting a vegan diet for health and environmental reasons. Readers are welcome to use this book freely for educational purposes without seeking permission. Citing this book is already good enough if you wish to include it in your classes, seminars, or other educational activities.

I wish everyone excellent health and a happy life!

Thank you, Casey
November 28, 2025

“选择营养均衡的纯素饮食可以降低患多种慢性疾病的风险。”

“A well-balanced vegan diet lowers the risk of contracting many chronic diseases.”

Note to readers:

i. *Plant-Powered Diet: Inseparable from Health and ESG* shares my experiences as a vegan, highlighting the health and environmental benefits of adopting a vegan lifestyle. This book leaves out much of the content related to Buddhism and the author's interpretations of Buddhist views on a vegan diet. Readers interested in exploring the author's Buddhist insights, and personal perspectives from a Buddhist point of view should refer to *Plant-Powered Diet: Inseparable from Health and ESG, with Buddhist Thinking*, which is a separate book.

   Plant-Powered Diet: Inseparable from Health and ESG is essentially a shorter version of *Plant-Powered Diet: Inseparable from Health and ESG, with Buddhist Thinking*. Chapters 1 to 17 and the appendices in this book are identical in both books.

   This book aims to make information about the environmental and health benefits of a vegan diet more accessible to a broader audience, as some people may not want to read content related to Buddhism and are only interested in the science. Therefore, I have excluded content on Buddhism from this book to suit these groups. However, this book includes a brief explanation of why most Buddhists who follow a vegetarian or vegan diet avoid garlic (and garlic shoots), onions, spring onions, leeks, and chives—the five vegetables restricted in Buddhism.

ii. For those who wish to know more about my personal philosophy on a vegan diet and how Buddhism is related to the vegan lifestyle, you can refer to, "*Plant-Powered Diet: Inseparable from Health and ESG, with Buddhist Thinking*" which covers the topics, "*Farm Animals Have No Choice*", "*My Personal Philosophy with Regards to a vegan diet and Buddhism*", "*Treating Fellow Human Beings, and Compassion for Animals*", and *What did the Buddha tell his disciples about the Vegetarian/Vegan Diet?*" which are not addressed in this book. *Plant-Powered Diet: Inseparable from Health and ESG, with Buddhist Thinking* will be released in 2026.

iii. To understand the chemical equations and technical details in Chapters 15.5, 16.2, 16.3, Appendices 1, 2, and 3, it is helpful to have knowledge of Chemistry, Biology, and Physics as covered in the O-Level to A-Level syllabi (UK), or Year 12 to similar undergraduate introductory courses at universities in North America. Readers without a background in Chemistry, Biology, and Physics can skip the chemical equations.

   The discussion involving chemical equations aims to provide the scientific basis for various nutritional, medical, and climate-related findings. Including these chemical equations and technical details is essential, as all scientific findings must be supported by evidence. Readers can then better understand, for example, how specific chemical reactions in the human body can cause harm. To illustrate a damaging chemical reaction, I describe how free radicals attack the human body.

iv. Any recommendations or advice given here cannot replace the advice that nutritionists and qualified doctors provide.

v. I strongly encourage all to seek medical advice from their respective registered doctors and/or nutritionists before adopting a vegan diet. It is also wise to get different professional opinions on any dietary recommendations.

vi. I do not support self-medication for those who are not feeling well, and I will definitely visit a medical doctor if I am sick. Those who are feeling unwell, including those who are on a vegan diet, are advised to seek medical advice promptly.

vii. If you are unwell, you may have to take sick leave. I will undoubtedly take sick leave to get a good rest if I am unwell.

viii. The content, comments, opinions and views expressed herein are solely my own and do not necessarily reflect the views of any entity, company or organization.

ix. The first version was released on July 26, 2022 (totaling 65 pages) and was mainly circulated among family members and friends. This second version, *Plant-Powered Diet: Inseparable from Health and ESG,* contains 168 pages in total, including the References Section, which spans 26 pages. This version reflects my latest health status as of November 28, 2025, and has been updated with additional content.

x. Please do send me an email at caseykclim@outlook.com if you spot errors in this book. Thanks a lot!

Possible conflicts of interest: The author may set up companies to provide plant-based foods and invest in the securities of companies that sell plant-based foods and services.

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PART I. THOUGHTS AND EXPERIENCES

1 Introduction

I strongly believe in the power of plants to nourish us. Yes, I am all in for 100% plant-based foods. My plant-based journey has been joyful, peaceful, and fruitful. My amazing experience with this diet has prompted me to share my thoughts and expertise with as many people as possible.

A plant-based diet, also known as a vegan diet, excludes all animal products. Some articles may define a vegan diet as primarily composed of plants, with some meat and seafood included. In this book, a plant-based diet is 100% vegan. Those who follow a vegan diet do not eat meat, seafood, dairy products, or eggs, meaning there are no animal products in their diet.

The case for a broader adoption of a vegan diet is compelling. To me, a well-balanced vegan diet is inseparable from good health and environmental protection. In this book, I present supporting findings from research publications to demonstrate that a vegan diet is indeed inextricably linked to both good health and a healthy environment.

On health, various studies discussed in this book have shown that adopting a vegan diet lowers the probability of contracting colon cancer, breast cancer, prostate cancer, liver cancer, kidney cancer, heart-related diseases, strokes, diabetes, chronic kidney disease, Parkinson's disease, and certain eye diseases. It also helps to relieve constipation. While a 100% adoption rate of a vegan diet by people all over the world will not eliminate the risks of pandemics linked to animal farming, the risks are nonetheless reduced.

Regarding environmental protection, the evidence is overwhelming that a vegan diet is an indispensable tool to safeguard our Mother Earth. Estimates from several research articles on the incremental emissions of global anthropogenic (i.e., human-caused) greenhouse gases from animal farming range from 14.5% to 20%. These are very high figures, and a widespread adoption of a vegan diet for all meals certainly goes a long way toward helping Earth combat global warming. A vegan diet also reduces pollution of freshwater.

A vegan diet works hand in hand with renewable energy to combat global warming. The upward trend in total energy generated from renewable sources is welcome and expected to continue as new projects on renewable energy worldwide are carried out to fight against global warming. Technologies are being developed to reduce greenhouse gas emissions and remove greenhouse gases already in the atmosphere. All these avenues are, of course, much welcome and needed. A more widespread adoption of a vegan diet will go a long way to complement efforts to combat global warming and reduce air and water pollution.

This book provides support for the principle that a vegan diet and Environmental, Social, and Governance (ESG) principles are inseparable. Recommendations are provided to governments, corporate leaders, universities, medical schools, medical associations, etc. The environmental damage associated with animal farming is well documented and has been widely highlighted in numerous publications, including reports by the Intergovernmental Panel on Climate Change (IPCC). The case that adopting a vegan diet is related to the "E" in ESG, or environmental standards, is nothing new. The issue is the need for education and more widespread adoption of this diet.

I hope this book can motivate more firms, schools, universities, financial institutions, and governments to actively inform people about the benefits of a vegan diet while advocating ESG. It combines the latest research on the health benefits of adopting a vegan diet with details on how animal farming contributes to the environmental damage currently facing the Earth.

The number of people worldwide on a vegan diet remains very small, and I hope this book contributes to further understanding of the benefits of going plant-based. I am also sharing my experience with a vegan diet as a case study. I hope readers can use the information provided to decide for themselves whether a vegan diet suits them. The goal is to give more people access to relevant information for their health.

The dining table is a powerful avenue through which people across the globe can participate in achieving the target of reducing global temperature rise. The target is currently to limit global temperature rise to no more than 1.5 degrees Celsius (1.5°C) above the pre-Industrial Revolution era, measured over a 20-year average. The base period is the average temperature between 1850 to 1900. Measurements of temperature are based on near-surface air temperatures over land and sea ice, and on sea surface temperatures over ice-free ocean regions.

The year 2024 saw a global average of near-surface temperature increase of 1.55°C above the pre-industrial baseline. The Earth is now between 1.34°C and 1.41°C warmer than it was in the pre-industrial era. Based on a 20-year period of 2015–2034, the World Meteorological Organization (WMO) projects the temperature increase to reach around 1.44°C above pre-industrial levels.

Given that the incremental reduction of greenhouse gases via adopting a vegan diet is significant, it is clear that a vegan diet is a critical component to strengthen the ‘E’ in ESG. To me, a vegan diet and ESG are inseparably linked.

A vegan diet has gained increasing acceptance, but its adoption is still insufficient to make a significant dent in greenhouse gas emissions. Meat consumption is projected to grow from 324 million tons in 2020 to between 460 to 570 million tons in 2050, a staggering increase of between 42% to 76% from the 2020 level if the global appetite for meat does not change. [1] [2] The world population has to drastically cut down on meat and transform from a meat-based diet to one much heavier in plants, or a 100% plant-based diet.

While a 100% plant-based diet worldwide is ideal, it is not achievable. A more sensible strategy is to aim for a dramatic reduction in the growth of meat consumption. Given the environmental benefits, a valid question everyone should ask is whether a vegan diet is healthy. Based on testimonials from vegans and research published in medical and nutrition journals, a vegan diet is healthy and is generally a powerful tool for preventive medicine. I summarize the research findings from medical and nutrition journals on the health benefits of adopting a vegan diet. I show, based on past research and available data, that the widespread adoption of a vegan diet worldwide will undoubtedly lead to a healthier population.

The question of whether a vegan diet is healthy is largely resolved by the evidence in journal articles, some of which are listed in this book. But to go a step further, is a vegan diet healthier than a meat-based diet? Given the research findings, a vegan diet appears to be healthier than a meat-based diet. The risks of contracting certain chronic diseases for someone on a vegan diet are much lower than those of a meat-based diet. But a vegan diet must be well balanced. Testimonials from vegans further add to the growing body of evidence that a well-balanced plant-based diet is healthy.

Companies and financial institutions that are at the forefront of socially responsible investing should consider taking a more proactive role in disseminating information on the pros and cons of a vegan diet to their workforces, including senior management. Governments, international agencies, schools, universities, and medical schools could also devise campaigns to provide information on what constitutes a well-balanced plant-based diet, list its benefits, and outline guidance notes, such as the need to take vegan Vitamin B-12 supplements.

Those in leadership positions at the top levels of a firm and administration can lead the way in bringing this information to a much wider audience and letting the people decide. As for the role of government, it should not favor any firm or be unfairly biased toward any sector of the industry. The government should, of course, not favor the vegan diet or meat-based sectors, or any industry. The government's role is to provide the information and let the people decide for themselves.

This book describes my experience as a vegan and adds to the body of case studies of those on a vegan diet. My experience and research findings on the health benefits of a vegan diet will hopefully provide some confidence for those who wish to embark on a vegan diet journey.

The benefits of adopting a vegan diet are aplenty, but it carries some risks. The choices of life partner, social life, and interactions with friends and family members, etc., may be fewer for certain people or groups. This may result in mental stress and a high psychological cost for those affected. The reader will have to weigh the benefits and costs of this diet, including its behavioral consequences.

2 My Plant-powered Journey

Over the past 23 years, I have been very fortunate not to have contracted severe flu or chronic diseases that would require sick leave. I had a high fever for a single day after the COVID-19 jab. I have had allergic bouts owing to pollen and dust from time to time, but the allergy has luckily not developed into severe illnesses that would require sick leave. I did have cases of runny nose due to allergies and experienced two episodes of dry cough.

I hope my good health continues for many more years. Twenty-three years ago, I began my journey on a vegan diet (vegan diet and plant-based diet are used interchangeably throughout). I feel very blessed that I have not suffered from any significant diseases like diabetes, heart-related issues, low or high blood pressure, etc. My good health enables me to raise my son, Darren, and continue doing what I enjoy and carrying out my current and past job duties. Darren is now in his late 20s. I attribute my good health principally to my vegan diet.

Those not on a vegan diet are advised to do their own research before they adopt this diet. A vegan diet is an essential driver of preventive medicine, but it must be well balanced.

I firmly believe that, in general, everyone can benefit enormously from a well-balanced vegan diet. For those who are presently suffering from diabetes, heart-related diseases, etc., I encourage you to seek the help of a medical doctor or nutritionist if you wish to adopt the diet for alleviating the symptoms of these chronic diseases.

For those who are suffering from hereditary, congenital, and genetically linked diseases, it is worthwhile to talk to your doctor about diet and nutrition to see if specific diets can aid in controlling the severity of some of these diseases. Some people are suffering from genetically-linked diseases, and more research should be undertaken to see if diets can help people mitigate the suffering from certain genetically-linked diseases. A well-balanced vegan diet may help, and patients should seek nutritional advice from medical professionals.

Everyone is different, and the tremendous health benefits that I have experienced so far may not apply to others. Some doctors and specialists may not be informed about nutrition and the benefits of vegan diets. Medical schools and medical associations have a major role in educating medical students and re-educating doctors and specialists on the benefits of a well-balanced vegan diet. To many other researchers and me, it is an effective tool for preventive medicine. The possible disadvantages, if any, of a vegan diet as the daily diet for those suffering from certain illnesses are worth examining further.

3 My Health

I presently do not have any chronic diseases. I feel very energetic and can do the usual daily tasks and job duties. Based on my lab tests and medical examinations in January 2020 and December 2021, all my indicators were normal except for my Vitamin D level.

My Vitamin D level was on the low side because I wore long pants and did not wear shorts or T-shirts during the day. I have since tried to wear shorts and T-shirts as much as possible to get some sunlight for vitamin D production. I now take vegan vitamin D3 supplements almost daily. I try to follow the doctor's recommendation to wear shorts and short-sleeve shirts for about 30 minutes daily—10 minutes each in the morning, mid-afternoon, and from about 4 to 5 pm.

My eyesight is very good, and I have no difficulty seeing at night. I had a mild fever for about a day after receiving the AstraZeneca vaccine in 2021. Other than that, I did not have other bouts of fever. I have had minor headaches perhaps twice so far over the past 23 years, and these incidents lasted for no more than 30 minutes. I think the number of Panadol pills that I had consumed over the past 23 years was at most twenty.

My major health indicators showed normal readings, including blood pressure, blood sugar, and cholesterol levels. I get a runny nose on some days, particularly in the morning. If I do get it, it lasts for about 20 minutes on and off. I am allergic to pollen. In past pollen seasons, I got a runny nose for the whole day on some days, but fortunately, it was manageable.

My vitamin B12 level is good too, within the normal range. I take vegan Vitamin B12 supplements regularly. I had a health check-up in December 2021 and was certified fit for work by a medical doctor.

4 Factors for Good Health with a Vegan Diet as the Anchor

A vegan diet is, of course, not the only input for good health, but it is a crucial component. To enjoy good health, we need money to buy nourishing food, clean water, clean air, minimal use of pesticides in vegetable farming, a healthy environment with safe levels of radiation, support from family and friends, moderate exercise, some skills to manage stress, and a healthy diet. Genetic makeup is a factor, too.

What then is a healthy diet? For me, it is undoubtedly a vegan diet. Many papers published in medical journals emphasize that a vegan diet can help lower the risk of chronic diseases such as diabetes, heart disease, and certain cancers.

I adopted a vegan diet in October 2002. I was 41 then. For the past 23 years, the only serious illness I've had was having a 1-cm long but tiny benign nodule on the surface of my chin removed in 2023 (which no longer recurs), and having two bouts of cough, lasting for about ten days in October 2019 and for about two weeks in early 2025.

In October 2019, I took some cough tablets and about three tablespoons of cough mixture to control my cough. I went to work and had the energy to work, but my productivity was not as high as when I was cough-free.

The cough that happened in October 2019 started when I was about to leave for Beijing from Sydney. I made the trip to attend the graduation ceremony for my students from the Macquarie University Master of Applied Finance program. I was on stage as my students received their degree scrolls. I was lucky to be able to control my cough and runny nose. Fortunately, I did not make any sound of coughing or sneezing while I was on the stage in a Beijing hotel.

As for the dry cough in early 2025, I took codeine tablets and anti-histamine pills that a medical doctor prescribed. I recovered from the cough after being on medication for about seven days. I could still work on my job tasks. Except for a 2-day rest after the COVID-19 vaccination and a short surgery lasting for an hour to remove the benign nodule on my skin, I have not taken any other medical leave in the past 23 years.

I am lucky not to have had any chronic diseases for the past 23 years. It is a false notion that vegans will not suffer from any chronic diseases. Individual cases differ. The types of foods that someone on a vegan diet consumes matter. If it is just relying on vegan potato chips primarily as part of a vegan diet regime, that obviously will not work. Another issue is the age at which one begins a vegan diet. The composition of the diet and the amount of non-plant-based foods consumed before starting a vegan diet are also important factors.

Alcohol consumption and smoking certainly affect a person's health. To me, a combination of alcohol, smoking, and meat will make matters worse for those on a meat-based diet. Those who drink, including those who are on a vegan diet, should monitor their alcohol intake, and those who smoke should think of quitting. It is not uncommon to see people doing business, bankers, and customers downing glasses of alcohol.

Those who care for others should advise those who have already had two glasses of wine or equivalent to stop drinking. Excessive drinking can lead to stroke and death. I do not drink much alcohol, and I do not smoke. The total amount of alcohol that I consumed was at most ten glasses since I reached the legal age to drink. I do take sips of alcohol to give a toast during weddings and birthdays.

The amount of meat consumed in the past is also a factor. Even if some people have consumed a large amount of meat in the past, it is, of course, not too late to consider adopting a vegan diet with the help of a nutritionist and/or a medical doctor. The environment the vegan lives and works in, etc., is also part of the equation. A cleaner environment with good air and water is extremely important.

I want to briefly touch on the other factors essential for good health. Possessing money to buy food is a factor. Indeed, many people are still struggling to find money to buy food. Governments and aid agencies play a critical role in getting food to people. Sound national economic policies and anti-corruption efforts are needed to raise the income level.

Access to clean water remains a challenge for many people. Clean air and clean water are the responsibilities of governments, industries, and consumers, too. Consumers have a role in recycling plastic products, batteries, and other materials, as well as conserving water and energy. Air pollution is a serious health hazard in some cities, and the benefits of a vegan diet are far outweighed by the severe adverse health effects caused by severe air pollution.

Radioactive radiation is always present in the environment from natural sources and human activities, e.g., X-ray generation and the operation of coal-fired power plants. Dangerous levels of radioactive pollution can cause death and harm to a person's health. Past cases of severe radioactive pollution include the Chernobyl Nuclear Plant disaster in Ukraine (1986), the Fukushima Nuclear Plant disaster (2011), and the Techa River highly hazardous radioactive waste incident (1949)[3].

The ability to handle daily stress in life is crucial. It might be due to work or family stress, or a combination of both. A very stressful situation at the workplace, e.g., is working with a very abusive supervisor. Over the years, I have had conversations with close relatives, friends, and ex-students who have had abusive immediate supervisors.

The usual behavior of the abusive supervisors is to lord over someone as if they are 100% perfect and can do no wrong. It is fine to be demanding, but the supervisor's role is to provide guidance, encouraging words, and emotional support. Indeed, there are better ways to do a job task, and mistakes, if any, should be pointed out. There are tactful and proper ways to talk to colleagues about specific ways to do things better. Supervisors who cannot perform these roles in a caring manner and are not willing to find out the facts should never assume leadership roles.

The abusive supervisors are living in another world, as they themselves have also made mistakes in their respective job tasks. Other forms of behavior include jumping to conclusions about one's actions and character, and assigning blame to someone without looking into the facts. Supervisors should consider matters from colleagues' perspectives and think from their colleagues' perspectives in certain situations. Supervisors should gather sufficient information, as others and they themselves may be responsible for those errors and blunders.

The abusive language that supervisors use can be very damaging in a workplace environment, and some supervisors are unfortunately happily doing that. I heard of relatives and friends informing me of four-letter words being used at the workplace, and subtle emotionally damaging words being hurled at subordinates either verbally or in emails. Subordinates who have domineering supervisors may try to understand why their supervisors are domineering. Perhaps the supervisors are dealing with emotional, personal, or family problems.

Sexual harassment at the workplace is a major problem for quite a few people, particularly women. Victims have to endure immense stress. Those who are at the most senior levels should be aware of the abuse that is going on. Some are aware, but they are not taking action.

A spouse may be in an abusive marriage. Either the wife or husband may use abusive language or engage in violence. Children using drugs may be creating stress for their parents. I encourage all to talk to their friends, relatives, and someone qualified (like a psychologist or psychiatrist if necessary) if they are being abused and see if there is a way out. Reporting to a higher authority within a firm or filing a police report in cases involving violence may be other avenues they can pursue. As this book is primarily on a vegan diet, dealing with abusive supervisors or family stress is another topic for the future. I am touching on this briefly as excessive stress is indeed detrimental to health.

5 “Is it Cruel to Slaughter Animals for Human Consumption?”

I was about ten when I asked some questions related to the slaughtering of animals, “Is Eating Meat Causing Cruelty to Animals?”, “Are Humans Allowed to Eat Meat?”, “Is it Cruel to Slaughter Animals for Human Consumption?”, “Is it Alright for Humans to Eat Meat?”, and other questions related to eating meat.

I did not know about the word “ethics” then, but I was thinking about whether humans should be eating meat since slaughtering animals brings pain to the animals. The answer to my first question when I was ten was, “I thought it was cruel to slaughter animals for meat.” But I did continue to eat meat.

As for the second question, there were many rules to follow for young students in primary school. Some actions were allowed while others were not. I did not get to thinking about a particular entity that would allow or disallow people to eat meat. As a young kid, I thought there might be entities that are of a higher level than us. I did not know much about religions. My parents and grandmother prayed to gods and to Buddhist images one would see in Chinese temples, including the Bodhisattva Guan Yin (Avalokiteśvara).

At that time, it would have been good if I had not consumed meat. However, I did not know much about nutrition or a well-balanced diet. I was thinking that if slaughtering of animals brings suffering to animals, my other question was, “Am I harming animals if I eat meat?”. I was told by my family, friends, and relatives that it was all right to eat meat, as animals like pigs and chickens were there for us to eat. I did not think at that time that I got clear answers to these questions. I just followed what others were doing for their regular meals, i.e., I ate meat when I was a kid and continued doing so till I was 41.

I grew up in Kuala Lumpur, Malaysia – I lived at 4th Mile, Gombak Road (in the Malaysian language, it is Batu 4, Jalan Gombak) for most of my childhood and during my teenage years. My family reared chickens and ducks in our backyard. Some of my neighbors also reared chickens and ducks. I saw chickens being slaughtered at home and at the wet market, which was about 3 miles away. In the slaughtering process, the necks of the chickens were slit, and the blood drained away from the slit openings.

I had pondered the enormity of the pain that the chickens and ducks had to go through as I watched them being slaughtered as a kid. It was clear to me that the chickens felt enormous pain. I could feel the titanic force the chickens exerted to struggle free of being slaughtered. It was very clear to me then that the chickens wanted to escape from the hands that were about to slaughter them. The seed for me to adopt a vegan diet years later was beginning to take shape.

A mile further down Gombak Road, i.e., 5th Mile Gombak, was where some of my relatives stayed. Some of my relatives are still staying there. I visited my uncle, auntie, and cousins at 5th Mile, Gombak, quite frequently when I was growing up. The neighbors of my relatives in that area also reared pigs. The conditions the pigs were kept in were not pleasant. I started asking as a kid if it was all right for humans to slaughter the pigs and eat them.

When I was about ten or eleven, I held a chicken for slaughter. I experienced firsthand the enormity of the force of a chicken trying to escape slaughter. At the instant when the chicken's neck was slit, I felt vividly the massive energy the chicken exerted as it struggled to escape, which was very much like a titanic force impinging on my hands. It was quite a dreadful experience for the chicken and me. That was the only time I ever held a chicken for slaughter. The gigantic power that the chicken exerted to free itself is still very much in my mind. Once is enough. Before this incident, I watched chickens, etc., being slaughtered from a distance, and I could feel their pain. Having experienced holding a chicken for slaughter by myself, it is clear that the slaughtering of farm animals is an energy-sapping and harrowing experience for them.

I told my grandmother and mother that I would never want to hold the chicken again for slaughter. All these experiences as a kid looking at chickens, ducks, and pigs being slaughtered are etched in my mind. The thought of the chickens' necks being slit came across to me from time to time. I felt guilty whenever I ate meat and seafood from when I was ten until I turned vegan. After adopting a vegan diet, I bow in my mind or physically, if I can, to the meat of slaughtered chickens, ducks, pigs, etc., whenever I see them.

I was brought up the traditional way. My brothers, sisters, and I were taught to do good to people. We were told we must treat people kindly and help whoever needs assistance. We helped out relatives and friends in whatever way we could. My late mother loved driving and gave lifts to my neighbors, family friends, and my friends from school days whenever the opportunity arose.

There were several other related questions. Another question is, "Can humans be in good health without eating meat?". There was not much information about a vegan diet when I was in primary and secondary school. My classmates and I were taught in school that it was essential to eat meat and seafood for a well-balanced diet. Meat and seafood were and still are part of the food pyramids in many schools. Also, killing animals for food has been going on for centuries, and it was a well-accepted culture to eat meat.

Given my experience as a vegan and medical research on a vegan diet, it is clearly wrong to state that one has to include meat and seafood as part of their diet. It is not necessary; a vegan diet is enough to maintain a healthy lifestyle as long as it is balanced.

I did not know much about nutrition when I was a kid. I did not know that a diet without meat could be healthy. I did not know what a vegan diet was back then. I never heard of the word vegan when I was a kid. I did read some books on yoga, and some authors discussed the benefits of a diet that excludes meat and seafood. There were some news articles that I read when I was a kid about meat increasing the likelihood of contracting some cancers, like bowel cancer. Other than that, there was not much information about a vegan diet back then.

Had I been told in school that a vegan diet was healthy, I would not have eaten meat from the age of ten. But back then, information about a vegan diet was not available to me. I limited my meat intake because I felt guilty about consuming animal flesh, including fish and other aquatic creatures.

On dairy and eggs, vegans do not consume dairy products and eggs out of compassion for cows and hens that lay eggs. Vegans do not wish to see cows confined to small areas to produce milk. Most cows are slaughtered after their milk-producing capabilities have evaporated. In India, some farms do not slaughter cows at all, even when they are no longer producing milk. These cows are not sold for beef. This, to me, is laudable. Most hens are enclosed in cages for egg production. Most are also slaughtered if they are no longer producing eggs on a cost-benefit basis.

Those times when I had meat-free dishes before I turned vegan were happy occasions for me. I went to vegetarian restaurants at times to buy vegetarian dishes while studying in Singapore and the United States. I should have turned vegan much earlier, but I did not have access to information and data.

I believe my low meat intake since I was ten likely contributed to my good health. I am not obese, and this probably helps. My height is about 5 feet 9 inches, and many friends joked that I could put on much more weight. It is alright to be of a slight to medium build to save energy and resources for Mother Earth, so long as one is healthy. Note that vegans can be overweight, and some vegans are indeed overweight.

It is well known that animals possess intelligence. Adult pigs, as many already know, have the intelligence of a 3-year-old human child. Even ants possess intelligence. I like to share a story about ants, and it raises an important question: “Are ants more compassionate than humans?”

In early 2022, I saw dozens of ants in the bathroom of the apartment I was staying in. The story took place in North Point, Hong Kong. The ants were looking for food. They were walking all over, and some came to the restroom basin. One of the ants was trapped in a droplet of water. I used a piece of dry tissue paper to very gently scoop up the trapped ant and place it on a nearby dry area. I was not sure whether the ant had already died, but I hoped it was still alive. I was waiting for the tissue to dry and for the ant to walk away. I was pleasantly surprised that, not long after, the brethren of ants walked toward the injured ant and came to its rescue. They lifted the previously trapped ant and helped it move along with them. That ant was saved.

I was overjoyed at the brotherly love that those ants showed toward one another. They showed skills in lifting the ant. When I compared this incident to the senseless killings of humans in the war zone, I wondered what had happened to human nature. Here, we have ants helping each other. On the battlefield, we have humans killing other humans.

Are ants more compassionate than some humans? Humans killing other humans on the battlefield, etc., have been going on for ages. I am hopeful that humans, particularly a country’s leader, will show compassion when needed and make the right decisions regarding human lives.

I am all in for the vegan lifestyle, which means I do not use any products containing animal products, such as leather wallets, belts, clothing, and shoes. I am already very happy with cheap vegan wallets, belts, shoes, bags, etc. I support the vegan lifestyle as far as I possibly can. If I am on a plane and the seat is leather, I could not do anything about it. I will certainly use it. If a non-vegan restaurant has meat dishes and I cannot find any vegan restaurants nearby, I will ask the chef to customize a vegan dish for me. I will absolutely be very thankful for the chef’s efforts.

6 My Resolve to Go on a Vegan Diet at 41

When I was 41, I was not entirely sure my decision to go on a meat-free diet would keep me healthy. It was a gamble. For about two years before I turned vegan, I had already drastically reduced my meat intake to a few small pieces daily.

My resolve to become a vegan came much earlier than I expected, as my late father passed away suddenly in September 2002 in a car accident. It was unexpected. I was devastated when my late father passed away. I wanted to do something to honor my late father. I thought of various ways to do good deeds and honor him. My plan was initially to adopt a vegan diet one to two years after 2002.

As I have been having thoughts since I was small that humans should not consume meat or seafood, I was already psychologically ready for a meat-free diet. In terms of psychological readiness, going vegan for me is not an issue. The key question for me then was whether the diet was healthy. I have been lucky to have known closely a vegetarian and a vegan when I was in the USA, and a vegetarian when I was in Hong Kong. They are Gopi Maliwal, Patrick Brady, and Vikas Kakkar. They all looked healthy. They gave me more confidence that it can be healthy to adopt a vegetarian or vegan diet.

I first met Gopi Maliwal, a vegetarian, in 1986, when we were both pursuing an MBA at Virginia Tech in Blacksburg, Virginia, USA. Gopi looked healthy, though he was quite skinny. Gopi has been working in Hong Kong for more than two decades, and I met him from time to time in Hong Kong before I left Hong Kong for Sydney.

I met him again in early May 2022 for afternoon tea near his office. During that meet-up in Hong Kong, he told me that the milk he had consumed was specially air-freighted from India. There is something very extraordinary about the milk that he bought directly from India – he said the cows in India that provided his milk were not slaughtered. I, of course, fully support the practice of not slaughtering any cows, but I have some concerns about the consumption of dairy milk, given the literature on the adverse health effects of milk.

Patrick Brady is the vegan friend I met while studying in Gainesville, Florida. I first met Patrick in 1989 at an apartment complex in Gainesville. At that time, I was pursuing a Ph.D. in Finance at the University of Florida.

Patrick did not eat any meat, eggs, or dairy products when I first met him. Curious, I asked him why. He told me that he was “allergic to meat”. He sounded serious about his “meat allergy”. At that time, I erroneously believed his body was uniquely suited to a vegan diet and not suited to a meat-based diet. Of course, given my experience, that was erroneous thinking. It is not due to his body being more suited to a vegan diet.

I strongly believe that a person can be healthy on a vegan diet if they can find the right composition of plant-based foods. That said, I know some ladies who lack iron on a vegan diet. We need to look for sources of iron for some ladies who cannot get enough iron on a vegan diet. Patrick did give me a certain boost of confidence when I decided to go vegan, though I was not entirely sure.

I met Patrick again in July 2019 at Virginia Beach for afternoon snacks. I was visiting the USA at that time. I told Patrick during our afternoon tea that my health has been superb since adopting a vegan diet in 2002. It was only at that meet-up that he told me he was not medically allergic to meat. He was hesitant to inform people that he was on a vegan diet and did not want to get into a long discussion or arguments about it. Patrick further told me he adopted a vegan diet as he did not want to cause suffering to animals.

I first met Vikas Kakkar, a vegetarian, at the City University of Hong Kong, Hong Kong. He joined the faculty in 1996 and became my colleague. Vikas consumes some dairy products and does not eat eggs, but there is no meat or seafood in his diet. Vikas looked energetic when we met at the department during those days. He still looks great and energetic.

7 Gratitude to My Friends Who Gave Good Advice

I am lucky to have known several friends who are on a vegan diet. They are a source of information for me and have provided me with valuable advice on a vegan diet. Friends who are not on a vegan diet also offered helpful advice on certain supplements to take.

After I adopted a vegan diet (I was in Hong Kong at the time), I joined a meet-up led by Shara Ng, the late Dr. John Wedderburn, and a few others. John, a medical doctor, advised me to take vitamin B12 supplements. John passed away in 2024. I have been taking the vegan B12 supplements orally (about 500 micrograms every other day) since then. My B12 level is within the normal range according to the test results.

Another vegan friend who was in Hong Kong, Lucy Chang, advised me to eat flaxseed. I have been consuming flaxseed quite regularly since I turned vegan. Flaxseed contains Omega-3 fatty acids and helps in reducing the risks of heart-related issues, cognitive decline, and certain cancers. Fish also contains Omega-3 fatty acids. As far as I know, there are 11 types of Omega-3 fatty acids.

The Omega-3 fatty acids found in fish and animal products include eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA), which are beneficial to the human body. EPA and DHA lower the risk of cardiovascular disease, improve brain function, strengthen immunity, reduce hair loss, and support eye health. The Omega-3 fatty acid, Alpha-linolenic acid (ALA), is found in plants. Canola oil, chia seeds, flaxseeds, flaxseed oil, full-fat soy foods, etc., contain ALA, but ALA is also found in some animal fats. The human body can convert ALA into EPA and DHA.[4]

8 Social Circle, Gatherings, and Vegan Diet

A factor to consider for someone considering a vegan diet is the likelihood of getting support from family members, spouses, dating partners, etc., for the dietary change. A person's social circle could be smaller if they adopt a vegan diet. Dating relationships could also be affected. Depression may set in, e.g., if a person who was on a meat-based diet suddenly finds that friends and relatives are not calling the new vegan for social gatherings. It is also possible that in a community of vegans or vegetarians, the person who is on a meat-based diet may feel out of place.

Anyone wanting to turn vegan must consider all these factors, but in the end, they will have to weigh all the factors that are relevant to them. Those who are dating may end up in a break-up if their dating partners disagree. One's priorities in life are a factor, and the decision is not easy. It is, of course, up to the individual to decide. There may be a need to seek counseling.

The ideal situation is if both dating partners or spouses agree to adopt a vegan diet. But this is not always the case, and life is not perfect. To some, it may not be an easy issue to resolve. A dating partner may turn vegan to keep the relationship alive with their vegan partner, and feeling happy doing so can be important for some people.

People react differently to new circumstances, and the person will have to weigh all relevant factors on this issue. Some may weigh turning vegan to be far more important than the likelihood of a smaller social circle. For example, some are not affected to a significant extent emotionally by a smaller social circle. Others find it harder to accept.

Some of my friends had told me that their social circles would be smaller if they adopted a vegan diet. This is unfortunately true currently. But if more people are on this diet, then the issue of a smaller social gathering circle and dating pool will be less of a problem. Currently, a small dating pool of vegans is a significant issue. Unfortunately, this problem will not go away that quickly, as the percentage of vegans in this world is still tiny. I wish them the best of luck on their quest to find their lifelong partners.

Some vegans adopt the diet as they care a lot about animal welfare and compassion. It is understandably harder for some vegans to have a lifetime of relationships with those who are not on a vegan diet. Some would be disturbed to see meat on the dining table. Dining together is an avenue for bonding, relaxation, mutual enjoyment, and intense communication, but a clash of diets at the dining table is not an easy matter to resolve.

Some who are on a meat-based diet could not understand why their partners turned vegetarian or vegan. I know a few who are on a meat-based diet, but their partners are vegetarians or vegans. One of those I know told me they seldom eat or go on outings together as a couple.

Some couples are fortunate because neither partner minds if one is vegan or vegetarian and the other is not. They seem to have happy marriages or relationships.

9 Vegan Advocacy

Though more information is currently available, many people have not heard of a vegan diet. Most have heard of the vegetarian diet. A vegan diet is a powerful tool for preventive medicine and has numerous health benefits, as documented in research articles and the testimonies of vegans. Those on a vegan diet are encouraged to discuss its benefits with their friends, relatives, and colleagues. I have been sharing my experience as a vegan with my friends, ex-students, students, colleagues, ex-colleagues, and anyone who wishes to know more about this diet since I turned vegan.

Those who wish to go vegan should not be discouraged by cases of babies who were fed on a vegan diet and later died from malnutrition. These cases are sporadic. Some of these cases were due to child abuse. Unfortunately, these cases happened, and we all pray for these babies. Parents who wish to raise their children on a vegan diet should regularly seek advice from their nutritionists and bring their babies to pediatricians or doctors for medical examinations, on a schedule as advised by their doctors.

Babies can be fed a vegan diet without adverse effects, but the diet must be well balanced. The Academy of Nutrition and Dietetics (formerly the American Dietetic Association) has stated that a vegan diet is healthy and provides adequate nutrition for all stages of a person's life, i.e., at the stage as a fetus in a mother's womb, baby, child, teenager, and adult. [5] [6] [7] Athletes can also be healthy on a vegan diet. The Academy further states that a vegan diet may help prevent certain diseases.

You do not have to be a vegan to talk about past research on the benefits of a vegan diet. Discussing a vegan diet with friends and relatives, even if one is not vegan, may lead some to reduce their meat and seafood intake. However, there is a likelihood that one may risk losing a friendship at the mere mention of the word vegan. Some are very used to having meat and do not like anyone to talk about a vegan diet to them.

Some medical doctors I had spoken to were not convinced that a vegan diet can be healthy. Sharing information about the importance of a vegan diet must continue regardless. Some doctors advised their patients to include meat and dairy products in their diet, and patients should follow this advice if they cannot find better advice.

I strongly suggest that medical bodies and medical schools organize seminars and lectures to better inform doctors about the composition and nutritional value of food items that can help their patients. Invite nutritionists, including plant-based nutritionists, to these seminars. Should doctors recommend a vegan diet to those who have colon cancer, given the extant medical research? This is up to the doctors after weighing other conditions that their patients are suffering from.

In the long run, I firmly believe that healthcare costs will drop significantly if more people reduce their meat intake. If more people adopted a well-balanced vegan diet, governments would allocate less of their national budgets to healthcare. Of course, going 100% plant-based is the ideal outcome, but it takes time for people to get used to a vegan diet.

10 Compositions of Vegan Diets

People who are in different parts of the world consume different compositions of vegan diets. Vegan diets among Caucasians from North America and Europe differ to some extent from those of Asian origin in East Asia, e.g., China, Singapore, Malaysia, Taiwan, and Japan.

10.1 My Typical Vegan Diet

I like to share with readers what I typically eat. I get advice on plant-based nutrition from websites such as www.pcrm.org and https://nutritionfacts.org/.

My typical breakfast includes some selections of the following: oats, whole wheat bread, multigrain bread, black sesame, black beans, almond powder, walnuts, chia seeds, flaxseed, etc. For lunch and dinner, I would have vegetables, rice, noodles, etc. I will try to include a variety of vegetables of different colors.

The vegetables which I consume for each meal include some selections of the following: ginger, lettuce, carrots, celery, cucumber, alfalfa, kidney beans, chickpeas, green beans, long beans, okra, kale, bean sprouts, turtle beans, eggplants, broccoli, mushrooms, tomatoes, cabbage, red and green bell peppers, bitter gourd, squash, basil, corn, potatoes, curry leaves (as flavor), spinach, oregano, parsley, avocado, etc. The nuts I consume include walnuts, almonds, and cashews. I choose organic foods at times. What I do encourage is for all to eat vegetables and fruits of multiple colors, if possible.

The fruits I consume include oranges, mandarin oranges, minneola tangelo, apples, kiwi fruits, papayas, lychee, longans, mangoes, dragon fruit, pineapples, dates, pears, bananas, passion fruit, persimmons, grapes, strawberries, peaches, rambutans, blueberries, raspberries, cherries, watermelon, honeydew, rock melon, lemon, figs, grapefruits, apricots, nectarines, etc.

I avoid monosodium glutamate (MSG) because I get very thirsty after eating food cooked with it. Whole-wheat bread is highly recommended, and I will avoid white bread if possible. Preservatives are very common in food items to extend shelf life, but I will avoid them to the fullest extent possible. A few bread brands do not use preservatives. So far, my body's reaction to preservative-free foods has been very good. I keep some food items in the fridge and consume preservative-free foods before the expiry date.

Bear in mind that some vegetables, such as sweet potatoes, onions, and garlic, should not be refrigerated. For bread, I finish it within three days. I got stomach upset once or twice a year in the past, but I do not think it was related to preservative-free foods. When I buy almond milk and soya milk, I try to avoid additives such as maltodextrin, stabilizers, and preservatives.

10.2 Possible Allergy to Certain Vegetables and Nuts

Some people may be allergic to certain nuts, fruits, and vegetables. Those who have allergies to certain foods should seek medical advice. Allergy to, e.g., peanuts can cause hives, and for certain people, it can be fatal.

I am allergic to peanuts and hazelnuts. I would get rashes, but luckily, they are not life-threatening. I found out about this allergy by chance through trial and error. I developed urticaria (or hives) on my skin about 15 years ago. I visited a medical doctor trained in Hong Kong, and he gave me antihistamines. This drug did control my symptoms but when I stopped taking this drug, the rashes came back.

I talked to one of my former students about my problem, and he suggested I see a Chinese Traditional Medicine (CTM) doctor. The Chinese doctor advised me not to eat bread. In the past, I ate bread with peanut butter. After I stopped taking bread, the rashes went away. At that time, I did not know that peanut butter was the culprit for my rashes. After that, I did not eat bread for several years. It was by chance that I was cured of my rashes, as the Chinese doctor did not know that I was allergic to peanut butter.

About five years ago, I tried eating bread, and I used peanut butter and hazelnut spread again. The rashes came back. At that time, I guessed that peanut butter and hazelnut spreads were the culprits. I experimented with using almond and cashew nut spreads. I was right. I did not develop those rashes when I used almond and cashew nut spreads. So, I stopped consuming peanuts and hazelnuts altogether.

10.3 Should Vegans Avoid Garlic, Onions, Spring Onions, Leeks, and Chives?

In 2014, my Buddhist friends said that it was best to avoid consuming garlic (and garlic shoots), onions, spring onions, leeks, and chives (the five restricted vegetables) for health reasons. Since then, I have avoided consuming these five vegetables as much as I can. There were rare occasions when I ate some bits and pieces of these five vegetables during flights and at friends' places. I do not think I can completely avoid them in the future. For example, some airlines will not be able to fully customize their on-board meals to exclude these five restricted vegetables. Some Buddhists who travel or eat outside will not be able to fully observe this restriction. To me, this is not a big issue, as some situations are unavoidable.

I am not sure about the reasons my Buddhist friends put forward for avoiding these restricted vegetables. They told me that these foods may upset the digestive tract and kill the good gut bacteria. I am not sure if this advice is accurate, but it may make sense. Garlic paste is sometimes applied to a wound because it has antibacterial properties. If garlic can kill the bacteria on the wound, it may kill the good bacteria in the gut. More scientific research is needed to determine whether these food items can harm or benefit the human body.

While some have no medical issues with consuming garlic and onions, others may experience digestive problems.[8] Garlic and onions are very high in a sugar molecule called fructan, a complex carbohydrate that is not easily digestible by humans, but it provides nourishment for the gut bacteria. There have been cases of patients having trouble digesting and showing symptoms of intolerance to fructan, which include bloating, diarrhea, constipation, and intestinal pain. It is good to monitor if one might develop these symptoms when consuming garlic and onions. It is possible to be allergic to garlic, but it is very rare. A few cases have been reported.

When I adopted a vegan diet in 2002, I did not avoid these five restricted vegetables altogether. I did eat some spring onions, but not much. I do not like garlic or onions because they have a strong taste.

It was fine with me if onions and garlic were cooked with other vegetables, and I ate the other vegetables without garlic or onions. I rarely ate leeks and chives in the past — probably five times a year.

Buddhists who are on a strict vegan or vegetarian diet, in general, do not consume these restricted food items. However, what was prescribed many centuries ago may no longer be applicable today owing to environmental changes. We have to be flexible. If these five vegetables could cure certain diseases, vegans and vegetarians should eat them.

Venerable Master Chin Kung (净空法师), a highly respected Buddhist monk, said that it might be acceptable to consume these restricted vegetables in certain circumstances. For example, if someone is sick and needs these vegetables for treatment.[9]

According to Buddhist teachings, these five restricted vegetables affect those who are in the early stages of cultivation in that disciples would find it harder to concentrate. These restricted vegetables may adversely affect one's meditative mind, awareness, and consciousness. Avoiding garlic and onions may help better control feelings of anger.[10]

Buddhists cultivate awareness of their actions and emotions to the fullest extent possible. For example, when one is angry, one should know that one is furious. The problem arises when a person does not know the extent of their anger, particularly when they are in an extreme state of rage.

Allicin, which is present in garlic, improves blood flow to the sexual organs. Allicin can help to increase nitric oxide production, which is important for sexual arousal. Perhaps this is one of the reasons why Buddhists are advised not to consume the restricted vegetables, so they can better control their minds and meditate more effectively.

Ven Chin Kung said that garlic has specific medicinal properties and may cure certain diseases. Ven Chin Kung told a true story of a medical doctor, Dr. Tang, who used garlic to cure a patient. Dr. Tang had a patient who suffered from end-stage tuberculosis. Doctors told the patient that they thought he only had three months to live. Dr. Tang's patient consumed garlic regularly and recovered. It is not clear whether garlic helped the patient, but it is a blessing that the patient ate garlic and recovered. Dr. Tang thought that garlic cured the patient.

Vegans who follow Buddhist practices may seek medical advice before consuming large amounts of these restricted vegetables. It may well be helpful for medical treatments, and so a trained medical specialist must administer it. They should monitor their health to see if there are any adverse effects from consuming these vegetables.

I recommend ginger for those who avoid these five vegetables. I eat ginger almost daily. Ginger has anti-inflammatory and antioxidant properties. An anti-inflammatory substance reduces inflammation or swelling. Briefly, oxidation occurs when an atom or molecule loses one or more electrons. When cells lose electrons, cellular damage can occur. Agents that can inhibit oxidation in the human body boost a person's immunity. Oxidation can trigger a chain reaction that damages an organism's cells. So, the anti-oxidative property of ginger is good.

These five restricted vegetables may harm a vegan's health if consumed in large quantities. Buddhists, especially those in the Mahayana tradition, are advised not to consume these restricted vegetables unless necessary. Those who are sick and need these five vegetables for treatment should eat them if no other option is available.

10.4 Possible Iron Deficiency

Iron deficiency is a concern for some vegans. Several female friends had told me that they suffered from iron deficiency when they were on a vegan diet. They were tested for iron deficiency, and doctors advised them to eat meat after their test results showed low iron levels. They gave up on a vegan diet and resorted to eating meat, including beef.

To women who suffer from iron deficiency on a vegan diet, my recommendation is to try out vegetables that contain high levels of iron before giving up on a vegan diet. Vegetables that contain a high amount of iron include soya beans, chia seeds, beans, peas and lentils, pumpkin, black and white sesame, flaxseeds, almonds, cashews, pine nuts, macadamia nuts, spinach, kale, Swiss chard, collard, beet greens, tomato paste, potatoes, mushrooms, palm hearts, fruits, chocolate, oats, coconut milk, quinoa, whole grains, spelt, dried thyme, etc. Also, to increase iron absorption, it is good to eat foods rich in vitamin C, minimize coffee and tea intake during meals, and consume lysine-rich foods like quinoa, lentils, avocados, nuts, seeds, and leafy greens.[11]

10.5 Importance of Calcium in Our Diet

Calcium is often associated with an essential mineral for healthy bones. Calcium helps fight cancer and regulates cell growth. It helps our cells, muscles, and nervous system to function normally.

Plant-based foods that contain calcium include soybeans, tofu (soybean is an essential ingredient for tofu, and possibly from manufacturer-added calcium), beans, peas, lentils, kale, figs, almonds, broccoli, chia seeds, flax seeds, tahini, amaranth, teff, leafy greens, seaweed, etc.[12]

11 Does a Vegan Diet Help in Reducing the Risks of Future Pandemics?

Episodes of viruses that jumped from animals to humans have led to calls for more people to adopt a vegan diet. Animal to human transmissions of diseases include the 1997 bird flu outbreak in Hong Kong, the Severe Acute Respiratory Syndrome (SARS)-Coronavirus Disease (Covid) outbreak in 2002-2003, the 2014-2015 bird flu outbreak in the US, the Covid-19 pandemic that raged globally from early 2020 till May 2023, and the bird flu outbreak in the USA that began possibly in Feb 2022. The reasoning is that if we put no meat on the dinner plate, the risk of animal-to-human transmission will be greatly reduced.

The 1997 bird flu outbreak in Hong Kong led to the culling of about 1.6 million chickens.[13] The H5N1 virus responsible for the bird flu outbreak jumped from chickens to infect humans. Eighteen people in Hong Kong contracted the virus, and six people died.

The SARS-CoV-1 outbreak in 2002-2003 was highly likely to have originated in Guangdong province, China.[14] Researchers found that a significant proportion of food and animal handlers at markets in Guangdong had antibodies against SARS-CoV-1. Tests conducted at markets in Guangdong showed that civet cats, ferret badgers, and raccoon dogs harbored the SARS-CoV-1 virus. The results do not suggest that these animals play a significant role in the outbreak, but it cannot be ruled out that these animals were the source of the outbreak. The virus spread to 26 countries. The reported cases totaled 8096, and 774 persons died.

The 2014-2015 bird flu outbreak in the US resulted in more than 50 million chickens and turkeys being killed due to highly pathogenic avian influenza (HPAI) or being culled. Thirty million poultry birds perished in Iowa alone.[15] Turkey farms affected were in Arkansas, Iowa, Missouri, North Dakota, South Dakota, Wisconsin, and Minnesota, where the virus was initially identified. The affected chicken farms were in Wisconsin, Iowa, Minnesota, North Dakota, Nebraska, and South Dakota.

The COVID-19 virus was first detected in late 2019, and countries all over the world are still dealing with this pandemic. As of May 6, 2022, globally, 513,955,910 cases attributed to the 2019 COVID-19 virus have been confirmed, and 6,249,700 deaths have been reported to the World Health Organization (WHO).[16] However, WHO's own estimates of deaths are higher when indirect deaths are included.

WHO estimates that, if including indirect deaths, which refer to fatalities related to COVID-19 but not directly attributed to COVID-19 complications, 14.9 million people died by the end of 2021 globally.[17] Indirect deaths refer to those who died as they did not or could not seek treatment for other severe conditions owing to the stress on the health care systems that had to deal with COVID-19, and patients were not attended to due to lockdowns. The source of the virus that led to the pandemic has not been clearly identified.[18] As of May 2, 2023, the cumulative number of cases was approximately 687,225,609, and the reported total number of deaths (excluding indirect deaths) was 6,866,783.[19]

The 2022 Highly Pathogenic Avian Influenza outbreak in the USA has posed a serious challenge to affected states, which are still dealing with the COVID-19 pandemic as of November 2025. The virus was highly contagious among chickens and turkeys, and it was first discovered in Indiana in February 2022.[20] Better known as the bird flu, it has since spread to all 50 states in the USA, and 166 million commercial birds, including chickens, turkeys, and ducks, have died or been culled as of February 2025.[21] More poultry birds are expected to be culled. As of July 2025, 70 cases of humans who contracted the virus have been reported, and a backyard chicken owner in Louisiana died in January 2025.[22]

The outbreaks described earlier are all severe and have led to economic hardships for those affected. COVID-19 resulted in the loss of many precious lives and led to very severe economic crises for many countries. Several countries had declared defaults on their debt obligations primarily due to the adverse financial impacts of COVID-19. In late May 2022, many countries decided to live with the virus and relaxed restrictions, including allowing travelers from other countries to enter without quarantining in an approved hotel or facility.

I believe that if all people turn vegan, animal-to-human transmission could still happen. Many others hold the same view.[23] Humans interact with animals in many other ways, not just when animals are raised on farms.

Possible avenues for animal-to-human transmissions that are non-farming related include possible experiments on biological agents for warfare or protective purposes that involve pathogens, keeping pets, horse riding, horse racing, dog racing, pet shows, coming into contact with animals when in the wilderness, hiking, zoo visits, and wild animals intruding into homes. Transmissions from non-farming-related avenues are certainly possible. Assuming no laboratories are doing experiments for biological warfare, I still firmly believe that the probability is drastically reduced if there is mass adoption of a vegan diet worldwide. Billions of farm animals are kept in crowded conditions worldwide, making it easier for pathogens to spread.

PART II. VEGAN DIET AND HEALTH: THE SCIENCE

12 Research on the Benefits of the Meat-Based Diet

Several articles and health websites advocating for a meat-based diet argue that meat is an essential component of a well-balanced diet. The common thread for supporting meat in a person's diet is that meat is a source of many types of proteins, iron, Vitamin B12, other vitamins, and essential minerals like zinc, selenium, and phosphorus. For a sample of findings on various research issues related to meat-based diets, refer to de Castro Cardoso Pereira et al. (2013)[24], Binnie et al. (2014)[25], McNeill (2014)[26], and Wyness (2016)[27].

Given these conflicting research findings, it is not surprising that several nutritionists and doctors may disagree with the evidence that a vegan diet is a tool for preventive medicine. Many people are already accustomed to eating meat, and a meat-based diet is deeply ingrained in their daily lives. Meat and seafood are already part of many people's way of life. It is not easy for them to get off the meat-based diet, given what has been passed on for generations that “meat is an essential part of one's diet”.

My personal view is that it is good to seek appropriate medical advice on their diet. I recommend that health professionals, including doctors, nutritionists, and nurses, review the relevant literature on vegan diets to provide more comprehensive advice to their patients or clients. To many other health professionals and me, a well-balanced vegan diet is healthy.

13 Medical and Nutritional Research on the Benefits of a Vegan Diet

Aging is a natural process. A person's tissues and organs undergo wear and tear as they age. Even if one does not suffer from any chronic diseases, wear and tear is a natural process. My main goals are to stay healthy, maintain a high quality of life, and avoid contracting chronic diseases. My idea of a high-quality life is to prevent chronic diseases as much as I can. Mortality is not something that I can avoid, but I try my very best to reduce the risks of contracting chronic diseases.

Based on past medical research, a balanced vegan diet can drastically reduce the probability of contracting certain chronic diseases like diabetes, some cancers, heart-related problems, and hypertension. It is not realistic to talk about avoiding sickness altogether if one were to be on a vegan diet.

I have been very fortunate that I have been able to avoid chronic diseases for about 23 years since 2002. I firmly believe this is primarily due to my vegan diet. Before 2002, I had a fever about every 3 to 5 years. In the past 23 years, I have had one bout of fever, which lasted about 24 hours. That was when I received the COVID-19 jab.

More research is needed to determine whether a balanced vegan diet could boost immunity to help fight pandemics like COVID-19. My healthy medical record provides me with more confidence to write my story and hopefully encourages more people to take a closer look at a vegan diet.

Based on past medical research, a vegan diet alters gene expression for the better and significantly reduces the risk of contracting the following diseases. I describe briefly the diseases and the functions of the various organs of the human body below, where applicable. For more details on the anatomy and physiology of the human body, readers may refer to Betts et al. (2022),[28] which provides a more detailed description of the diseases that afflict humans and the functions of the various organs and organ systems.

13.1 Genes Behave for the Better with Vegan Diet

Virtually all human cells contain deoxyribonucleic acid (DNA). DNA is the same in all cells of a particular person, but the functions of the organs and tissues depend on which parts of DNA are turned on and off in the cells that comprise the various organs and tissues. The human cell is the basic unit of life. It carries out essential functions, such as taking in nutrients and oxygen, removing waste products such as carbon dioxide, providing energy, and performing specialized functions depending on the organs or tissues.

DNA, depending on which part is turned on and off in the cell, holds the hereditary material and governs a cell's growth, function, and reproduction. A person's genome — the complete set of DNA in a cell — varies from person to person. Genes are sections of DNA. You can think of the genome as an entire manual, and DNA as its pages. Genes are like paragraphs and sentences in the manual, with specific instructions to make certain proteins and carry out certain functions.

The vast majority of human DNA sequences, however, are identical across individuals; i.e., about 99.8–99.9% of a person's genome sequence is similar to that of an average person's. Though there is a high similarity rate, small variations in the genome across individuals explain why people differ. A

DNA molecule consists of two strands that form a double helix. The double helix looks like a ladder with rungs. These rungs form the genetic codes. A genome has billions of "these rungs", and so slight variations in genomes across individuals indeed give rise to millions of differences that make people uniquely different.[29]

Elizabeth Blackburn, the 2009 Nobel Prize in Physiology or Medicine co-winner, and Dr. Dean Ornish find that 500 genes change in behavior for the better in only three months with a vegan diet.[30] [31] This is a pathbreaking study and deserves more awareness among health officials, politicians, teachers, parents, etc.

Their groundbreaking research shows that a vegan diet and lifestyle changes turn on the genes that prevent diseases like cancer, and turn off genes that cause breast cancer, heart disease, and prostate cancer. The lifestyle changes include exercise and stress reduction. It should be noted that people cannot get different genes, but they can change how the genes act through their lifestyle and diet.

13.2 Meat, the Production of Free Radicals, ROS, and Antioxidants

Free radicals are unstable atoms, molecules, or ions with an unpaired electron in their outermost orbital, and they can harm or destroy the cells in the human body. Free radicals and radicals are used interchangeably in this book.

Free radicals can cause oxidative stress and cellular damage throughout the human body, leading to various health problems. Oxidative stress occurs when there are more free radicals than antioxidants. Excessive free radicals have been associated with damage to the DNA, cells, and tissues, skin aging, and the development of chronic diseases such as colorectal cancer, breast cancer, prostate cancer, liver cancer, kidney cancer, lung cancer, cardiovascular diseases, liver diseases, renal diseases, and neurodegenerative disorders.[32]

Cancer-related diseases are discussed further below. Heart-related diseases are the leading cause of death in the USA, followed by cancer. A simplified summary of how the heart works is provided in Appendix 1. Appendix 1 will hopefully help readers to understand the basic terms and the medical research on heart-related diseases, discussed later.

As free radicals are responsible for cell and DNA damage, leading to the development of numerous diseases, I provide a moderately detailed write-up on free radicals in Appendix 2. Appendix 2 describes the underlying scientific principles of how free radicals harm the human body.

Free radicals are produced in the human body internally as a result of essential metabolic processes. Externally, lifestyle choices such as smoking, meat consumption, alcohol consumption, and environmental factors like pollution, radiation, and second-hand smoke result in increased production of free radicals in the human body. A high level of emotional stress can also lead to the production of free radicals in the human body.

While meat is not a free radical, it can play a significant role in inducing the production of free radicals in the human body. That meat consumption is associated with the production of free radicals in the human body should not be taken lightly. The preservatives in processed foods such as sausages, bacon, ham, and salami induce the production of free radicals.[33]

Meat, particularly red meat, contains heme iron. The high heme iron content in red meat promotes oxidative stress through chemical reactions that generate free radicals. The processing, storage, and cooking of meat can generate free radicals and carcinogenic compounds.[34]

Heme iron, which is found in animals, contains iron. The lipids in the meat consumed are susceptible to oxidation due to their heme iron content. The polyunsaturated fatty acids, which are components of the lipids in the meat consumed, are particularly vulnerable to attacks by free radicals in the oxidation process. The oxidation process generates free radicals in the human body. When heme iron reaches the colon, it stimulates oxidation reactions there. The oxidized lipids in colon cells may be a factor in why consuming red meat is linked to colorectal cancer development.[35]

There are molecular differences between heme iron and non-heme iron. There is an iron atom in the heme iron molecule. Heme B has the chemical formula $C_{34}H_{32}FeN_4O_4$ and is found in the hemoglobin in humans and animals.[36] There are other kinds of heme with different chemical compositions, but all have the iron component, Fe.

An example of non-heme iron that originates in plants is phytoferritin.[37] Phytoferritin is a protein complex that stores ferric iron, Fe^{3+}. Phytoferritin is not part of the heme protein complex. Note that non-heme iron can also be found in meat when animals consume plants.

An important difference between the heme iron and non-heme iron is bioavailability. In general, bioavailability refers to the rate at which the human body absorbs nutrients. Heme iron is absorbed at a faster rate than non-heme iron. That does not mean that non-heme iron is not as good as heme iron. When iron levels are too high in the blood, it can lead to iron toxicity, which can cause organ failure. Non-heme iron poses a lower risk of iron toxicity given its lower absorption rate.

Cooking at high temperatures can cause oils and fats in meats to oxidise. Higher heat intensity can lead to greater oxidation, as heat provides the energy for the relevant molecules to participate in oxidation. Cooking vegetables in oil can also produce free radicals. However, the issue is more of a problem for meats than for plants, as meats contain heme iron and relatively higher levels of fat than plants.

Free radicals are not necessarily harmful if they are not excessive. Free radicals, in moderation, are essential for normal metabolic activities, including cellular respiration and immune responses. For example, the immune system uses free radicals to fight pathogens.[38] Certain immune cells produce free radicals to damage the microbes' membranes and critical parts.

Free radicals can damage the unsaturated fatty acids, particularly the polyunsaturated fatty acids. In the human body, polyunsaturated fatty acids are essential components of cell membranes and are crucial for nerve function, brain health, and blood clotting.

Oxidative stress occurs when free radical levels are excessive and antioxidant levels are insufficient, making it difficult for the body to cope. The human body can neutralize free radicals through an internal antioxidant system, but excessive free radicals can create an imbalance. Antioxidants protect human cells from damage caused by free radicals by donating to or sharing an electron with the free radical. An antioxidant is a substance that inhibits oxidation.

Free radicals can also initiate chain reactions, producing more free radicals that harm the human body. The molecule or atom that has lost the electron now becomes a free radical itself, continuing the chain reaction, which can terminate if two free radicals bond to form a stable molecule or if antioxidants intervene.[39] It is scarce, however, in the human body for two free radicals to react with each other to form a non-radical molecule.

Meat consumption also induces the production of reactive oxygen species (ROS) in the human body. ROS molecules are highly reactive and contain oxygen. ROS are not necessarily free radicals, as some ROS lack unpaired electrons. There are different types of ROS with distinct chemical compositions, such as the hydroxyl radical HO• (also a free radical) and hydrogen peroxide (not a free radical). Meat contains unsaturated fats, which are prone to ROS-mediated oxidation. These attacks result in cellular damage, including damage to the DNA.

The antioxidants that the human body produces include glutathione, superoxide dismutase (SOD), catalase (CAT), melatonin, uric acid, and alpha-lipoic acid.[40] [41] Externally consumed antioxidants support the human body's internal antioxidant system. After antioxidants neutralize the free radicals, the resulting molecules are stable and will not cause a chain reaction that produces free radicals. Examples of antioxidants include Vitamin A, Vitamin C, Vitamin E, beta-carotene, selenium, manganese, flavonoids, lycopene, and lutein. They are found in fruits, vegetables, whole grains, nuts, seeds, tea, coffee, and dark chocolate.

Dark chocolate contains flavonoids. They improve blood flow, heart, and brain health.[42] Lycopene is found in tomatoes, watermelon, pink grapefruits, pink guavas, and apricots, and also has anticancer, anti-inflammatory, and antidiabetic properties.[43] Lutein is found in spinach, kale, broccoli, corn, zucchini, and squash, and is essential for eye health. Lutein helps in preventing macular degeneration and cataracts. It may also benefit the skin and cardiovascular system.[44]

The body can convert provitamin A carotenoids from plants into vitamin A, which means the human body cannot make vitamin A from nothing. A provitamin is a substance that can be converted into a vitamin in humans and animals through a cellular mechanism. Vitamin C, E, beta carotene, selenium, manganese, flavonoids, lycopene, and lutein are not manufactured in the human body.

It is advisable to consume antioxidants from plants rather than from supplements. If one takes supplements such as Vitamin C, Vitamin E, and beta-carotene supplements in tablet or other forms, do not overload. Studies have shown that some supplements may contain excessive amounts of antioxidants that may protect cancerous cells.[45]

The human body can repair damaged cells caused by free radicals, but we need to consume a balanced intake of antioxidants and other essential nutrients to support this repair. It is indisputable that meat also contains antioxidants such as vitamin E and glutathione. However, it is noteworthy that a vegan diet is richer in antioxidants than a meat-based diet.[46] Though meat contains antioxidants, it also induces the production of free radicals.

The likelihood for two free radicals to react with each other to form a stable non-radical molecule is low. This is an important fact, as free radicals can damage DNA in cells, including the DNA in sperm and ova. Damage to the DNA in sperm and ova may adversely affect fertility and may cause abnormalities in offspring.

Plants are rich in antioxidants that help minimize or eliminate the damage caused by free radicals and reactive oxygen species. But a vegan diet must be balanced with a wide variety of vegetables, fruits, and nuts.[47]

13.3 Lower Risks of Contracting Cancer

Cancer occurs when normal cells grow abnormally and become cancerous cells. Normal cells have a controlled cycle of growth and death, but cancerous cells do not. The cancerous cells can grow and divide without limit.

According to WHO[48] [49], processed meats, including ham, bacon, salami, and frankfurters, belong to Group 1 carcinogens, which means there is strong evidence that these foods cause cancer. In its unprocessed form, red meat, such as beef, lamb, and pork, has been classified as a Group 2A carcinogen. Group 2A carcinogen means these foods probably cause cancer. The fact that meat in its processed form is a carcinogen has been well established. Meat, in its unprocessed form, probably causes cancer.

The probability of contracting colorectal cancer, breast cancer, and prostate cancer is very much reduced for those who are on a vegan/vegetarian diet. The researchers usually employ a prospective study, a research method that tracks participants over time to examine specific outcomes aligned with the study's objectives. For example, they may assess whether the incidence of a particular type of cancer is significantly lower with a well-balanced vegan diet, using data collected over a specified period.

13.3.1 Colorectal Cancer

The relationship between colorectal cancer and diet has been a subject of immense interest in medical research. Orlich et al. (2015)[50], using cohorts from a study that spans about 7.3 years, find that those on a vegetarian diet, as a group that includes participants on a vegan, lacto-ovo vegetarian, pesco-vegetarian, and semi-vegetarian diet, have a 43% lower risk of contracting colorectal cancer than those who are on a non-vegetarian diet.

A future study that has a larger sample size of vegans that spans a more extended period will provide a better understanding of the relationship between the risks of contracting colorectal cancer and those who are on a vegan diet and a non-vegan diet. This study, however, provides support for the relationship that those who eat meat less frequently and with a lower intake amount have lower risks of contracting colorectal cancer.

13.3.2 Breast Cancer

Toniolo P. et al. (1989)[51] in an NYU Cancer Institute study find that breast cancer patients ate more meat, cheese and butter than women without breast cancer. They find that those who consumed a larger amount of animal products had as much as three times the breast cancer risk of those who consumed less.

13.3.3 Prostate Cancer

The prostate gland produces a significant portion of the seminal fluid, which nourishes and transports sperm. Sperm is produced by testicles, also known as testes. Other roles of the prostate include the production of a hormone called dihydrotestosterone (DHT), which acts with other hormones to promote the development of the male external genitalia.

Tantamango-Bartley et al. (2015)[52] find that those who follow a vegan diet are 35% less likely to suffer from prostate cancer than those who follow a non-vegetarian, lacto-ovo-vegetarian, pesco-vegetarian, or semi-vegetarian diet.

13.3.4 Liver Cancer

The liver plays a vital role in filtering and processing blood, aided by the blood itself. Indeed, all organs and tissues require nutrients, and all are aided by blood, which carries nutrients and oxygen to the cells. The organs of the human body, including the liver, perform functions that involve blood.

The liver has more than 500 vital functions and performs specific tasks, including removing waste products from metabolic processes and toxins and harmful substances from the blood. The functions include the production of bile which helps to carry away waste and breaks down fats, the production of specific proteins for blood plasma, the conversion of excess glucose into glycogen (the storage form for glucose) for storage and from glycogen back to glucose when needed, the conversion of poisonous ammonia to urea which is excreted in the urine, the production of cholesterol which is an essential component for cell membranes and a starting material for hormones such as testosterone and estrogen, the processing of hemoglobin from worn-out red blood cells, etc.

Whole blood contains plasma, blood cells (red blood cells and white blood cells), and platelets (large cell fragments that can form a plug at the site of wounds). Plasma is the liquid component of blood and helps to transport the blood cells, platelets, antibodies, nutrients, waste products, and hormones. Plasma is obtained by adding an anticoagulant to whole blood to prevent clotting. Blood is then centrifuged to separate the liquid portion, i.e., plasma, from red blood cells, white blood cells, and platelets. As no clotting has occurred during centrifugation, the plasma contains clotting factors such as fibrinogen.

Serum is the liquid portion that remains when no anti-coagulants are added to whole blood, and so clotting or coagulation of blood takes place naturally. In this case, whole blood consists of serum and blood clots. Blood clots so formed this way in the test tube include red blood cells, white blood cells, clotting factors, and platelets.

Blood clots at the injury site differ from naturally formed blood clots in that the initial clot at the injury site is composed primarily of fibrin (a clotting agent), red blood cells, and platelets. White blood cells (WBCs) can be part of the blood clot at the injury site as they fight bacteria. Serum is plasma minus the clotting factors, such as fibrinogen. Fibrinogen converts into insoluble fibrin during the final stages of clotting at the injury site. Blood plasma does not contain fibrin.

Hemoglobin's role is to transport oxygen from the lungs to the tissues and organs, and to carry carbon dioxide from the body cells to the lungs to be expelled. A hemoglobin molecule comprises heme groups and globin chains. Heme is the non-protein iron-containing component found in meat and fish. Heme is also known as heme iron. Globin is a protein component.

The liver helps to break down the hemoglobin into heme and globin. The heme is converted into bilirubin, and the globin into amino acids. Bilirubin binds to albumin and is transported to the liver, where it is used to make bile.

Dong et al. (2025)[53] suggest that a stronger adherence to plant-based diets, particularly healthy plant-based foods, while limiting less healthy plant foods, may protect against liver cancer and liver disease-related deaths in males. Healthy plant-based foods include fruits, nuts, legumes, whole grains, and various vegetables, while unhealthy plant-based foods include refined grains, sugary drinks, and processed foods. However, they do not find a similar statistically significant relationship for females and are unclear as to why this is the case. They offer potential explanations, including the possibility that progesterone and estrogen in females may protect against some cancers, while higher testosterone levels in men may promote cell growth.

13.3.5 Kidney Cancer

Renal cell carcinoma is a type of kidney cancer and accounts for 90% of kidney cancer cases. Renal cell carcinoma refers to cells that make up the kidney's tiny tubules that have become cancerous. Kidneys remove wastes and excess fluid from the blood to form urine. Renal tubules are the tubes in the kidney that filter blood and produce urine. Another type of kidney cancer is transitional cell carcinoma, which refers to cells lining the renal pelvis, ureters, and bladder that have become cancerous. The renal pelvis is a funnel-shaped part of the ureter within the kidney. It collects urine, which is then funneled via the ureter to the bladder. Please refer to Brown (2025)[54] for a picture of the kidney.

Daniel et al. (2013)[55] find that high intake of fiber and fiber-rich plant foods is associated with a significantly lower risk of renal cell carcinoma in a sample of participants in the USA. Their findings support recommending plant-based, fiber-rich diets to prevent renal cell carcinoma.

13.4 Non-Cancer Diseases

With a vegan diet, the probability of suffering from heart-related diseases and diabetes is significantly reduced. Vegans who contracted COVID-19 had less severe symptoms, according to a recent study. Maintaining good eyesight is easier on a vegan diet.

13.4.1 Heart-Related Diseases

Before examining the research on the benefits of a vegan diet for health, a brief discussion of the heart's functions is presented below. A discussion of the chemical composition and functions of cholesterol follows, as cholesterol is closely linked to heart-related diseases. Lipids, fats, and triglycerides are also discussed, as they are related to heart disease.

13.4.1.1 Brief Introduction on How the Heart Works

(See Figure 1.1, Basic Anatomy of the Heart in Davies et al. (2015)[56] for a picture of the basic anatomy of the heart.)

The primary function of the heart is to pump blood throughout the body. Arteries are so named as they carry blood from the heart to other parts of the body, and veins are defined as blood vessels that carry blood to the heart from other parts of the body. The pumping of the heart is a cycle of contractions and relaxations of the heart muscles.

Pumping of the heart involves the contraction (systole) and relaxation (diastole) of the interconnected cardiac muscles that interact and work in a coordinated fashion. The heart-pumping action is initiated by electrical impulses generated by the heart's electrical conduction system. The natural pacemaker of the heart, also known as the sinoatrial (SA) node, is located in the right atrium. The SA node is part of the heart's electrical conduction system and generates electrical impulses that initiate each heartbeat.

The electrical signals or impulses that are generated by the SA node travel through specific pathways in the heart to coordinate the contraction and relaxation of the cardiac muscles. For more details on how the heart functions, please refer to Appendix 1.

The pulmonary veins carry oxygenated blood from the lungs to the heart. The heart then pumps oxygenated blood through the aorta, which connects to the heart. The blood then flows into the smaller arteries that branch from the aorta, delivering oxygen and nutrients to cells and tissues.

Cells need oxygen for metabolic activities, particularly for aerobic respiration. The carbon dioxide waste product of cellular metabolism is carried in deoxygenated blood through the veins to the heart. The heart then pumps this deoxygenated blood from the heart to the lungs through the pulmonary arteries. The carbon dioxide diffuses from the capillaries via gaseous exchange into the alveoli of the lungs and is expelled during exhalation.

In line with the definition of arteries, the pulmonary arteries carry deoxygenated blood from the heart to the lungs, and the other arteries carry oxygenated blood from the heart to different parts of the body. Except for the pulmonary veins, which carry oxygenated blood from the lungs to the heart, other veins carry deoxygenated blood from the body cells to the heart.

The heart itself needs nutrients and oxygen to carry out its functions and expels waste products as a result of its cells' metabolic activities. The part of the blood circulation through which the heart receives nutrients (including oxygen), and discharges wastes (such as carbon dioxide) is known as the coronary circulation. The heart gets its oxygen and nutrients from the coronary arteries, which branch off the aorta. The deoxygenated blood that carries carbon dioxide and other wastes as a result of the metabolism of the cells of the heart flows into the coronary veins. The coronary veins drain into the coronary sinus vein, which carries deoxygenated blood to the heart.

13.4.1.2 The Functions and Composition of Cholesterol

Cholesterol is related to heart-related diseases. High-density lipoprotein (HDL) cholesterol is commonly called the "good" cholesterol. Low-density lipoprotein cholesterol is frequently called the “bad” cholesterol. LDLs and HDLs are lipoproteins made of lipids and proteins. Cholesterol is a waxy substance that is insoluble in water. Cholesterol contains the elements carbon, hydrogen, and oxygen, and has the chemical formula $C_{27}H_{46}O$.

Cholesterol contains a hydroxyl group, OH, a stable, non-radical group. Cholesterol is not a fat, technically, as it does not contain fatty acids. There is no cholesterol in plant-based foods. Cholesterol is found in meat, dairy, and eggs.

It should be noted that cholesterol is not all “bad”, as some may mistakenly think. Cholesterol is essential as a component of the cell membrane, serves as a precursor for producing vitamin D, is a precursor for synthesizing steroid hormones, including sex hormones, and is a central component of bile acids, which are made in the liver. Bile acids are components of bile and help break down fats for digestion.

Lipoproteins serve as carriers for cholesterol in the bloodstream. As cholesterol carriers, HDL and LDL transport the same cholesterol in the blood; i.e., the chemical composition and nature of the cholesterol they carry are identical. The high amount of cholesterol carried by LDL, not its chemical composition itself, is a health concern. Though LDL cholesterol is known as the “bad” and HDL cholesterol the “good”, the chemical composition of cholesterol in both LDL and HDL is the same.

Low-density lipoproteins (LDL) and high-density lipoproteins (HDL) do not consist of cholesterol only. LDL and HDL are lipoproteins composed of proteins and lipids, including cholesterol. Proteins contain the elements nitrogen, carbon, hydrogen, and oxygen. The nitrogen element is not part of the molecular structure of cholesterol.

LDL and HDL lipoproteins differ in their chemical composition and function. The lipids in lipoproteins are made up of cholesterol and triglycerides. LDL and HDL differ in their lipid and protein compositions, and these differences dictate their functions.

LDL has a lower protein content and a higher lipid content than HDL, which has a higher protein content. Hence the name, “lower density (of protein)” for LDL. HDL is known as “high-density” lipoprotein because it has a higher protein content than LDL. About 25% of LDL is protein, and 50% of LDL is cholesterol. About 50% of HDL is protein, and 20% of HDL is cholesterol.

LDL carries cholesterol from the liver to cells and tissues, which is why excessive levels can be harmful. Hence, LDL cholesterol is known as the “bad” cholesterol, but bear in mind that cholesterol is essential to the human body and is needed by cells for many functions. Cholesterol is bad only when it is excessive.

LDL contains more cholesterol and less protein than HDL, and this characteristic explains why LDL deposits cholesterol in arteries, which can lead to plaque buildup. The cholesterol in the LDL is released to (or transferred to) the cells and tissues for their respective uses.

HDL carries cholesterol from tissues and cells back to the liver, which is why it is known as the good cholesterol. HDL contains less cholesterol but more protein. The composition of proteins and lipids in HDL explains why HDL serves as the "good" carrier that removes cholesterol from cells and returns the cholesterol to the liver for elimination through the bile in faeces.[57] [58]

Another type of lipoprotein is the very low-density lipoprotein (VLDL). The liver produces VLDL. VLDL is part of the cholesterol test and is included in total cholesterol in the blood.

Triglycerides make up 50-70% of a VLDL particle. VLDL delivers triglycerides to the cells after being produced by the liver. The chemical composition and roles of triglycerides in the human body are discussed in the following subsection, Lipids, Fats, and Triglycerides.

A lipid test measures cholesterol levels. Total cholesterol, the cholesterol in HDL, and the cholesterol in LDL are measured in mg/dL or milligrams per deciliter. The test results are calculated as the weight of cholesterol in a deciliter of blood. It does not mean that the test requires a deciliter of blood. 1 liter equals 1,000 milliliters. 1 deciliter equals 100 milliliters.

The usual optimal range for LDL cholesterol is for LDL not to exceed 100mg/dL, but this varies depending on whether patients have heart-related diseases. If that is so, doctors will recommend a lower value. LDL cholesterol is not to exceed a certain level, as LDL carries cholesterol to the cells. Cholesterol in VLDL is not included in LDL cholesterol measurements because VLDL and LDL are distinct lipoproteins.

A high concentration of LDL in the blood can be damaging to health, as LDL particles can get stuck to the artery wall. Over time, plaque builds up. The higher the number of LDL particles in a given volume of blood, the greater the level of bad cholesterol and the higher the risk of plaque buildup. A smaller particle size is associated with a higher risk of heart disease than a larger particle size.[59]

For HDL, the optimal range is above 60 mg/dL. For HDL, it is generally good to have a high HDL level, as HDL lipoproteins carry cholesterol to the liver for further processing. But the HDL cholesterol level cannot be too high. HDL does not stick to artery walls like LDL because HDL has a higher protein-to-fat ratio than LDL. Lipoproteins with a higher protein-to-lipid ratio are more soluble in blood, as there is a higher percentage of protein. Proteins are generally more water-soluble than lipids. As noted previously, 50% of HDL is protein, and 20% is cholesterol, compared with 25% protein and 50% cholesterol in LDL.

The normal range for total cholesterol is usually below 200mg/dL, but it varies by individual. Total cholesterol consists of cholesterol from LDL, HDL, and VLDL.[60]

Cholesterol in the blood exists in free cholesterol (or unesterified cholesterol) and cholesteryl ester forms. Cholesteryl esters are also called cholesterol esters. In the blood, cholesterol is typically about 70-80% esterified, i.e., present as cholesteryl esters. Cholesteryl ester is simply the free cholesterol attached to a fatty acid. Both the free cholesterol and cholesteryl ester are constituents of the lipoproteins, i.e., both the LDL and HDL have cholesterol in the form of cholesterol ester and free cholesterol.

In cholesterol tests, the cholesterol within cholesteryl esters must be released from the fatty acids. The enzyme, cholesterol esterase, is typically used to accomplish this task. The free cholesterol released from cholesteryl ester is combined with the free cholesterol in the blood to get accurate cholesterol measurements.

As for triglyceride testing, a normal triglyceride level is less than 150 mg/dL in adults. In children and teens, normal triglyceride levels vary with age. Note that triglycerides and cholesterol are not the same. Triglycerides are fats, while cholesterol is technically not considered a fat. Triglycerides store unused calories for energy, while cholesterol is used to build cells, hormones, and other structures.

For more technical details on the tests for cholesterol and triglycerides, including the chemicals used and the chemical reactions, see Appendix 3. These tests are quite common, and cholesterol levels are associated with heart disease. There are many other important medical tests, and I am providing examples of cholesterol and triglyceride tests to explain the scientific basis and chemical principles behind them.

13.4.1.3 Lipids, Fats, and Triglycerides

Lipids are a broad term for substances that consist of hydrocarbons (consisting of carbon and hydrogen), and include organic compounds that are insoluble in water but soluble in organic solvents. Lipids include fats, waxes, oils, phospholipids, cholesterol, steroids, and fat-soluble vitamins such as vitamins A, D, K, and E. Fat-soluble vitamins are those soluble in fats but not in water.

Fats are a general term that includes triglycerides, mono- and diglycerides, free fatty acids, phospholipids, and sterols. Fats are insoluble in water and must contain fatty acids. The definition of fats depends on how they are characterized. If fats are used in a dietary sense, fats refer to triglycerides and do not include wax and sterols. Fats are insoluble in water.

Fats and lipids are not used interchangeably in a scientific sense in chemistry. Lipids include fats, but we cannot say that lipids are always fats. For example, Vitamin D is not a fatty acid but is a lipid.[61] Cholesterol is a lipid, not a fat technically, as it does not contain fatty acids. Unofficially, fats and lipids are sometimes used interchangeably, but technically, they are not necessarily the same.

Triglycerides are a type of fat found in one's blood and are also found in body fat. Triglycerides are the most common fats in the human body. Triglycerides are formed in the following way. Three fatty acid chains and glycerol react, forming triglycerides and water. The "tri" in triglycerides refers to three fatty acid chains. The chemical formula for glycerol is $C_3H_8O_3$. Glycerol has three hydroxyl groups attached to three carbon atoms.

The glycerol in triglycerides is considered the backbone. The fatty acid chains are attached to the glycerol backbone. A fatty acid chain consists of a hydrocarbon chain and a carboxyl group.

The fatty acid chains in triglycerides can be wholly saturated fatty acids, wholly unsaturated fatty acids, or a mixture of saturated and unsaturated fatty acids. Triglycerides composed entirely of saturated fatty acid chains are called saturated fats, while triglycerides wholly consisting of unsaturated fatty acids are called unsaturated fats. Triglycerides composed of both saturated and unsaturated fatty acids are called mixed triglycerides.

Monoglycerides ("Mono" means one fatty acid chain) refer to glycerol attached to one fatty acid chain, and diglycerides ("di" means two fatty acid chains) refer to glycerol attached to two fatty acid chains. Free fatty acids are fatty acids not attached to glycerol. A difference between triglycerides and free fatty acids is that free fatty acids are not attached to the glycerol backbone. In contrast, the fatty acid chains in triglycerides are attached to the glycerol backbone. See Appendix 2 for the molecular structure of free fatty acids and triglycerides.

A phospholipid is composed of a glycerol backbone, two fatty acids, phosphoric acid, and an organic alcohol group. Sterols are characterized by four hydrocarbon rings, a hydrocarbon tail (or chain), and a hydroxyl group. Cholesterol is a type of sterol.

Triglycerides are mainly derived from the foods we consume, particularly fats and oils. Triglycerides are stored in the fat cells of the human body when the calorie intake exceeds the calories used up. When the body needs energy, triglycerides are converted into energy. Fat cells are specialized cells that store energy in the form of fat, primarily as triglycerides.

Excessively high levels of triglycerides from animal sources are harmful because they can contribute to the hardening and thickening of arterial walls, a condition called atherosclerosis, which can result in blockages of blood vessels. Thickening of the arteries means the arteries become less hollow, and blood flow is not as smooth in the arteries. Reduced blood flow can reduce oxygen delivery to cells. It can combine with LDL to build up plaque, which may lead to a heart attack and stroke.

Triglycerides from plant-based sources are generally considered safer than those from animal sources. Plant-based triglycerides, which are primarily unsaturated fats, are associated with a lower risk of heart disease. In contrast, animal-based triglycerides, often saturated fats, are linked to higher LDL cholesterol and increased risk of heart-related problems.

Animal-based triglycerides are often rich in saturated fats. Saturated fats are less healthy than unsaturated fats, as saturated fats can raise LDL cholesterol, which increases the risk of heart disease.

Saturated fats are found primarily in animal sources, dairy products, palm oil, and coconut oil. It does not mean, however, that palm oil and coconut oil should not be consumed. Palm oil contains vitamin E and phytosterols, which can help a person lower LDL cholesterol. The lauric acid in coconut oil can help increase HDL cholesterol, the good cholesterol. However, coconut water does not contain saturated fats and helps to lower LDL and increase HDL. If an individual wishes to consume palm oil and coconut oil, it is advisable to monitor their intake and to follow dietary guidelines.

Unsaturated fats are from plant-based food items. Plant-based triglycerides, on the other hand, are primarily composed of unsaturated fats, which can be monounsaturated or polyunsaturated, and can help lower LDL cholesterol.

13.4.1.4 The Research on Heart-Related Diseases and Meat

Papier et al. (2021)[62] also present systematic evidence of a link between meat consumption and other non-cancer diseases. The authors, after adjusting and controlling for factors like smoking, alcohol consumption, body weight, and other factors, show that higher consumption of unprocessed red meat and processed meat is linked to a 15% higher risk of ischemic heart disease (heart disease caused by narrowed heart arteries).

A reason put forward for the higher risks of heart diseases is that eating meat increases a person’s bad cholesterol, i.e., low-density lipoprotein (LDL) cholesterol. Excessive amounts of LDLs in the blood may build up as plaque in the walls of the arteries. If it increases over time, the arteries will get more blocked. Blood flow will be restricted, and this may lead to a myocardial infarction (commonly known as a heart attack) or angina, which is a type of chest pain caused by reduced blood flow to the heart. As stated earlier, the heart needs oxygen too to obtain the energy to pump continuously. The coronary arteries branch off from the aorta and carry oxygen and nutrients to the heart muscles. The aorta is the main artery from the heart.

If plaque builds up in the coronary arteries, a blockage could develop. A heart attack occurs if the blood supply to the heart muscles is completely blocked or severely reduced. Symptoms may include squeezing and tightness across the chest. Cardiac arrests, which are rarer than heart attacks, may happen. Cardiac arrest is a condition in which the heart stops beating properly, or suddenly stops beating altogether.

Alasmre and Alotaibi (2020)[63] review articles on the link between a vegan diet and heart failure and advocate a vegan diet for heart failure patients. Their review supports adopting a vegan diet alongside implementing the primary treatment regimen as prescribed by doctors and cardiologists for heart failure patients. Heart failure is defined as the heart's inability to pump blood effectively throughout the body. This can happen to either the right or left side of the heart, or both at the same time.

Heart failure patients who adopt a vegan diet show a positive clinical experience and improvements in the risk factors, including hyperlipidemia, hypertension, and diabetes mellitus. Risk factors for heart failure are medical conditions that can contribute to its development.

A heart attack can lead to heart failure, and it is medically incorrect to equate heart failure with a heart attack. Heart failure is a condition that often develops over time and is associated with the deterioration of the heart muscles (also known as cardiac muscles). A heart attack can lead to heart failure as the cardiac muscles may not be able to function properly to pump blood. Some heart attacks occur suddenly, but early warnings weeks or days before they happen can include shortness of breath and chest pain or pressure.

Hyperlipidemia is an excess of LDL and triglycerides in one’s blood. Hypertension, also known as high blood pressure, is a condition in which blood pressure is exceedingly high, pressing against the walls of the arteries. High blood pressure can damage arteries, which may lead to blockages of arteries that result in heart attacks or strokes. Renal artery blockages can cause kidney disease. Diabetes mellitus is the full name for diabetes and is discussed in a separate subsection below.

Landry et al. (2024)[64] use an umbrella review of systematic reviews to compare the relationships between vegetarian, vegan and non-vegetarian dietary patterns and cardiovascular diseases and the contributing risk factors including the level of LDL cholesterol (the bad cholesterol), blood pressure, body mass index, and c-reactive protein concentrations, and find that adopting a vegan diet has been linked to a reduction in the aforementioned CVD risk factors.

An umbrella review is an overview, a synthesis, or a review of original studies or systematic reviews. Systematic reviews often employ databases and use specific methodologies involving statistical methods to study a particular issue and draw conclusions, for example, whether a vegan diet could help reduce the risk of colorectal cancer. Cardiovascular diseases (CVD) are a broad term that includes all diseases of the heart and blood vessels, like heart attack, coronary artery disease, stroke, and heart failure.

LDL and blood pressure have been discussed above. Body Mass Index (BMI) is a relative measure of an individual's weight-to-height ratio that estimates body fat in adults. A very high BMI above a certain range for obesity is a cause for concern, but the BMI index is combined with other measurements, such as LDL levels, to provide information on the risks of an individual contracting CVD.

High levels of C-reactive protein have been associated with an increased risk of heart attack and ischemic strokes. C-reactive protein is a protein produced by the liver in response to inflammation in the body. Landry et al. (2024) recommend that medical practitioners advise their patients to adopt a vegan diet so that the risks of contracting CVD can be reduced.

Storz and Helle (2019)[65] review the evidence available at the time of their study and find that a whole-food plant-based diet may be a valuable tool for managing and reducing common risk factors for atrial fibrillation, including hypertension, coronary artery disease, inflammation, obesity, and diabetes. Storz and Helle (2019) conclude that a plant-based diet is a valuable tool for lowering the risks of developing atrial fibrillation.

Atrial fibrillation is a type of arrhythmia and refers specifically to an irregular and often rapid heartbeat that occurs in the atria. See Appendix 1 for a description of the atria. Fibrillation refers to the irregular and unsynchronized contraction of muscles. Tachycardia refers to the heart beating too fast, and AF often involves tachycardia. Arrhythmia may be broadly classified into tachycardia and bradycardia. Bradycardia is a medical condition characterized by a slow heart rate.

Kuipers et al. (2024)[66] also review several studies and show that plant-based diets can help prevent and reduce many of the risk factors that contribute to atrial fibrillation (AF), such as hyperthyroidism, diabetes, obesity, and hypertension, as well as a history of stroke or heart attack. Hyperthyroidism is a medical condition in which the thyroid gland produces excess thyroid hormone. The symptoms include hand tremors and a rapid or irregular heartbeat.

In the USA, the number of deaths from heart attacks per 100,000 has declined from 354 per 100,000 in 1970 to 40 per 100,000 in 2022. This decline in deaths per 100,000 is attributed to better health care, advances in treatment, more frequent doctor visits, and medical procedures patients undergo to diagnose these conditions before a patient’s health worsens. Many other countries with well-established medical systems also show similar reductions. However, studies have shown a drastic increase in deaths related to arrhythmia and heart failure.[67] [68]

The studies above have shown that a vegan diet is a preventive tool against certain cardiovascular diseases. For those already suffering from CVD, a vegan diet is a valuable tool to manage CVD in addition to the primary treatment.

13.4.2 Strokes

A stroke can occur either from a blockage in an artery supplying blood to the brain (ischemic stroke) or from bleeding in the brain due to a ruptured blood vessel (hemorrhagic stroke). In rare cases, both events may happen simultaneously. When a stroke occurs, the brain is deprived of oxygen and nutrients.

Chiu et al. (2020)[69] find that the Taiwanese vegetarian diet is associated with a lower risk of ischemic and hemorrhagic strokes. There were about 13,000 participants in their prospective study. The Taiwanese vegetarian diet referred to in the study is largely based on the diet adopted by the Tzu Chi Buddhist group.

Baden et al. (2021)[70] find that healthy plant-based diets may lower overall stroke risk by up to 10%. Their results were based on a sample of 73,890 women participants in the Nurses' Health Study (NHS; 1984–2016), 92,352 women participants in the Nurses' Health Study II (1991–2017), and 43,266 men participants in the Health Professionals Follow-Up Study (1986–2012). The healthy plant-based diet referred to in Baden et al. (2021) includes leafy greens, whole grains, beans, and nuts with limited intake of processed foods, refined grains, and added sugars.

13.4.3 Diabetes

When the pancreas, the primary organ that produces insulin, does not produce enough insulin, or when the body cannot effectively use the insulin it produces, high blood sugar levels can result. Consistently high blood sugar levels lead to diabetes. Insulin is a hormone that acts like a key to regulate the uptake of glucose by cells.

Type 1 diabetes is a type of autoimmune disease, and it occurs when the immune system abnormally attacks the insulin-producing cells responsible for producing insulin. Type 2 diabetes is characterized by inadequate production of insulin. While Type 2 diabetes is more common than Type 1 diabetes, it is more challenging for doctors to manage Type 1 diabetes owing to the autoimmune abnormalities inherent in Type 1 diabetes. Symptoms of diabetes include slow-healing sores, tiredness, blurred vision, and frequent infections. In certain unfortunate situations, patients may have to undergo amputations of the lower limbs.

Papier et al. (2021), who establish a relationship between unprocessed red meat and processed meat and a higher risk of ischemic heart disease (as discussed earlier), also show that unprocessed red meat and processed meat are linked to a 30% higher risk of diabetes. On the adverse effects of poultry meat, which is considered white meat, a 30-gram increase in poultry meat intake per day was associated with a 14% greater risk of diabetes.

In an NUS study, Koh et al. (2017)[71] find that there is a link between the amount of red meat and poultry consumed and the risk of developing Type 2 diabetes. The participants in the study were divided into four quartiles according to their red meat and poultry intake. The top quartile with the highest red meat and poultry intake shows a 23% and 15% increase, respectively, in the risk of contracting diabetes compared with those in the lowest quartile of red meat intake.

Some studies examine the association between intake of heme iron and the risk of contracting Type 2 diabetes. Heme iron is found in animals, while non-heme iron is found in both plants and animal products like eggs and dairy.

Based on a meta-analysis (i.e., an analysis that utilizes results from multiple studies), Shahinfar et al. (2022)[72] show that a higher heme iron intake is associated with a 20% increase in the risk of Type II diabetes.

Li et al. (2020)[73] suggest that higher dietary intake of heme iron, particularly from red meat, is associated with a greater risk of contracting type 2 diabetes in middle-aged and older adults. Further, Li et al. (2020) show that non-heme iron is not associated with a higher risk of contracting Type 2 diabetes.

These studies show that heme iron intake, which is found in meat, is associated with a higher risk of Type 2 diabetes. Given the results of these studies, one should examine very carefully before taking iron supplements that are made of heme iron. It is best to talk to a pharmacist, nutritionist, or doctor before taking iron supplements and inform them of the results of these studies.

13.4.4 Chronic Kidney Disease

Chronic Kidney Disease (CKD) is characterized by the kidneys losing their ability to effectively filter waste and excess fluid from the blood. Waste and excess fluid must be removed; otherwise, a buildup of these byproducts will be catastrophic for the patient.

Kim et al. (2019) [74] present evidence that those on a healthy plant-based diet have a lower risk of contracting CKD. A healthy plant-based diet includes whole grains, fruits, vegetables, nuts, legumes, and tea. They recommend avoiding less healthy plant-based foods, such as refined grains, sugar-sweetened and artificially sweetened beverages, sweets, and desserts. They find that adhering to a healthy plant-based diet reduces the decline of the kidney's estimated glomerular filtration rate (eGFR). eGFR is a measure of the kidney's ability to filter waste and toxins in a person's blood.[75]

Joshi et al. (2020)[76] recommend a vegan diet for both primary and secondary prevention of CKD. Primary prevention is the prevention of disease before it strikes. Secondary prevention is about managing and reducing the impact of a disease that has occurred in a patient. They state that the risk of potassium overload (i.e., hyperkalemia) that medical professionals usually associate with plant-based diets is not justified.

Cases et al. (2019)[77] argue that a vegan diet offers health advantages to those with chronic kidney disease. A vegan diet, when coupled with professional nutritional advice, is safe for these patients.

13.4.5 Parkinson's Disease

Parkinson's disease becomes worse with age, and a patient may only show motor symptoms such as tremors and slowness in movement long after the onset of the underlying neurodegenerative processes that are associated with the disease. McCarty (2001)[78] presents three case-control studies and concludes that diets that are high in animal fat or cholesterol are linked with a significant increase in the risk for developing Parkinson's disease. Conversely, fat from plant-based foods does not appear to increase the risk of Parkinson's disease.

Tresserra-Rimbau et al. (2023)[79] provide evidence that a healthy plant-based diet that includes sufficient intakes of vegetables, nuts, and tea in one's usual diet is associated with a lower risk of Parkinson's disease. Their results are based on 11.8 years of follow-up data for 126,283 participants.

13.4.6 Lower Severity of Covid-19 Symptoms and Vegan Diet

Based on data from six countries, Kim (2021)[80] finds that those on plant-based or pescatarian diets have 73% lower odds of experiencing moderate to severe COVID-19 than those following protein-rich, low-carbohydrate diets. Protein-rich, low-carbohydrate diets refer to higher intakes of animal proteins, such as poultry, red meat, and processed meats.

This study is important because it provides evidence that a plant-based diet, or diets low in poultry, red meat, and processed meats, offer protection against the severe form of COVID-19. The severity and symptoms of COVID-19 are related to dietary factors.

13.4.7 Eye Diseases

To maintain good eye health, I strongly recommend a well-balanced plant-based diet based on my experience so far. Good eye health can be maintained on a well-balanced vegan diet.[81] Fruits and vegetables are good for eye health and reduce the risk of acquiring certain eye conditions and diseases. The eye conditions and diseases include macular degeneration, night vision, age-related degeneration, dry eyes, UV damage to the eye, cataracts, and glaucoma.[82] Carrots contain Vitamin A and are rich in carotenoids. Carotenoids are also found in fruits and other colored vegetables.

Carotenoids are required by our body to make Vitamin A. Vitamin A, Vitamin C, and zinc are essential to help reduce the risk of cataracts and macular degeneration.

Macular degeneration is an incurable eye disease, but treatments can slow its progression. The macula is part of the retina, and its function is to provide sharp, clear, and central vision. The antioxidants lutein and zeaxanthin, found in broccoli, kale, spinach, peas, and lettuce, help preserve the macula.

Higher intake of bioavailable lutein/zeaxanthin is associated with a long-term reduced risk of advanced age-related macular degeneration (AMD).[83] A public health strategy to increase the consumption of a wide variety of fruits and vegetables rich in carotenoids can reduce the incidence of advanced AMD.

Vitamin C is also essential for retinal health. Vitamin C is found in fruits and vegetables and is an antioxidant. Vitamin E is also an effective antioxidant that protects the eye from harmful free radicals. Plant-based foods that contain Vitamin E include almonds, peanuts, hazelnuts, pine nuts, sunflower seeds, wheat germ, and red bell pepper.

A cataract refers to the cloudy area in the lens of the eye. Cataracts worsen as a person gets older and are caused by cumulative oxidative stress over the years. However, cataracts can occur at a young age owing to UV exposure, smoking, diabetes, and other factors.

Imelda et al. (2022)[84] recommend that plants be incorporated into one's diet (with lesser meat) as a strong preventative measure to delay cataract progression or to minimize the risks of contracting cataract. Consuming a variety of fruits and vegetables, which contain antioxidants, is encouraged as antioxidants can counteract the free radicals generated internally, and externally, e.g., through meat consumption. Wearing sunglasses is also very important.

I strongly recommend that everyone wear sunglasses when they are out during the daytime. Sunglasses protect our eyes against harmful ultraviolet (UV) radiation. UV rays can damage the eyelid, cornea, lens, and other parts of the eye. So, do wear sunglasses when you are out in the sun in any season. Those sunglasses with UV 400 protection are highly recommended as they block nearly all light rays with wavelengths up to 400 nanometers, i.e., almost all UV light.

A short description of waves and wavelengths follows. Sunlight consists of waves in the visible spectrum and the invisible spectrum, such as UV and infrared radiation. Our eyes are genetically programmed to detect light within the visible spectrum, i.e., approximately 400–780 nm.[85]

White light (also known as visible light) seen from the sky is the combination of the colors red, orange, yellow, green, blue, indigo, and violet (with the acronym, VIBGYOR) in approximately equal proportions. A wavelength is measured from peak to peak or from trough to trough. E.g., if the wavelength is 400 nm, it is measured from peak to peak.

We cannot see UV light (approximately 100 to 400 nm wavelength) or infrared wavelengths (starting from 700 – 800 nm) because our eyes are not adapted to these wavelengths. For example, we can see red as red corresponds to the wavelength of about 627 – 780 nm. Violet has a wavelength of about 400–436 nm. These colors are within the visible spectrum, i.e., approximately 400–780 nm, that our eyes are programmed to see. Light itself does not have colours but is composed of different wavelengths.

When light hits a red object, the red object reflects the waves of the wavelength corresponding to red, i.e., about 627 – 780 nm, and absorbs the other waves of wavelengths, i.e., only waves of wavelength of about 627 – 780 nm are reflected. A black object is interpreted as black by the human brain, as the black object absorbs all the colours of white light. A white object reflects all colours of white light.

It is more accurate to state that the object reflects the waves of a particular wavelength (not the wavelength itself). The eye processes the wavelength, sends signals to the brain, and the brain interprets the signal as indicating that the object is red. Solids reflect light - that is why we can see them. A vacuum does not reflect light because there are no particles in a vacuum.

The conversion of meter to micrometers and nanometers is as follows: 1 meter = 1 million µm or micrometers; 1 meter = 1,000,000,000 nm or nanometer; 1 µm = 1,000 nm.

Sunglasses reduce the risk of cataracts, photokeratitis, and growth masses in the eyes, such as Pinguecula and Pterygium.[86] [87] Photokeratitis is a sunburn-like condition affecting the cornea. A pinguecula is a yellowish, raised growth on the conjunctiva.

A pterygium refers to a growth of fleshy tissue containing blood vessels that may start as a pinguecula and may grow large enough to cover part of the cornea. The cornea is the outer transparent part of the eye and covers the iris, pupil, and the anterior chamber of the eye. It refracts light and helps our eyes to focus. The conjunctiva is the clear tissue that covers the outer portion of the sclera and the inside of the eyelids. The sclera is the white part of the eye.

Wearing sunglasses is very important to prevent eye diseases, as free radicals are produced when the eyes are exposed to ultraviolet light. Free radicals are discussed in more detail in Appendix 2.

13.4.8 Constipation

Lee et al. (2016) [88] find that switching from a meat-containing diet, referred to as a "normal" diet in Lee et al. (2016), to a diet rich in fruits and vegetables reduces the incidence of constipation. The subjects participated in a vegetarian diet for 12 weeks.

I could add to this issue based on my own experience with the issue of bowel movements. My digestive system gently "wakes" me up almost every morning, prompting me to go to the restroom. I have no problem with this, and it has been a daily morning activity for me. I drink water as soon as I get up, and this helps.

Those on a well-balanced vegan diet eat plenty of fruits and vegetables. All these foods are loaded with fibers that gently move the food we consume along the digestive tract more smoothly. However, those on a vegan diet should take more liquids, as vegans consume more fiber. The liquids can be water, juices, or soup. It is advisable not to consume large amounts of water or other liquids immediately after or during a meal. This can lead to bloating and indigestion for some.[89]

It is alright to take sips of water during a meal and immediately after meals, but not too much, say about a glass.[90] It is advisable to take more liquids, preferably lukewarm, about an hour after a heavy meal. However, do not overload with too much pure water as it can lead to hyponatremia, a condition arising from exceedingly low levels of sodium in a person's blood.[91] I take soup, drink juice or tea, and do not necessarily drink only water.

I do get stomach upsets, but luckily, about once or twice a year. I just had to go to the toilet to unload, and I would be alright after a few hours. It is certainly possible to get food poisoning from vegetables, and one is advised to take the usual precautions, such as eating at hygienic places and avoiding consumption of vegetables after the expiry date.

For food items consumed before their expiry date, do take note of possible deterioration of the food item that may render the food item unsafe to consume. I once bought a can of plant-based powdered food item months before its expiry. It caused me some gastrointestinal discomfort. I discontinued using it, and the gastrointestinal discomfort disappeared. Maintain some awareness that the food item may have deteriorated and discard it if there is discomfort.

13.5 Summary of the Medical Research

The evidence and published research show that adopting a vegan diet has benefits. The risks of contracting cardiovascular diseases, strokes, chronic kidney diseases, Parkinson's disease, and certain eye diseases, such as cataracts, are lower.

A very important finding of research papers is that plant-based diets, rich in antioxidants, counteract the free radicals in the human body. Free radicals harm the cells in the human body, including damaging the DNA. Meats, while not a free radical, induce the production of free radicals in the human body. Meats contain unsaturated fatty acids, and the unsaturated fatty acids are easily prone to attacks by free radicals and reactive oxygen species.

A vegan diet is a very powerful preventative tool against a range of chronic diseases. There will be substantial savings in healthcare costs for the government and individuals if more people adopt a vegan diet.

14 What about Milk and Eggs?

There are conflicting research results on whether milk and eggs harm a person's health.

14.1 About Milk

The essential nutrients in milk include calcium, Vitamin D, Vitamin B12, proteins, Vitamin K, potassium, etc.[92] These nutrients can also be found in plant-based food items or supplements. Research findings are conflicting on whether milk harms a person's health.

Thorning et al. (2016)[93] support milk as part of one's diet and argue that milk consumption is associated with reduced risks of childhood obesity, neutral or reduced risks of Type 2 diabetes, reduced risks of cardiovascular disease, such as stroke, and is beneficial for bone mineral density. Further, their findings suggest that milk and dairy intake are associated with lower risks of colorectal cancer, bladder cancer, gastric cancer, and breast cancer. Their research does not show an association between milk intake and risks of pancreatic cancer, ovarian cancer, or lung cancer, and the evidence presented for prostate cancer risk is inconsistent. They find no support for a relationship between milk consumption and overall mortality risk.

Fraser et al. (2020)[94], however, find that a higher intake of dairy milk is associated with higher risks of contracting breast cancer. Drinking one cup of milk (8 ounces) a day increases the risk by up to 50%, and consuming two to three cups a day further increases the risk to 70–80%. A notable finding is that the risk of contracting breast cancer is 30% for those drinking as little as 1/4 to 1/3 cup of dairy milk.

Fraser et al. (2020) suggest that the link between dairy milk and cancer could be attributed to the sex hormones in milk, such as estrogen and progesterone, and serum insulin-like growth factor-1 (IGF-1) in milk. While some researchers and medical professionals argue that the levels of estrogen and progesterone are small in milk, low-fat milk and whole milk promote mammary tumor growth in rats.[95] [96]

A growth factor is a natural substance that helps to promote growth and development, and is found in the human body and in food. Insulin-like growth factor (IGF) is a growth factor that is structurally similar to insulin. To make it clear, IGF is not the same as insulin. Insulin is a hormone that helps to regulate the amount of glucose in the blood. IGF is called a growth factor as it stimulates the growth of many types of cells in the human body, such as muscle cells, neurons, and bone cells. Insulin is produced in the pancreas, while IGF is produced primarily in the liver.

There are two principal forms of IGFs, i.e., IGF-1 and IGF-2. IGF-1 is a hormone that regulates growth in adults and helps in maintaining and managing blood sugar levels.[97] IGF-1 is primarily produced by the liver (as noted earlier). IGF-1 and IGF-2 are called insulin-like as their functions are similar to insulin, and they are involved in glucose metabolism. IGF-2 is different from IGF-1 in that IGF-2 is a major growth factor in the fetus. IGF-2 is produced in a variety of somatic cells (all of the cells in a human body except sperm and ova) during fetal development and in the liver after birth.[98]

One in eight women in the USA will develop breast cancer during their lifetime. The research findings by Fraser et al. (2020) deserve attention from doctors and other members of the medical profession. Fraser et al. (2020) find no clear association between soy intake and breast cancer.

Higher levels of IGF-1 are linked with an increased risk of developing cancer.[99] Milk contains IGF-1, and certain substances in milk may trigger the production of IGF-1 in the body.[100, 101] I hope there will be more research in this area to further our understanding of these issues.

Romo Ventura et al. (2020)[102] measure IGF-1 in blood samples against milk intake, and find that higher milk intake is associated with higher concentrations of IGF-1. Kakkoura et al. (2022)[103] find that a higher dairy intake increases the risks of developing cancers, particularly liver cancer, female breast cancer, and possibly lymphoma. Dairy intake was not segregated into milk, cheese, yoghurt, etc., in their study.

The possible explanations that Kakkoura et al. (2022) put forward include the following:

- IGF-1 in milk is associated with several cancers, including breast cancer.
- There are substances in milk that could activate mechanisms that lead to growth in cancer cells.
- The saturated fatty acids (SFA) and trans-fatty acids from dairy products are linked with insulin resistance and increased levels of proinflammatory cytokines. Proinflammatory cytokines are possible risk factors for liver cancer and lymphoma.
- Sex hormones in milk, such as estrogen and progesterone, likely have a role.

Saturated fatty acids are one of the two major categories of fat, and it is advisable to limit their intake to reduce the risk of heart-related diseases. The trans fatty acid, also known as trans fat, is a type of trans-unsaturated fatty acid molecule, discussed in more detail in A2.9 of Appendix 2. It occurs naturally in animal fats and is also produced industrially.

Trans fats produced through industrial processes have been banned by the FDA. They harm the human body by increasing bad cholesterol and lowering good cholesterol. Cytokines are molecules typically produced by immune cells, but also by non-immune cells. Cytokines that are "good" help the body fight off and kill infections. But too many cytokines can be bad, like a big storm.[104] Proinflammatory cytokines are cytokines that are "bad" and make diseases worse.[105]

Rahmani et al. (2022)[106] find that there is an optimal specific mid-range of IGF-1 associated with the lowest mortality (i.e., the most extended lifespan). Very high and very low levels of IGF-1 shorten lifespan, i.e., increase mortality risk. Further, Rahmani et al. (2022) show that a high intake of milk-based products such as milk, cheese, and yoghurt leads to very high IGF-1 levels.

For those who are worried about the adverse effects of milk and wish to switch to plant-based milk, it is safe, based on my experience. Do take the usual precautions, such as not consuming after the expiry date, etc., and make sure the quality is good. I have been drinking soy milk for more than 23 years, and I have also been drinking almond milk for the past few years. I try to avoid preservatives and additives that are not natural. I feel fine. It is crucial to ensure that everyone on a vegan diet meets the daily nutrient requirements.

14.2 About Eggs

Eggs contain essential nutrients such as proteins, potassium, choline, vitamin A, vitamin D, vitamin E, lutein and zeaxanthin, iodine, folate, phosphorous, selenium, etc.[107] [108] However, a whole egg contains about 200 mg of cholesterol and IGF-1. Cholesterol and IGF-1 in eggs are substances that have been the subject of research by nutritionists and medical professionals to determine whether they are related to heart-related diseases and other illnesses. There are conflicting research findings on whether eggs are detrimental to a person's health.

Hu et al. (1999) [109] find that an egg a day is unlikely to have any adverse effect on coronary heart disease (CHD) or stroke among healthy men and women. However, Zhong et al. (2019)[110] find that for the sample comprising US adults in their study, higher intakes of dietary cholesterol or eggs are associated with higher risks of cardiovascular diseases (CVD) and all-cause mortality. CVD diseases are related to the heart and blood vessels, and all-cause mortality refers to death from any cause.

Zhong et al. (2019) find these relationships to be statistically significant and that higher intakes of either cholesterol or eggs increase the risks. For every 300 milligrams (mg; 1 gram = 1,000 mg) increase in cholesterol intake, the risks of CVD and all-cause mortality increase by 17% and 18%, respectively. For every additional consumption of half an egg, the risks of CVD and all-cause mortality increase by 6% and 8% respectively.[111]

PART III. VEGAN DIET AND THE ENVIRONMENT: THE SCIENCE

15 Vegan Diet is Good for the Environment

A vegan diet can surely help Mother Earth. The incremental emissions of greenhouse gases can be reduced by about 14%-20% if everyone follows a vegan diet, but this is, of course, impossible to achieve.

This chapter reviews the potency of the various greenhouse gases, explains the reasons why greenhouse gases trap the heat irradiated from Earth, describes how carbon sinks are indeed facing their own problems, highlights the fact that the ocean is becoming more acidic, provides details on how overfishing is causing more greenhouse emissions, explains how animal farming is undoubtedly threatening the supply of freshwater, and adding to the pollution of freshwater and the emissions of greenhouse gases, and reports on the melting of glaciers that is causing the problem of seawater rise.

There is no doubt that greenhouse gas emissions are not being brought under control. The concentration of carbon dioxide in the atmosphere has increased to 430 ppm, the level that must be capped at to prevent the global temperature from rising by more than 1.5°C. All is not lost, however, as efforts are underway to increase the use of renewable energy and to research innovative solutions to reduce or capture greenhouse gas emissions.

15.1 Global Warming: The Basic Facts

Mass adoption of a vegan diet globally will significantly reduce the adverse impacts of climate change. Global warming is a critical issue that is endangering the planet and future generations. Greenhouse gases, i.e., carbon dioxide, water vapor, methane, nitrous oxides, halons, and fluorinated gases, contribute to global warming.

The world is still heavily reliant on fossil fuels for its energy needs. In 2020, about 83.1% of global energy consumption came from fossil fuels. Proportion-wise, that is a decline from 84% in 2019, due to reduced oil use and greater use of renewable and nuclear energy, offsetting an increase in natural gas use.[112] [113]

The proportions of the various energy sources are as follows approximately for 2020 and 2019 (the figures for 2019 are in brackets): Oil makes up 31.2% (33%), natural gas accounts for 24.7% (24%), coal comprises 27.2% (27%), nuclear energy constitutes 4.3% (4%), hydroelectric power amounts to 6.9% (6%) and renewables provides the remaining 5.7% (5%) of the total energy consumed.

While fossil fuels account for a major share of global daily energy consumption, the good news is that there is an upward trend in total renewable energy generation worldwide, as shown by data from 2001 to 2020.[114] The main sources of renewable energy include hydroelectric, solar, and wind power.

Total energy generated from all renewable energy sources in 2001 was about 2,815 terawatt-hours. Since then, renewable energy production has increased, reaching 7,444 terawatt-hours in 2020. The share of solar and wind power in total renewable energy generation grew from about 1.4% in 2001 to about 33% in 2020. Solar energy generated in 2001 was only one terawatt-hour, but had increased to about 856 terawatt-hours in 2020.

About 52.42 billion metric tons of greenhouse gases (GHGs) in carbon dioxide equivalents were emitted anthropogenically in 2018. The value of 52.42 billion metric tons of GHGs is a gross figure, estimated without subtracting GHGs removed by carbon sinks such as forests and oceans. GHG emissions went up in 2019 but declined in 2020 due to COVID-19.

GHG emissions increased from 50.79 gigatons in 2020 to an estimated value of 53.82 gigatons in 2023. The estimated value for 2024 is 53.2 gigatons.[115] These estimates include incremental changes owing to land use. Reforestation, for example, mitigates climate change, while deforestation worsens it.

It is fair for someone to state that there are also greenhouse gas emissions through natural means, such as volcanoes, decomposition of wetlands (lands covered by water), decaying vegetation and other organic materials, respiration of animals in the wild, release of nitrous oxide via microbial activities in the soil, forest fires, and water vapor. Estimating the amount of greenhouse gases emitted by natural sources is very challenging.

It is almost impossible for humans to control GHG emissions through natural means, which are part of an ongoing natural cycle. The incremental production of greenhouse gases from human-related activities is something governments and individuals can act upon to mitigate the problem.

Carbon dioxide equivalents are adjustments for the heating potency of other greenhouse gases. The other GHG produced when using fossil fuels include methane and nitrous oxides, and their potency is measured relative to carbon dioxide.

Globally, livestock farming accounts for about 14.5%-20% of anthropogenic greenhouse gas emissions annually. The Food and Agriculture Organization of the United Nations (FAO) estimates that animal farming accounts for about 14.5% of all anthropogenic greenhouse gas emissions.[116] Twine (2021)[117] reports a higher figure and estimates that 16.5% of all greenhouse gas emissions are attributed to animal farming. Xu et al. (2021)[118] also come up with a higher figure and estimate that animal farming contributes about 20% to global anthropogenic greenhouse gas emissions.

Based on circa 2010 data, Xu et al. (2021) estimate that globally, the entire food production system emits 17.3 billion tons of anthropogenic greenhouse gases, and that animal farming, including livestock feed, accounts for 57% of all food production emissions. It follows that about 0.57*17.3 or 9.86 tons of greenhouse gases are attributed to animal farming. The global greenhouse gas emissions for 2010 are estimated to be about 49.8 billion tons.[119] This means that about 19.8% (i.e., 9.86/49.8) of all greenhouse gases come from animal farming. In this book, I use a figure of about 14.5% to 20% to account for global anthropogenic greenhouse gas emissions attributable to animal farming. These are incremental estimates owing to livestock farming.

If everyone adopted a vegan diet, 14.5% to 20% of global greenhouse gas emissions would be removed from the atmosphere. This is currently an impossible wish, as only a tiny percentage of people are on a vegan diet. The most important greenhouse gases from animal agriculture are methane and nitrous oxides, in addition to carbon dioxide. Those on a vegan diet are contributing to Earth in combating global warming.

Renewable energy sources, such as solar and wind power, are crucial to winning the battle against global warming. Mass adoption of a vegan diet also helps. Do not underestimate the small contributions at the individual level. A friend of mine joked that if he were to be on a vegan diet, it would be hugely insignificant, as a lot of people in the world are not vegans. It is indeed insignificant if only a few people adopt a vegan diet. If everyone contributes a little or eats less meat, that is a lot on a global scale, as we add up the contributions across billions of people all across Earth. We can all contribute to bringing about change. It may seem small and insignificant, but if added up globally, it can have a huge impact.

According to NASA, global temperatures have already risen by about 1.10°C compared to pre-industrial levels (1850 to 1900). We are currently seeing the consequences of global temperature rise. For example, sea levels have risen 8–9 inches since 1880.[120]

The central aim of the Paris Agreement in 2015 is to limit global temperature rise to well below 2°C and, ideally, to 1.5°C above pre-industrial levels (1850 to 1900).[121] The IPCC now uses 1.5°C as the target instead of 2°C, i.e., the target global temperature rise is limited to 1.5°C above the pre-industrial period.[122]

With a target limiting temperature rise to 2°C, the consequences of climate change would be more severe than if the target were 1.5°C. These consequences include higher sea-level rise, species extinction, greater frequency and severity of heat waves, droughts, and flooding, and greater declines in the yields of farm crops.[123]

More than 130 countries have committed or are considering achieving carbon neutrality by 2050. Carbon neutrality, according to the Intergovernmental Panel on Climate Change (IPCC), can be achieved if an entity that produces anthropogenic carbon dioxide (say 10 metric tons) removes a similar amount of carbon dioxide (i.e., 10 metric tons) through, e.g., additional tree planting and technological advancements. Storing the carbon dioxide produced securely is also acceptable as meeting the requirements of carbon neutrality.

Based on 2016 data, carbon dioxide accounts for about 74.4% of greenhouse gas emissions, methane about 17.3%, nitrous oxide about 6.2%, and hydrofluorocarbons (HFCs) and sulfur hexafluoride (SF6) account for the remaining 2.1%.[124] To keep the temperature rise below 1.5°C, we need a 7.6% annual reduction in GHG emissions from 2020 to 2030.[125] It remains to be seen whether this reduction in GHG emissions can be achieved, but it does not look promising, as a significant reduction is required. GHG emissions from 2020 to 2023 increased when we needed a decline. Mass adoption of a vegan diet can certainly contribute to this target.

National policies in all countries need to respond to this vital issue, and all people have to look at their usage of fossil fuels (including natural gas, oil, and coal). Governments across the globe need to encourage the widespread adoption of a vegan diet, solar and wind power, and other renewable energy sources to manage the global temperature rise.

Limiting coal, oil, and gas extraction will undoubtedly hit employment and the profitability of companies affected by this policy. Some governments, at the local, state, or national level, have banned the extraction of coal, oil, and gas in certain areas. These policies have economic and political consequences. While others have argued for a free-market approach to the extraction of coal, oil, and gas with no interference from the relevant governmental authorities, others are concerned that the climate change problem is severe and demand drastic government action.

Many others hold the view that climate change is severe but advocate a more measured approach on the extraction of fossil fuels. Jobs and economic growth are at stake when there are restrictions on the extraction of fossil fuels. The conflict between jobs in the fossil fuel industry, economic development, and global warming is difficult to manage, as countries around the world implement remedial measures to address global warming.

The fossil fuel industry is also related to energy independence and a lesser reliance on foreign energy imports. The industry is intertwined with financial and national security.

15.2 Greenhouse Gases: Varying Potencies and the GWP

This adjustment to account for the potency of other greenhouse gases relative to carbon dioxide involves a numerical figure known as the global warming potential (GWP) of a particular greenhouse gas. The GWP of a greenhouse gas is the ratio of its cumulative radiative forcing to that of CO2 over a given time period, such as 20 or 100 years.

Radiative forcing refers to the imbalance between the energy that reaches the Earth and the energy radiated away from the Earth, and this imbalance is caused by human and natural factors. Natural causes include volcanic eruptions and changes in the Sun's solar activities, e.g., sudden bursts of energy (solar flares) and solar wind.

The term "Radiative" refers to the imbalance between energy flow from incoming solar radiation and the heat energy Earth emits back into space as outgoing infrared rays. The Earth radiates heat back into the atmosphere as infrared radiation because the Earth is cooler than the Sun.

The term "forcing" refers to the imbalance in Earth's energy flow that is driven by external influences, such as human activities. Hence, the term "cumulative radiative forcing" refers to the total or cumulative effect of radiative forcing over a certain timescale, e.g., 20 years. When the Earth warms, it means more heat energy is trapped by greenhouse gases than is radiated back into space.

The GWP adjusts for the heating potency of a particular greenhouse gas relative to carbon dioxide over a given time scale.[126] A '100-year GWP' of a gas refers to the equivalent amount of carbon dioxide one has to release into the atmosphere to have the same effect on the Earth's temperature over 100 years. The warming potential of a GHG can be measured over, say, 20 years, 100 years, or another time scale. But because carbon dioxide is the benchmark, carbon dioxide has a GWP of 1 regardless of whether we are considering warming potential over 20 years or 100 years.

Methane (CH_4) has a lifespan of 12 years when released into the atmosphere, after which methane is oxidized to water (H_2O) and carbon dioxide (CO_2), following a series of chemical reactions based on the oxidation process with the oxygen molecule (O_2) as a reactant: $CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$. So, the end product of methane after its lifespan is water and carbon dioxide.

Methane traps heat at 100 times the rate of carbon dioxide immediately upon release, but its potency declines over time. The water and carbon dioxide by-products can, of course, still cause damage. For example, based on a 20-year GWP and using a GWP of 84-87, a metric ton of methane will translate to between (1*84) and (1*87) or 84 to 87 metric tons of carbon dioxide equivalents. This means that a metric ton of methane is 84-84 times more potent than a metric ton of carbon dioxide in warming the Earth over 20 years.

Carbon dioxide can remain in the atmosphere for hundreds of years. The GWP over 20 years is higher than the GWP over 100 years because methane has a short lifetime of 12 years, and its potency is diluted over time as it is removed from the atmosphere. The Intergovernmental Panel on Climate Change (IPCC) recommends a GWP for methane of 84 - 87 when considering its impact averaged over a 20-year timeframe. It suggests a lower GWP figure of 28 - 36 when considering its impact over a 100-year timeframe (GWP100). Both figures for the GWP of methane, whether based on a 20-year period or a 100-year period, are still greater than the GWP 1 for original carbon dioxide emissions.

15.3 How Greenhouse Gas Traps Heat

Carbon dioxide in the atmosphere, along with water vapor, serves its purpose in trapping heat. Otherwise, Earth's temperature would be nearly zero Fahrenheit or about -18°C. Earth practically gets all its energy from sunlight. Though Earth emits energy of its own through, e.g., geothermal radiation and radioactive decay, Earth's own emitted energy is comparatively minuscule compared to what Earth receives from sunlight.

There is a difference between energy and heat. Sunlight consists primarily of ultraviolet (UV) light, visible light, and infrared radiation. Sunlight carries energy in the form of UV radiation, visible light, and infrared radiation. Heat is generated when sunlight impinges on the object, exciting its atoms and molecules and causing electrons to move, which in turn generates heat. When sunlight travels through space as electromagnetic radiation, it can pass through a vacuum. Space is, for all intents and purposes, a vacuum (not a perfect one), though there may be gases, asteroids, and particles. In a vacuum, no heat is generated, but sunlight contains energy and travels through space, which is almost a vacuum.

Some of the energy that Earth emits into the atmosphere is trapped by greenhouse gases. The heat that the greenhouse gases trap is emitted in all directions, with some of the heat heading back to Earth. This heat is radiated back again into the atmosphere.

The heat that Earth emits back into the atmosphere comes from the energy of sunlight that impinges on Earth, and also the heat that is trapped by greenhouse gases radiating back onto Earth. But, as noted earlier, we should be clear that Earth gets practically all its energy from sunlight, and the heat trapped by greenhouse gases derives its energy from sunlight.

Listed by increasing order of the wavelength, the components of sunlight with their respective wavelengths are i) ultraviolet light (UV) with wavelengths shorter than 0.4 µm, ii) visible light, with wavelengths between 0.4 and 0.8 µm, and iii) infrared radiation with wavelengths between approximately 0.7 µm and 3 µm.

While sunlight also consists of other wavelengths that are longer than the infrared component of sunlight, such as radio waves (but produced naturally), these other longer wavelengths are inconsequential, as practically all of the energy from sunlight is attributed to ultraviolet (UV) light, visible light, and infrared radiation. Only a very tiny amount is from longer wavelengths.[127] Note that 1 µm = 1 micrometre.

The components of sunlight have higher energy and shorter wavelengths than the lower-energy, longer-wavelength infrared radiation Earth emits back into the atmosphere. The radiation intensity in the infrared portion of sunlight is mostly between 0.8 µm and about 1.4 µm, with insignificant intensity beyond 1.4 µm. Of the total incoming solar radiation, UV accounts for 8%, visible light for 42.3%, and infrared for 49.4%.

The infrared spectrum is, generally, a segment with wavelengths ranging from approximately 780 nanometers to 1 millimeter, but note that the infrared component of sunlight has waves of various wavelengths measuring between 700 nm and about 3,000 nm. 1 millimeter is equal to 1 million nm (or nanometer). The infrared component of sunlight that contributes to energy is essentially in the wavelength range of 700 nm to about 2,500 nm.[128]

The Sun is, of course, hotter than Earth, and so the wavelength of sunlight is, on average, shorter than the wavelength of radiation emitted from Earth. As sunlight travels from the Sun through space and impacts Earth, its full spectrum of various wavelengths remains essentially unchanged. However, there are minor modifications, such as absorption by certain particles and gases (e.g., the UV component of sunlight absorbed by ozone) and reflection by clouds.

Because Earth is cooler than the Sun, the infrared radiation it emits back into the atmosphere has longer wavelengths, about 3,000 nm to 100 µm, and lower energy than the shorter-wavelength, higher-energy sunlight.[129] We feel the heat owing to infrared radiation.

An analogy to explain why waves with longer wavelengths are of lower energy than waves with shorter wavelengths is to look at the waves in the ocean. A slow-moving wave with low energy in the ocean has a longer distance between crests, but fast-moving waves with lots of energy have a shorter distance between their crests. UV and gamma rays have shorter wavelengths than infrared radiation. Gamma rays from nuclear radiation have very intense and pinpointed energy with a wavelength of less than 0.01 nm. Gamma rays can penetrate and destroy human and animal cells.

Visible light and infrared radiation constitute about half of the radiation that hits the Earth's surface. UV light constitutes a minor but important portion of the radiation. UV light is important for the production of vitamin D. Together with infrared radiation, UV light is important for photosynthesis and plant growth.

A greenhouse gas has the molecular structure to absorb infrared radiation emitted from the Earth's surface and re-radiate it back to the Earth's surface. Heat re-radiated by greenhouse gases radiates in all directions, but the radiation toward the Earth's surface is of major concern.

The heat-trapping behavior of carbon dioxide is related to its molecular structure. Owing to this molecular structure, carbon dioxide absorbs energy over a range of wavelengths from 2,000 to 15,000 nm (i.e., 2 µm to 15 µm).[130] Hence, carbon dioxide is able to absorb radiation within the spectrum of between 3 µm to 100 µm that is emitted from Earth. The carbon dioxide molecules in the atmosphere absorb the emitted radiation from the Earth and do not interact with the infrared component of incoming sunlight, which is of shorter wavelength.

Methane primarily absorbs infrared radiation at wavelengths of about 3.3 µm and 7.6 µm, but also at other wavelengths, such as 1.7 µm, 2.3 µm, and 1.65 µm. These wavelengths are also within the spectrum of the infrared radiation Earth emits back into the atmosphere. 1 µm or micrometer = 1,000 nm.

Oxygen and nitrogen, the other major atmospheric gases, absorb energy within the wavelength of about 200 nm or less, i.e., 0.2 µm or less, which falls outside the wavelength range of the infrared radiation emitted from Earth. Hence, oxygen and nitrogen do not contribute to global warming.

Elaborating on the outgoing part of "radiative forcing" referred to earlier, we are concerned about the heat energy Earth emits back into the atmosphere as outgoing (from Earth) infrared radiation, which is then trapped by greenhouse gases. Greenhouse gases resonate with the wavelength unique to infrared radiation, i.e., the GHGs trap or absorb this particular wavelength.

The heat trapped by greenhouse gases is essential for humanity and life on Earth. Otherwise, Earth would be very cold. It also explains why Earth is warm at night: the heat trapped by greenhouse gases radiates back to Earth. Note that the heat trapped by greenhouse gases emits in all directions, including into outer space and, of course, back to Earth.

The glass or plastic material covers in a typical greenhouse for growing plants and vegetables are similar to the greenhouse gases in the atmosphere, which keep Earth warm. Sunlight goes in through the glass. Heat radiated by plants and soils in the greenhouse is trapped by the glass covering, keeping the greenhouse warm.

While the heat-trapping effect of greenhouse gases is beneficial when balanced, the concern is that as more greenhouse gases are emitted from human activities, more of this infrared heat is trapped. This increases the heat engulfing Earth as the trapped heat radiates back into Earth, resulting in global warming. The concentration of carbon dioxide during the pre-industrial revolution was about 278 parts per million (ppm) in the mid-1700s, and it exceeded 417 ppm in February and March 2021.[131] For 2024, the monthly average was 424.61 ppm.[132]

The IPCC estimates that, to cap global temperature increase at 1.5°C, atmospheric carbon dioxide concentration should not exceed 430 ppm on average.[133] The 430-ppm value was reached in March 2025. The Mauna Loa Observatory reported that the daily average CO_2 levels exceeded 430 ppm twice in early March, with a high of 430.60 ppm.

A widely used authoritative measurement of carbon dioxide in ppm is from the National Oceanic and Atmospheric Administration (NOAA) Mauna Loa Laboratory. What NOAA used is a measure called the dry mole fraction. A dry air mole fraction is defined as the number of molecules of carbon dioxide divided by the number of all molecules in air, including CO_2 itself. This dry air mole fraction is "dry" as water vapor in the air has been removed. On the definition of ppm for carbon dioxide, suppose there are 1 million molecules in a parcel of air, of which carbon dioxide is a constituent. The number of carbon dioxide molecules in that parcel of air is the ppm for carbon dioxide. Water vapor is excluded as a constituent in that air parcel.[134]

Another way of stating this is to measure the number of carbon dioxide molecules in a parcel of "dry air" (i.e., excluding water vapor) and divide this number by the total number of all molecules that constitute air in that air parcel. This result is the dry mole fraction. Suppose the result is “z”. To get the figure in ppm, simply multiply “z” by 1 million. Other constituent gases of air include nitrogen, oxygen, methane, and other gases, including inert gases.

The composition of water vapor in the air is highly variable and is hence excluded from the measurement. The Mauna Loa Lab is located at 3,400 m above sea level and is at a good altitude to measure carbon dioxide dry mole fraction. At that altitude, it is far from vegetation or industrial activities, and the measurements can be used to establish a baseline for the carbon dioxide dry mole fraction.

To get an approximate total weight of carbon dioxide in the atmosphere, we use the estimate of the total mass of Earth’s atmosphere of $5.15*10^{18}$ kg or $5.15*10^{15}$ tons.[135] 1 gigaton (Gt) = 1 billion tons. “*” is the multiplication sign. In gigatons, the total mass = $5.15*10^{6}$ Gt. The average molecular weight of dry air is approximately 28.97 g/mol. 1 mole (mol) = $6.0221408*10^{23}$ atoms (or molecules, where relevant), which is Avogadro's number.

The number of moles of air is equal to ($5.15*10^{18}$ *1,000/28.97). Assuming the parts per million of carbon dioxide is 417 ppm, the number of moles of carbon dioxide = ($5.15*10^{18}$ *1,000*0.000417/28.97). 1 mole of carbon dioxide weighs approximately 44.01 grams. The total weight of carbon dioxide in the atmosphere is approximately equal to ($5.15*10^{18}$ *1,000*0.000417*44.01)/(28.97*1,000,000) tons, i.e., 3,262.5 Gt.

Assuming the concentration of carbon dioxide in the atmosphere is 417 ppm, this means that out of 1 million total molecules of air, 417 are molecules of carbon dioxide.

There are two atoms of oxygen and one carbon atom in the carbon dioxide molecule. The mass number of carbon is 12, and that of oxygen is 16. Hence, the mass number of carbon dioxide is 44 (i.e., 12 + 16 + 16).

Each element has a different atom. Carbon has a mass number of 12 as it has 6 protons and 6 neutrons (a total of 12). Oxygen has eight protons and eight neutrons (a total of 16). The weight or mass of an atom of an element is very much related to its mass number. The mass of the electron is very small and is about 1/1,836 that of the proton. We can ignore electrons in our calculations to obtain the weight of carbon dioxide.

To see how the mass of 1 mole of carbon dioxide is obtained, we note that the weight of a single carbon-12 atom is approximately $1.99*10^{-23}$ grams. One mole of carbon-12 atoms has about $6.022*10^{23}$ atoms, and the weight is 12 g/mol. But the mass of carbon should consider the carbon atom with an additional isotope, i.e., carbon-13, which occurs naturally in tiny amounts. Isotopes refer to atoms of the same element with different numbers of neutrons.

The weighted average mass of a carbon atom is 12.01 g/mol. The mass of 1 mole of oxygen gas is 32 grams. So, the mass of carbon dioxide is 12.01 g/mol + 32 g/mol, i.e., 44.01 g/mol.

The net weight of carbon dioxide emissions equals anthropogenic carbon dioxide production minus removal by carbon sinks. Of interest to many is estimating the weight of net carbon dioxide emissions required to increase the ppm of carbon dioxide by 1 ppm. We saw earlier that 417 ppm of carbon dioxide corresponds to a weight of 3262.5 Gt. Hence, 1 ppm of carbon dioxide corresponds to a weight of 3262.5/417 Gt, which is 7.82 Gt. This means that a net increase of about 7.82 Gt of carbon dioxide from human activities will result in a net gain of 1 ppm in atmospheric carbon dioxide.

To get an estimate of the net increase in the weight of carbon in the atmosphere for a 1 ppm increase in carbon dioxide, we note that the (carbon/carbon dioxide) ratio is (12.01/44.01). Hence, the weight of carbon is (12.01*7.82/44.01), i.e., 2.13 Gt (note it is carbon, not carbon dioxide) for a 1 ppm increase in carbon dioxide in the atmosphere. An increase of 10 ppm in atmospheric CO_2 concentration is associated with an approximate increase of 0.1°C in global temperature.

It is clear that higher emissions of carbon dioxide and other greenhouse gases from human activities will result in more of the heat energy emitted by the Earth's surface being retained. More of this energy, in the form of infrared radiation, will lead to higher temperatures because greenhouse gases trap it in the atmosphere.

15.4 Carbon Sinks

We all love carbon sinks. They are either human-made or natural avenues to capture carbon dioxide. Human-made systems often require significant technological solutions. Many are in a race against time to reduce anthropogenic sources of carbon and other greenhouse gases. Anthropogenic carbon dioxide emissions are due to fossil fuel combustion, deforestation, the calcination process in cement production (heating of calcium carbonate, which releases CO_2), and other industrial processes. About 50% of anthropogenic carbon dioxide emissions remain in the atmosphere, 25% is absorbed by land plants and trees, and the remaining 25% is absorbed by the ocean.

Carbon dioxide is also emitted naturally from decaying vegetation (e.g., the rotting of trees), decomposing animal remains, volcanic eruptions, respiration, etc. These natural emissions are offset by carbon sinks, including absorption by the oceans and photosynthesis on land and in the oceans.

Forests and oceans are the major carbon sinks. Between 2001 and 2019, the world’s forests absorbed about 16 billion metric tons (Gt) of carbon dioxide into the atmosphere each year and emitted about 8.1 billion metric tons (Gt) of CO_2 per year.[136] This means that the forests can take up human-related carbon dioxide emissions of about 8 Gt to 9.5 Gt annually. Photosynthesis absorbs carbon dioxide and releases oxygen. The carbon isolated, i.e., green carbon, is used to build up the leaves, trunks, stems, branches, etc.

Plants also absorb oxygen day and night during respiration. Still, the amount of oxygen released from photosynthesis during the daytime is a lot more than the amount that plants take in during respiration in both daytime and nighttime. Plants produce approximately ten times more oxygen during the day than they take in during respiration at night.

Photosynthesis by phytoplankton and algae in ocean water also helps to absorb carbon dioxide from the atmosphere. Blue carbon refers to the carbon stored in the oceans, and photosynthesis is crucial for the formation of blue carbon. The oceans can take up on a net basis about 8.4 Gt of carbon dioxide annually.[137] So, phytoplankton in the sea and plants on land are an important source of oxygen for all humans.

Unlike carbon dioxide, natural carbon sinks do not absorb easily or absorb only a small amount of other constituents of greenhouse gases. Very little nitrous oxide is absorbed by natural carbon sinks. Nitrous oxide is absorbed mainly in the atmosphere, where high-energy UV light breaks up the gas molecule. But emissions of nitrous oxide through human means exceed this absorption.

As for methane, it is mostly destroyed in the atmosphere, with very little absorbed by soils and plants. About 640 million tons of methane emissions are attributed to human-related activities.[138]

15.5 Problems Faced by the Ocean as a Carbon Sink: Ocean Acidification

Carbon dioxide in the atmosphere interacts with ocean water and organisms in the ocean. Interacting with ocean water, the carbon dioxide gas first dissolves into the ocean water. Once the carbon dioxide molecules dissolve, the dissolved carbon dioxide enters the ocean. The dissolved carbon dioxide, now in its aqueous form, may sink deep into the sea or interact with the ocean water to produce certain products.

The "aqueous" state of a substance refers to the state in which the substance is dissolved in water. Some substances, such as fats, cannot dissolve in water and therefore cannot be said to be in the aqueous state. Some substances are dissolved in alcohol or organic solvents.

The dissolved carbon dioxide enters the ocean through i) the physical or solubility pump, ii) the biological pump, and iii) the carbonate pump.[139]

i) The physical pump

A portion of the atmospheric carbon dioxide gas (CO_2) dissolves in ocean water. The dissolved carbon dioxide is usually denoted as CO_2 (aq), i.e., carbon dioxide aqueous. "aq" stands for aqueous. Some of the dissolved carbon dioxide can be released back into the atmosphere in a reversible reaction:

$$CO_2 \text{ (gas)} \leftrightarrow CO_2 \text{ (aq)} \qquad (15.1)$$

CO_2 (aq) refers to molecules of carbon dioxide surrounded and stabilized by water molecules.

Ocean circulation further distributes the dissolved carbon dioxide from the surface, and some of the molecules sink deeper. It is easier for carbon dioxide to dissolve in colder waters than in warmer waters. The reaction in (15.1) shifts to the right in colder waters. Carbon dioxide dissolves more easily in the northern oceans and cold southern oceans than in the tropical waters. Compared to regions with cold waters, warmer tropical waters have lower concentrations of dissolved carbon dioxide.

Warming ocean waters release more carbon dioxide into the atmosphere. Global warming leads to even greater warming of ocean waters, reducing the ocean's ability to absorb carbon dioxide and forming CO_2(aq), which in turn increases the amount of carbon dioxide remaining in the atmosphere. More carbon dioxide remaining in the atmosphere leads to more global warming.

The cold, dense water sinks in a process called downwelling, which occurs mainly in very cold waters. Dissolved carbon dioxide is carried into the deep ocean and can remain there for hundreds of years before upwelling occurs.

Wind and the rotation of the Earth along its axis give rise to upwelling. As the Earth rotates along its (imaginary) axis, the wind tends to veer right in the northern atmosphere and veer left in the southern hemisphere.

As wind blows surface water away, water from below the surface rises to replace it, creating upwelling currents. When it happens in warm tropical waters, carbon dioxide can be released into the atmosphere. We know that warming a bottle of fizzy drink will release the gas in it.

ii) The biological pump

Phytoplankton and algae in the ocean absorb carbon dioxide from the atmosphere and/or dissolved carbon dioxide in seawater to produce oxygen in a process called photosynthesis. About 50%-80% of the oxygen in the atmosphere comes from phytoplankton and algae. Humans should thank phytoplankton and algae for providing this oxygen.

iii) Carbonate pump

As stated previously, carbon dioxide can be found in water as a dissolved gas. Some of the dissolved carbon dioxide reacts with ocean water to form carbonic acid (15.2): [140] [141] [142]

CO_2 (dissolved) + $H_2O \leftrightarrow H_2CO_3$ (15.2)

Notes:

- CO_2 is carbon dioxide.
- H_2O is water.
- H_2CO_3 is carbonic acid.

It should be noted that only a part of the dissolved carbon dioxide reacts with seawater to form carbonic acid.

The reactions in (15.1) and (15.2) are reversible. Reversible chemical reactions are reactions in which the formed product of a reaction, which in this case in (15.2) is H_2CO_3, can revert to form the reactants, which are CO_2 (dissolved) and H_2O.

Carbonic acid is unstable by nature in that it quickly splits into hydronium ions and bicarbonate ions. The chemical reaction in which carbonic acid reacts with water molecules to form hydronium ions and bicarbonate ions is as follows (15.3a or 15.3b):

$H_2CO_3 + H_2O \leftrightarrow H_3O^+ + HCO_3^-$, (15.3a)

which is simplified as:

$H_2CO_3 \leftrightarrow H^+ + HCO_3^-$ (15.3b)

Notes:

- H_3O^+ is called the hydronium ion.
- H^+ refers to the hydrogen ion.
- HCO_3^- refers to the bicarbonate ion.

HCO_3^- is also known as the hydrogen carbonate ion. As the term "bicarbonate ion" is still widely used, I will provide a brief history of this term. The term bicarbonate was coined in the 19th century in relation to the sodium atom and to the two compounds, sodium bicarbonate ($NaHCO_3$, baking soda) and sodium carbonate (Na_2CO_3, soda ash).

Note that there is one carbonate molecule per one sodium atom in sodium bicarbonate, but one carbonate molecule per two sodium atoms in sodium carbonate. This means there are twice as many carbonate molecules per sodium atom in sodium bicarbonate as compared to sodium carbonate, hence the term “bi” in bicarbonate. There may not be sodium in other compounds with the carbonate molecule. We will use the term bicarbonate ion for HCO_3^-.

The hydrogen ion is actually a proton, as it does not have an electron, and there is no neutron. Hydrogen ions readily react with water to form H_3O^+, the hydronium ion. The hydronium ion is what makes water acidic. In this case, ocean water becomes more acidic as more carbon dioxide dissolves in it.

The hydrogen atom is the only element with one proton and one electron. When an atom gains or loses one or more electrons, it becomes an ion. Atoms are electrically neutral as they have the same number of protons and electrons. Atoms can become an ion, but an ion is not an atom. The ion can become an atom if it gains one or more electrons to become electrically neutral with an equal number of electrons and protons. A hydrogen ion, which is formed when the hydrogen atom loses an electron, is hence positively charged with one proton and no electrons.

The higher the concentration of hydrogen ions (or hydronium ions), the more acidic the solution is. Acidity or alkalinity is measured by pH (the Power of Hydrogen). A pH below 7 indicates acidity, a pH above 7 indicates alkalinity, and a pH of 7 indicates that the substance is neutral. A higher pH reading indicates increased alkalinity, and a lower pH reading indicates increased acidity.

The formation of carbonic acid makes ocean water more acidic, as it dissociates into hydrogen ions and bicarbonate ions. The reaction in (15.3a or 15.3b, also abbreviated as 15.3) is reversible too. About the definition of ions, atoms that lose one or more electrons are positively charged and are called cations. Atoms that gain one or more electrons are negatively charged and are called anions. Opposite charges attract. Ions of opposite charges attract one another.

The bicarbonate ions (HCO_3^-) can dissociate into positively charged hydrogen ions and carbonate ions:

$$H^+ + HCO_3^- \leftrightarrow 2H^+ + CO_3^{2-} \qquad (15.4)$$

Notes:

- CO_3^{2-} is the carbonate ion.
- H^+ is a shorthand for the hydronium ion (H_3O^+). H_3O^+ is the form that hydrogen ions actually take in aqueous solutions, as the hydrogen ions quickly bond with water to form hydronium ions, $H^+ + H_2O \leftrightarrow H_3O^+$.

The reaction in (15.4) is also reversible. If the ocean becomes more acidic, the hydrogen ion (H^+) concentration increases. H^+ reacts with carbonate ions (CO_3^{2-}) to form the bicarbonate ion. Removal of carbonate ions is a worrying issue, as it reduces the formation of calcium carbonate, which is essential for shell formation.

The carbonate ions (CO_3^{2-}), from (15.4), react with calcium ions (Ca^{2+}), to form calcium carbonate, which is the building block of shells for aquatic animals with shells:

$$Ca^{2+} + CO_3^{2-} \leftrightarrow CaCO_3(aq) \qquad (15.5)$$

Calcium carbonate, $CaCO_3$, may also be formed this way:

$$Ca^{2+}(aq) + 2HCO_3^-(aq) \leftrightarrow CaCO_3 + CO_2(aq) + H_2O \qquad (15.6)$$

The calcium ions react with bicarbonate ions to form calcium carbonate (which forms the shells), carbon dioxide in aqueous form, and water.

Carbon dioxide in aqueous form also reacts with carbonate ions and water to form bicarbonate ions.

$$CO_2(aq) + CO_3^{2-}(aq) + H_2O \leftrightarrow 2HCO_3^-(aq) \qquad (15.7)$$

Carbon dioxide is also produced within the ocean itself from the respiration of ocean animals and aquatic plants, and the decay of marine animals and plants. From the above reactions, we see that carbon dioxide can react with ocean water to form carbonic acid. Carbonic acid can convert into bicarbonates, and bicarbonates can convert into carbonates.

The total dissolved inorganic carbon (DIC) compounds in seawater comprise bicarbonate, carbonate, and dissolved carbon dioxide. These carbon-containing compounds are inorganic because they are formed from non-biological sources and are not derived from living things such as animals and plants. For example, carbon dioxide is inorganic as it is not a part of plants or animals. The bicarbonate and carbonate ions, as seen in the above chemical equation, are also not part of the plants or animals.

Bicarbonate comprises about 90% of the DIC, followed by carbonate at about 9% and the remaining is dissolved carbon dioxide at about 1%. The current pH of seawater is about 8.1 and is more acidic than the pH recorded in the pre-Industrial period.

The principle to explain the chemical reactions is based on Le Châtelier's principle. As anthropogenic carbon dioxide emissions increase, more carbon dioxide dissolves in ocean water, consistent with Le Châtelier's principle.

Le Châtelier's principle states that when a change occurs in a system in equilibrium, the system will reach a new equilibrium after the change is reduced, nullified, or counteracted. For example, in (15.1), suppose one molecule of carbon dioxide gas is absorbed into the surface ocean water, another molecule of carbon dioxide is released into the atmosphere from the ocean water if the state is in equilibrium. Suppose the proportion of carbon dioxide in the atmosphere increases. By Le Châtelier's principle, the concentration of CO_2(aq) increases. This means more carbon dioxide will dissolve in the ocean.

For the reversible chemical reactions in (15.1) to (15.7), if the concentration of a reactant (s) is increased on the left-hand side of the chemical equation, the reaction to produce the product (s) on the right-hand side is favored, according to Le Châtelier's principle. For example, when the carbon dioxide in aqueous solution (CO_2(aq)) increases, CO_2(aq) interacts with water to form carbonic acid (15.2).

As more carbonic acid is produced, the shift toward the production of more bicarbonate ions and hydrogen ions is favored, i.e., to the right in reaction (15.3). In this state, the left-hand side of the chemical reaction (15.3), comprising H_2CO_3 (carbonic acid), is the reactant, and the right-hand side, comprising H^+ and HCO_3^-, is the product. If H_2CO_3 is increased, more H^+ and HCO_3^- are produced, by Le Châtelier's principle.

Applying Le Châtelier's principle to (15.4), the ocean becoming more acidic from more hydrogen ions is the stress or new change to the equilibrium state. The reaction to the left in (15.4), with bicarbonate as the product and hydrogen ions and carbonates (on the right-hand side) as the reactants, is favoured because there are now more hydrogen ions. Hence, the system will reduce excess hydrogen ions by their interaction with carbonate ions, thereby producing more bicarbonate ions, as stated previously. This is worrying, as the carbonate ions are now reduced, yet they are required to form the shells of aquatic animals.

As the ocean becomes more acidic, the reaction to the left of (15.4) is favoured as the carbonate ions react with hydrogen ions to produce more bicarbonate ions. This is very worrying. With a higher acidity, more carbonic acid is created as the reaction to the left of (15.3a or 15.3b) is favoured. With higher carbonic acid levels, the ocean's capacity to absorb carbon dioxide is reduced. Worse, carbon dioxide can be released to the atmosphere.

It is not surprising that the ocean, in terms of dissolved inorganic carbon, has more bicarbonate (90%) than carbonate (9%). This is because when carbon dioxide dissolves in seawater, part of the dissolved carbon dioxide reacts with water to form carbonic acid (15.2), which then dissociates into hydrogen ions and bicarbonate ions (either 15.3a or 15.3b). The bicarbonate ions can dissociate into hydrogen ions and carbonate ions. When the pH decreases, or the ocean becomes more acidic, there are *excess* hydrogen ions. To maintain pH balance, excess hydrogen ions react with carbonate ions to form bicarbonate ions. So, you have bicarbonate ions from the dissociation of carbonic acid, and also from the removal of carbonate ions when the ocean becomes more acidic.

As pH decreases, it is easier for hydrogen ions to combine with carbonate ions than for bicarbonate ions to dissociate. A lower pH drives the reaction to produce more bicarbonate and removes carbonate ions from seawater. The main point is that as more carbonic acid is formed, there are excess hydrogen ions. Hydrogen ions react swiftly with carbonate ions to form bicarbonate ions. If the pH increases, bicarbonate can release more hydrogen ions and carbonate ions (making the ocean more acidic) to counteract the pH increase.

The reduction of carbonate ions in the ocean triggers a series of reactions that lower the ocean's capacity to absorb and dissolve atmospheric carbon dioxide. It is clear that as ocean acidity increases, the concentration of carbonate ions declines. Carbonate ions can help lower ocean acidity by reacting with excess hydrogen ions. Equally valid is that higher ocean acidity lowers the concentration of carbonate ions. Carbonate ions are essential for the organisms in the ocean to thrive.

Some of the carbonate ions in seawater originate from the chemical weathering of rocks on land and also from geological formations that make up the ocean floor. It is not easy, however, to pinpoint the precise proportion of carbonate ions in seawater that arises from the weathering of rocks.

In reversible chemical reactions related to ocean acidification, the direction of the reaction depends on factors such as dissolved carbon dioxide concentration and ocean acidity. Based on modelling, the proportion of carbonates will decrease, and the proportion of dissolved carbon dioxide will increase as the ocean becomes more acidic. Suppose the ocean becomes highly acidic, with the pH falling to a much lower level. In that case, the predominant reaction is the dissociation of bicarbonate ions into carbonic acid, which in turn dissociates into carbon dioxide and water.[143]

Currently, the ocean is alkaline, and very high oceanic acidity will occur decades later if anthropogenic carbon dioxide emissions are not reduced. But one thing is clear – the concentration of carbonate ions will be lower as the ocean becomes more acidic. Though the ocean’s pH is not below 7 and is not currently highly acidic, it is becoming more acidic. This is not good news for marine animals.

As stated previously, the carbon dioxide in aqueous form (i.e., the dissolved carbon dioxide) increases as the ocean absorbs more carbon dioxide. Le Châtelier's principle can be applied again to (15.6). As the dissolved carbon dioxide, $CO_2(aq)$, increases, the reaction to the left of (15.6) is favoured, and there is less calcium carbonate and more bicarbonate ions will result.

Let us take a look at (15.7). As $CO_2(aq)$ increases, the reaction to the right of (15.7) is favoured - there are fewer carbonate ions, $CO_3^{2-}(aq)$, and more bicarbonate ions. With fewer carbonate ions, Le Châtelier's principle predicts that less calcium carbonate forms. This is bad news for ocean organisms, as calcium carbonate is an essential component of the shells of aquatic animals. Low calcium carbonate levels are a big problem.

The ocean has absorbed approximately 525 billion tons (525 Gt) of carbon dioxide since the beginning of the industrial era. The ocean's capacity to absorb carbon dioxide is not precisely known. Estimates range from 1400 to 20,000 Gt.[144]

There is a limit on the amount of carbon dioxide that the ocean can absorb annually, currently estimated at 10 Gt. Factors affecting the uptake of carbon dioxide by the sea include the ocean's temperature, the acidity of ocean water, the rate of mixing of surface ocean water, and the rate at which the strata of deeper waters mix, which can take decades or even centuries.

Colder water is preferred for the ocean to absorb the carbon dioxide. The ocean's uptake of carbon dioxide is more efficient in the colder North Atlantic and Southern Ocean waters as compared to the waters at the warmer equatorial region.

Colder water in deeper ocean depths can hold more dissolved CO_2. The pressure is also greater deeper in the ocean, and carbon dioxide is more soluble there. While colder, deeper waters can hold more carbon dioxide in aqueous form, if deep waters rise to the surface, the carbon dioxide can be released into the atmosphere, particularly in warm regions. Deeper waters act as a carbon sink or an avenue to store carbon, but if global temperatures rise, that role will be hampered.

The higher the ocean water's acidity, the higher its carbonic acid saturation, leading to lower carbon dioxide uptake. More human-related emissions of carbon dioxide into the atmosphere result in the formation of more carbonic acid in seawater, and the formation of hydrogen ions and bicarbonate ions increases. Also, fewer carbonate ions are available for these creatures as more carbon dioxide dissolves in ocean water.

Acidification can reduce carbon dioxide absorption by the ocean, cause breathing difficulties for aquatic animals, and dissolve the shells of certain marine animals. The ocean has become more acidic since the pre-Industrial Revolution (or equivalently, when the Industrial Revolution began). The pH during the pre-Industrial Revolution was 8.2, and it has since decreased to 8.1.[145] The ocean is currently alkaline, but this reduction in pH makes it more acidic. Each unit decrease in pH corresponds to a 10-fold increase in acidity. Based on this scale, the ocean has become about 25% - 26% more acidic since the Industrial Revolution began.

Mixing of the ocean's surface waters and waters at deeper depths is affected by winds, waves, and storms, and the density of water, which in turn is affected by salinity and temperature. Stronger winds and waves help move and mix the surface water more quickly.

If the surface waters are much less dense than the waters deeper in the ocean, it would be harder for surface waters to mix with the waters in deeper oceans, even with winds. This is akin to less-dense vegetable oil floating on top of freshwater – the two liquids do not mix well, leading to greater stratification in ocean waters.[146] If global warming continues to worsen, the oceans will draw more freshwater from melting glaciers and ice sheets to the point that surface waters will be much less dense.

Stratification in ocean waters has worsened with global warming. Li et al. (2020) find that stratification globally has increased by a substantial 5.3% over the period 1960–2018.[147] When the oceans stop circulating, the surface waters cannot continue to absorb carbon dioxide because they become saturated with it. The oceans' existing ability to absorb atmospheric carbon dioxide does not mean they can do this job indefinitely.[148]

15.6 Problems Faced by the Ocean as a Carbon Sink: Overfishing

Overfishing and mismanagement of marine ecosystems are a challenge for our oceans to function as effective carbon sinks. Global human consumption of seafood is about 156 million tons yearly from an estimated total production of about 179 million tons (2018 data).[149]

A fish stock refers to the mass of fish in a particular location, and a more detailed analysis could include the number of fish, the sizes of the fish, the fish species, and the age profiles of the fish. An overfished stock refers to the population of fish in a particular locality that is below the biomass that produces the maximum sustainable yield (MSY), B_{MSY}. The number of fish is denoted as B.

The MSY is the theoretical maximum fish harvest that can be sustained in the long term. If too many fish are harvested, the population of fish goes down a lot. The remaining low biomass will not be enough to repopulate in the future to the extent it could reach the maximum sustainable yield, B_{MSY}.

Certain places have experienced losses owing to overfishing or warming of the ocean or both. The Food and Agriculture Organization and other organizations have voiced out about the unsustainable trajectory of overfished stocks in our oceans. The FAO estimates that the percentage of fish stocks globally that are within biologically sustainable levels has dropped from 90% in 1990 to about 66% in 2017. For example, the Mediterranean and the Black Sea region are the world's most overfished sea regions. Fishing stocks in the Mediterranean Sea and the Black Sea are at unsustainable levels.

Fishing businesses contribute to greenhouse gas emissions[150]:

- Damage to natural carbon sinks: Some fishing equipment may damage the seabed and carbon habitats like seagrass meadows and muddy sediments. Seagrass meadows are important carbon sinks. Seagrass takes in carbon dioxide from water for photosynthesis, absorbs carbon up to 35 times faster than tropical rainforests, and sequesters 10% of the ocean's carbon each year.[151]

- Marine ecosystem destabilized: Overfishing can lead to imbalances in the ocean ecosystem. [152] Also, overfishing of predator fish, such as sharks and other large predators, can increase the ocean's carbon dioxide production. The killing of whales, our marine mammal relatives, takes out a part of the ocean's ability to store carbon.

- Whales feed on zooplankton. Zooplankton feed on phytoplankton. Whales' excrements feed the phytoplankton. Whaling is indeed causing lots of damage to the ocean's ability to produce oxygen and reduce carbon dioxide emissions. When the fishermen kill whales, the phytoplankton do not get nourishment from the whales' faces. This is bad news as phytoplankton produce oxygen. Oceans contribute about 50% of the Earth's oxygen. Phytoplankton play a significant role in producing oxygen through photosynthesis.

  Coming back to the predator fish, when the typically bigger predator fish eat the smaller fish, the bigger fish has a net gain of about 10 percent of the total calories available in the smaller fish. The figure of 10% used here is commonly referred to as the 10% rule. The predator has to burn energy to look for food, generate heat, carry out its own metabolic processes, etc.

  When the predator consumes its prey, it gains about 10% of the prey's available total calories. Why only about 10%? The predator cannot convert all of the prey's energy, as not all of the prey can be consumed. For example, the bones and skulls are not eaten. Not all the parts eaten will be digested and released as energy for the predator; some will end up in feces.

The predator also has to spend energy hunting for prey and carrying out its own metabolic activities before and after eating, such as respiration. Heat is lost in the process. Not all of the prey population will be eaten by the predators. Some are not eaten at all, and this accounts for energy lost at a trophic level that is not passed on to the predator at a higher trophic level.

The figure of 10% is approximate and varies depending on the types and species of animals and fish. When there are not that many bigger fish remaining to eat the small fish, the small fish population will grow bigger, and more carbon dioxide is produced than if the predator fish were available. There are more metabolic activities tallied up across the small fish as the population of the small fish grows relative to the population of the bigger fish. The respiration of this larger population of small fish is greater, leading to the release of more carbon dioxide.

The 10% rule also explains why it is very inefficient for humans to eat meat. It is more energy-efficient for humans to eat plants directly than for plants to be consumed by farm animals, which humans then eat.

Human fishing activities target the larger predator fish. The population of large predatory fish is estimated to be about 10% of its pre-industrial level by 2003. Many are at risk of extinction. Humans are predators of large predatory fish.

- Fossil fuel combustion from fishing vessels: Greer et al. (2019)[153] estimate that 207 million tonnes of carbon dioxide were released into the atmosphere by marine fishing vessels in 2016. This is equivalent to 51 coal-fired power plants. Quite a number of the fishing vessels are pretty old.

An important takeaway is that it is best for humans not to consume aquatic animals. Let the marine ecosystem find its own balance. The marine ecosystem can function on its own without human intervention.

15.7 Animal Agriculture and Greenhouse Gas Emissions

Animal agriculture uses fossil fuels for electricity on farms, for transportation, and for producing the grains fed to farm animals. Crop farming uses fossil fuels to generate the power needed for tillage, transportation, grain drying, fertilizer manufacture, pesticide manufacture, equipment manufacturing and operation, etc. A significant proportion of the crop products is used to produce animal feed. With fossil fuel combustion, there is no escape from the release of climate-changing carbon dioxide as a by-product, and pollutants such as carbon monoxide, sulphur dioxide, etc.

Focusing on the use of fossil fuels in animal agriculture, Pimentel (1997) estimates that, on average, one kilocalorie (kcal) of animal protein for human consumption requires approximately 28 kcal of fossil fuel energy. In comparison, 1 kcal of plant protein involves an input of 2.2 kcal of fossil energy.[154] The amount of energy needed to produce one kcal of meat protein is about 11 times that of the energy required for producing a kcal of plant protein.

For beef and pork, the ratios are much higher – it takes about 40 calories of fossil fuel energy to obtain 1 calorie from beef (40:1). For pork, the ratio is about 14:1. In contrast, it takes 2.2 calories of fossil fuel to obtain 1 calorie from corn (2.2:1).[155] [156]

There are billions of farm animals out there on any given day. The more farm animals there are out there, the more fossil fuels are needed to raise them. Growing crops to feed this large number of farm animals requires fertilizers derived from fossil fuels.

The population of chickens globally was estimated to be 33 billion (2020 estimate).[157] Consider this a reference figure, as it is difficult to estimate the number of chickens worldwide owing to their short time on Earth before slaughter and the uncertainty about the number reared in remote areas. However, the number of chickens today would still be substantial, even if the figure quoted earlier were overestimated by 5 to 10 billion. In 2022, the global cattle population was estimated at 1 billion, and the pig population at about 780 million.[158]

15.8 Global Food Supply Can Increase by 49% with a Vegan Diet

Foley et al. (2011)[159] estimate that the global food supply for humans could increase by 49% in calories delivered if the world population switched to a vegan diet. This does not require expanding croplands; the increase can be achieved on existing cropland.

This is significant as many people are still struggling to find food. With more plant-based foods added to the global food supply, prices will become more affordable as more supply becomes available for human consumption. That would reduce hunger and poverty. As more people are fed, they can work more to earn income to get themselves out of poverty.

The increase in food supply for human consumption if everyone became vegan comes as no surprise, as many farm crops are grown to feed livestock. For example, more than 90% of U.S. soybeans go to feed livestock and poultry.[160] More than 60 percent of the world's corn and barley are fed to farm animals.[161]

Cassidy et al. (2013)[162] estimate that humans directly consume 55% of the crop calories, another 36% is consumed by livestock, and the remaining 9% goes toward biofuels and other industrial uses. US agriculture could feed an additional 1 billion people by shifting crop calories exclusively for human consumption. Existing croplands can feed an additional 4 billion people if all crops are grown for human consumption. If people eat less meat, the increased food supply can be used to feed millions more malnourished children.

Livestock farming is generally an inefficient way to produce food for human consumption. For every 100 calories of appropriate feed that is fed to cattle, pigs, chickens, hens (for eggs), cows (for milk), the calories received back by humans ultimately are 3 calories for beef, 10 calories for pork, 12 calories for chicken meat, 22 calories for eggs, and 40 calories for milk, respectively.[163] Energy is lost in the process of raising animals for consumption by the next trophic level, which in this case is the human race. Animals need to be fed to go about their daily activities, such as walking, eating, breathing, and keeping warm. All these activities require energy input.

It takes some period of rearing and feeding before farm animals like cattle, pigs, and chickens are slaughtered for meat. For cattle, it takes about three years. For pigs, it is about 6 months (suckling pigs are slaughtered at about 6 weeks). For chickens, it is between 7 weeks and 1 ½ years. Raising them for these periods requires feed for livestock. Also, body parts such as certain organs, animal bones, fats, cartilage, and the head are not fit for human consumption.

Comparing the periods of rearing before these farm animals are slaughtered, their natural lifespans are much longer. The natural lifespan of cattle is 18 to 22 years. The natural lifespan of a pig is 15 to 20 years, and that of a chicken is 3 to 7 years.

It is worth noting that a pound of meat and a pound of plant-based foods, such as legumes, seeds, and grains, are, on average, almost on par in delivering protein for human consumption.[164] Some plants pack more proteins than animal proteins pound for pound. For example, about 36 grams of protein can be found in 100 grams of raw soya beans.[165] In comparison, 100 grams of beef contains about 20 grams of protein.[166]

Depending on the type of beef — cooked or raw — the amount of protein in 100 grams varies. Cooked beef contains more protein per 100 grams, as cooking reduces its water content, making it denser in nutrients — estimates of protein in raw red muscle beef range from about 25 to 25 grams.[167] Cooked beef contains about 36 grams.[168] 80% lean meat/20% fat, raw ground beef contains 17.2 grams of protein.[169] 100 grams of cheddar cheese contains about 25 grams of protein.[170]

Plant-based foods also provide fiber, sterols, and stanols. Plant sterols and stanols help reduce “bad” LDL cholesterol levels without affecting HDL cholesterol levels.

15.9 Significant Water Savings and Much Reduced Water Pollution with a Vegan Diet

Water use in animal agriculture has raised alarms, as livestock farming consumes far more water, a scarce resource in many parts of the world. To better understand water usage for animal agriculture and human consumption, water sources can be categorized into three types: green, blue, and grey. Green and blue water are from natural sources, while grey water is from human sources.

Green water is water in the soil that plants and soil microorganisms can access for their water needs and growth. Blue water sources include the water that we see in streams, wetlands, rivers, lakes, and reservoirs. Sources of blue water include glaciers, aquifers, and snowpack. Blue water can be used for drinking and irrigation. Rainwater replenishes green water and blue water. Blue water replenishes green water when necessary.

Grey water refers to water from domestic activities such as laundry, washing food items and kitchen utensils, and showers. Uses of recycled grey water include irrigation, toilet flushing, and general washing.

If the cattle's food is pasture grass, green water use is significant. If cattle are fed grains as in industrial livestock production, the blue water usage or footprint is high.

More water is used to produce animal proteins than plant proteins. For example, an estimate of the amount of water required to generate a pound of beef is about 1,800 gallons of water.[171] A pound of tofu requires only an estimated 302 gallons of water to produce, while a pound of unprocessed oats requires about 290 gallons.[172]

Jalava et al. (2014) [173] estimate that global water consumption can be reduced by as much as 21% if everyone adopted a vegan diet. Freshwater is a scarce resource in many parts of the world, and this is a significant saving.

Pollution of freshwater arising from animal agriculture, mainly from animal manure, is another very serious problem. The amount of animal manure from farm animals far exceeds that of human manure by 3- to 20-fold in the USA.[174] Human manure is usually treated in most developed countries, whereas animal manure is not.

15.10 Animal Agriculture and Land Use

The Earth's surface is made up of 29% land (149 million km^2), and the remaining 71% is ocean or seawater (361 million km^2). The Earth's total surface area is about 510 million km^2. 71% of the land surface is habitable (104 million km^2), 10% comprises glaciers, and the remaining 19% is barren land, which includes rocks, deserts, beaches, and dunes. Focusing on the area for habitable land, about 50% (about 51 million km^2) is used for agriculture, about 37% comprises forests (39 million km^2), about 11% comprises shrubs (12 million km^2), about 1% is used for urban and built-up area, and 1% includes sources of freshwater, e.g., lakes and rivers.[175]

Out of the 51 million km^2 of land area for agriculture, 40 million km^2 (or 79% of total agricultural land) comprises pasture land for grazing (59% of total agricultural land or 30 million km^2), and land used to grow crops for livestock feed (20% of total agricultural land or 10 million km^2). The remaining 21% (11 million km^2) is used to grow crops specifically for human consumption.

It is worthwhile to note that, based on estimates by Poore and Nemecek (2018)[176], the land area that is used for livestock farming (40 million km^2) supplies only 18% (37%) of the world's calories (proteins) for human consumption. The other 82% (63%) of calories (proteins) comes from the 11 million km^2 of land used to grow crops specifically for humans.

About 60 percent of the world's agricultural land is grazing land.[177] Much of the grazing land cannot be converted to crop production because of the soil's nature. Mottet et al. (2017) estimate that globally, out of the 2 billion hectares of grassland used for livestock grazing, about 700 million hectares (about 35%, or one-third) could be converted to cropland.[178] This means that about 65% of grassland cannot be used for growing crops. About 65% or close to two-thirds of the UK's farmland is best suited for growing grass rather than other crops.[179]

It appears, then, that there is a strong reason to raise cattle and sheep on grazing land, as most of this land cannot be used for growing crops. The argument is that humans can obtain animal protein and calories from cattle and sheep raised on grazing land that would otherwise go to waste. The grass the cattle feed on is not suitable for human consumption anyway.

Cattle raised on pasture land feed on pasture grass for most of their lives and are fed supplemental grains when necessary. They are also fed various grains at certain ages and weights to reach a targeted weight faster before slaughter. The argument that cattle and sheep convert the calories in grass unsuitable for human consumption into meat and milk for humans is valid.

The food items unsuitable for humans include grass on pastures, corn stalks, wheat straw, and byproducts such as distiller's grains (i.e., leftovers from beer brewing). The inefficiency argument that it takes a lot more energy to convert calories into beef from cattle that feed on grass on pasture land, corn stalks, wheat straw, and certain byproducts is not applicable, as these items are not suitable for human consumption anyway. However, other issues need to be looked at, which are discussed next.

Consumption of meat results in a higher likelihood of contracting several chronic diseases, including certain cancers, diabetes, and heart-related diseases. Pollution of freshwater due to animal manure is a serious issue. In poorly managed pasturelands, overgrazing may lead to drought, excessive soil erosion, loss of pasture, herbs, and rootstocks, desertification, and possibly starvation for the community. Cattle are also being fed grains, which can be used to feed humans. Many on a vegan diet are concerned about the slaughtering of animals.

Greenhouse gases such as methane from cattle and sheep contribute to climate change. Methane is more potent than carbon dioxide as a greenhouse gas. A Western cow produces about 120 kg of methane per year, mostly from belching (release of gas through the mouth). A small percentage of the methane produced by cattle comes from flatulence (the release of gas through the anus). A non-Western cow produces about 60 kg of methane per year. A sheep produces about 8 kg of methane per year, while a human being produces about 0.12 kg of methane per year from flatulence.[180]

If demand for beef, lamb, and dairy were to decline, owners of grazing land would have to adjust and find other uses for their land. Hopefully, better technologies will be in place to convert more grazing land for crop production to feed a growing world population. More effort is needed to encourage people to consider the benefits of a vegan diet. The current trend does not indicate that demand for beef, other animal meats, and dairy is on a downward trajectory, unless consumer preferences change significantly.

15.11 Permafrost, Glaciers, Sea Level Rise

Greenhouse gas emissions from animal agriculture currently account for about 14.5% to 20% of total emissions. If humans could cut down on meat, that would be a big step toward fighting global warming. Widespread adoption of a vegan diet helps mitigate permafrost thawing, glacier melting, and seawater warming.

Permafrost is ground that remains frozen for at least 2 consecutive years. It is essentially a mixture of organic materials, soil, rock, and sediments, usually bound together by ice.[181] Glaciers are accumulations of ice on land, formed from snow over many years. Most glaciers today can be traced to the Ice Age.[182] Some are a couple of hundred years old. Glaciers can take hundreds of years to thousands of years to form.

The Crater Glacier (also known as the Tulutson Glacier) on Mt. St. Helens in Washington state is a young, growing glacier that formed about 25 years ago. While many glaciers are receding, the Crater Glacier is atypical, as it is still growing owing to specific structural features that draw and retain snow.[183]

Extensive areas of permafrost are found in Russia and Canada, near and above the Arctic Circle. The melting of permafrost can worsen environmental damage, as methane trapped beneath it will be released.

The annual global methane emissions are about 640 million metric tons. About 40% is from natural sources, and the remaining 60% is from human activities.[184] About a third of man-caused methane emissions come from livestock.[185] If measures are not taken to control permafrost thaw, more methane will be emitted. That will be a disaster. About 40% of the world's permafrost could disappear by 2100 if the world does not take this seriously.[186]

Methane averaged 1895.7 parts per billion (ppb) of air in 2021. It might look like a small figure, but methane accounts for about one-sixth of the global warming in the last few decades.[187] The recent increase in atmospheric methane concentration has raised concern. The increment of 17 ppb in 2021 is greater than the increment of 15.3 ppb in 2020.

Methane emissions from the Arctic have been increasing. Knoblauch et al. (2018)[188] estimate that permafrost soils in the Northern Hemisphere would generate 1 gigaton (1,000 million tons, 1 Gt) of methane by 2100. With temperatures warming, the frozen organic matter will decay owing to thawing. If oxygen is available, this decaying process will produce carbon dioxide, and if oxygen is not available, methane will be released.

Thawing rock formations in permafrost also release methane, a constituent of methane hydrate found beneath and within the permafrost. Methane hydrate is a crystalline solid containing methane trapped by frozen water. In 2020, the Siberian heat wave led to a surge in methane emissions in the Arctic permafrost. The temperature increased by an average of 10.80°F above 1979-2000 norms. Studies have shown that temperature has risen by about 0.30 °C in the permafrost around the Arctic and Antarctic between 2007 and 2016.[189]

Melting glaciers is a serious issue. Glaciers are masses of snow and originate on land. If all of the glaciers on Earth were to melt, the sea level would rise by about 70 m or 230 feet. That will flood the coastal areas and cities. Glaciers have been melting at an alarming rate over the past few years. 227 gigatons of glacier ice were lost annually from 2000 to 2004, but the loss accelerated to an average of 298 gigatons each year after 2015. The melting glacier that flows into the sea from the land surface will raise the sea level.

Global sea levels have been rising. Sea level rose on average about 3.6 mm per year from 2006 to 2015. The global mean sea level is currently about 8-9 inches (21–24 centimeters) above the level in 1880. The sea-level rise has been accelerating in recent decades. A third of this sea-level rise has occurred over the past two and a half decades.[190]

Rising sea levels are primarily due to thermal expansion of warming seawater, melting of mountain and land-based glaciers, and calving of land-based glaciers and ice sheets. There is a slight increase from the melting of icebergs already in the ocean.

Thermal expansion is the increase in volume of water molecules when water is heated. This is similar to the water level rising as the water in the kettle heats. The ocean has warmed considerably over the years as it absorbs heat, leading to the thermal expansion of seawater.

Water from melting glaciers accounts for about 21% of sea level rise over the past two decades.[191] Icebergs that have melted also contribute to sea level rise, but the contribution is negligible. Icebergs are large chunks of freshwater ice that have broken off from land-based glaciers or floating ice shelves. We know that ice melting in pure water will not change the water level. However, an iceberg is of a density different from that of salty seawater.

Icebergs are made of fresh (non-salty) water. Sea water is salty and denser than an iceberg. When an iceberg melts, the volume of melted freshwater from the iceberg increases by about 2.6% more than the volume of seawater that was displaced by the iceberg. This is because seawater is denser than an iceberg. Note that the weight of an existing iceberg is the same as the weight of the seawater that was pushed aside (or displaced).

Note that the moment chunks of land-based glaciers calve off and glide to the ocean from land and form an iceberg on the ocean water, there is an immediate increase in the ocean level. When the iceberg later melts, the sea level will increase further. Sea level rise each year is due to chunks of land-based glaciers calving off and gliding into the ocean, the melting of mountain and other land-based glaciers, thermal expansion of seawater, and the melting of icebergs already floating in the sea.

Global warming has led to the thawing of permafrost, melting glaciers, and rising sea levels. A vegan diet can certainly help to mitigate these problems.

16 Fertilizers, Animal Wastes, and the Story Behind Nitrous Oxide

The crops used to feed the animals require fertilizers to increase yield. When used excessively, fertilizers increase nitrous oxide emissions, a notorious greenhouse gas. It is common knowledge that fertilizers are indeed overused in many parts of the world.

Animal wastes, including manure, from animal farming also contribute to the formation of nitrous oxide and to the pollution of freshwater for human consumption. It is time for more people to consider adopting a vegan diet to combat the production of nitrous oxide and the pollution of our freshwater.

16.1 Essential Elements for Plant Growth and Fertilizer Usage

Fertilizers feed the world. Fertilizers can be organic or inorganic. Organic fertilizers are plant- or animal-based, including compost, animal manure, and leaves. Inorganic fertilizers are produced through chemical processes, and the most commonly used fertilizers contain the elements nitrogen, phosphorus, and potassium.

The element nitrogen is essential for protein formation in all living organisms. Phosphorus is essential for photosynthesis and for storing and transporting nutrients. Potassium is essential for plant growth, photosynthesis, and strengthening a plant's ability to withstand dry weather and resist diseases. Nitrogen-containing fertilizers include ammonia, urea, ammonium nitrate, and ammonium sulphate. Without the production of nitrogen fertilizers, Smil (2004)[192] estimates that crop production would be half of today's levels.

The higher yields of various crops enabled by nitrogen fertilizers account for feeding about 50% of the population today. These crops include those that are used as livestock feed for farm animals, which provide meat and milk (from cows) for human consumption. Without nitrogen fertilizers, the world population would be about half of today's level.

Nitrogen fertilizers supply the nitrogen plants need to produce proteins. Plants require glucose and proteins for growth and reproduction. Glucose is made up of the elements hydrogen (H), carbon (C), and oxygen (O). In addition to the elements H, C, and O, which are necessary for glucose formation, the elements to form proteins in plant cells are nitrogen (N) and sometimes, sulphur (S). Sulphur is an essential element for plant growth and photosynthesis.

Plants absorb water through the roots. The carbon dioxide that plants absorb through the leaves during photosynthesis reacts with water to form glucose. During photosynthesis, oxygen is released into the atmosphere.

To form glucose, plants obtain hydrogen from water during photosynthesis and carbon from the carbon dioxide that is absorbed during photosynthesis. The oxygen in glucose comes from carbon dioxide. The oxygen that is released into the atmosphere comes from water.[193]

Plants get a minor supply of sulphur by absorbing sulphur dioxide (SO_2) and hydrogen sulphide (H_2S) present in the atmosphere. Most of the sulphur for protein formation comes from the absorption of sulphate ions through the roots. The next element discussed for protein production is nitrogen.

16.2 The Nitrogen Cycle and Its Importance for Plants

Nitrogen makes up 78% of the air in the atmosphere. However, plants cannot extract nitrogen from the air. For their nitrogen needs, plants can absorb nitrogen-containing ions in the form of nitrates (NO_3^-) and ammonium ions (NH_4^+) from soils. The nitrates and ammonium ions are formed in the nitrogen cycle. The nitrogen cycle is a series of processes that convert atmospheric nitrogen gas and other nitrogen-containing compounds, such as fertilizers, into a form of nitrogen usable by plants and other living organisms. In the final stage of the nitrogen cycle, nitrogen gas is released into the atmosphere or soils through another set of processes.

Plants can get nitrogen through lightning strikes. When lightning strikes, the tremendous energy released breaks the strong bond between the nitrogen atoms in the nitrogen gas. The nitrogen atoms can then react with oxygen to form nitric oxide (NO):

$$N_2 + O_2 \rightarrow 2NO \qquad (16.1)$$

The nitric oxide reacts with oxygen further to form nitrogen dioxide (NO_2):

$$2NO + O_2 \rightarrow 2NO_2 \qquad (16.2)$$

Nitrogen dioxide (NO_2), however, is a significant air pollutant.

Nitrogen dioxide reacts with water to form nitric acid (HNO_3):

$$2NO_2 + H_2O \rightarrow 2HNO_3 \qquad (16.3)$$

Nitric acid reacts with, e.g., calcium oxide (CaO) that is found in soils, to form calcium nitrates ($Ca(NO_3)_2$):

$$CaO + 2HNO_3 \rightarrow Ca(NO_3)_2 + H_2O \qquad (16.4)$$

Note that farmers sometimes add calcium oxide to soils to improve pH and soil structure for plant growth. Calcium nitrates formed in the soils dissolve quickly in water to form calcium ions (Ca^{2+}) and nitrate ions (NO_3^-):

$$Ca(NO_3)_2 + H_2O \rightarrow Ca^{2+}(aq) + 2NO_3^-(aq) \qquad (16.5)$$

Note:

- aq refers to the aqueous state, which is the state in which the substance has been dissolved in water.

- In the equation for the product side, there is no need to write H_2O on the right-hand side as the calcium ions (Ca^{2+}) and nitrate ions (NO_3^-) are dissolved in water.

The nitrate ions (NO_3^-) are absorbed by the plants for the production of proteins. Plants absorb nutrients, such as nitrogen, phosphorus, and potassium, in the form of ions, which are not electrically neutral atoms. Plants, however, do absorb water, which is electrically neutral.

Plants can also obtain nitrogen through natural processes with the help of nitrogen-fixing bacteria or through nitrogen fertilizers. Nitrogen fixing is about converting the nitrogen gas into a nitrogen-containing compound like ammonia. About nitrogen fixing in a natural process, the nitrogen-fixing cyanobacteria in the soil convert the nitrogen from the air into ammonia (NH_3).[194]

The simplified form of the equation is as follows:

$$N_2 + 3H_2 \rightarrow 2NH_3 \qquad (16.6)$$

Ammonia is then converted by nitrifying bacteria in a process called nitrification. Nitrification is a process in which nitrifying bacteria use oxygen to convert nitrogen-containing compounds, such as ammonia, into nitrates.

The overall steps of nitrification, which involve the nitrifying bacteria, are as follows:

Ammonia → Nitrites → Nitrates

The nitrifying bacteria are ammonia-oxidizing bacteria and nitrite-oxidizing bacteria.

During the nitrification process, the ammonia-oxidizing bacteria convert ammonia to nitrite ions (NO_2^-) through an oxidation process.[195] The oxidation of ammonia involves oxygen. Oxygen serves as the electron acceptor, and ammonia is the electron donor.

$$NH_3 + O_2 \rightarrow NO_2^- + 3H^+ + 2e^- \qquad (16.7)$$

The next step in the nitrification process is the conversion of nitrite ions into nitrate ions (NO_3^-) by another type of bacteria, the nitrite-oxidizing bacteria.

$$2NO_2^- + O_2 \rightarrow 2NO_3^- \qquad (16.8)$$

Nitrates are then absorbed through the roots of plants. Plants can convert the glucose formed from photosynthesis and the nitrates absorbed to produce amino acids.[196] Amino acids join to form proteins, i.e., proteins are made up of amino acids. We have to thank the nitrogen-fixing bacteria in the soil for helping humankind all these years.

The carbon, oxygen, and hydrogen elements in plant cells are produced during photosynthesis. The availability of nitrogen in the form of nitrates in soil often limits plant growth. Compared with carbon, oxygen, and hydrogen, nitrates in soils are naturally scarce.

Given a piece of land to produce crops, nitrogen fertilisers applied to the soil can increase yields in areas that are nitrogen-deficient. So, the scarcity of nitrates in many farm areas necessitates the application of nitrogen fertilizers.

Nitrogen fertilizers are widely used. They may be nitrates-based, ammonium-based, or both. Their use depends on soil conditions (pH and moisture), temperature, and cost. Examples of the fertilizers that contain nitrates include ammonium nitrate, calcium nitrate, and calcium ammonium nitrate. These nitrates are immediately available for plant uptake. Ammonium (NH_4^+) from ammonium-based fertilizers can be absorbed through the roots of a plant for protein generation.

In areas with oxygen shortage — usually in damp or waterlogged soils from rainfall —denitrifying bacteria can convert nitrates into nitrites. Denitrifying bacteria can survive in both situations, whether oxygen is available or unavailable in the soil. These bacteria get the oxygen from the breakdown of nitrates to support respiration.

In areas with oxygen shortage, the final product is nitrogen gas, but intermediate products from different reaction stages are possible depending on environmental conditions, such as soil pH. Denitrifying bacteria, in the presence of certain enzymes, convert nitrates into possible intermediate products — nitrite, nitric oxide, and nitrous oxide — with the final product being nitrogen gas (N_2).[197]

The series of enzymes found in denitrifying bacteria involved in the denitrification process is as follows. The nitrates can be converted to nitrites in the presence of the enzyme nitrate reductase. Nitrites can be converted to nitric oxide (NO), aided by the enzyme nitrite reductase.[198] The enzyme nitric oxide reductase aids in the conversion of nitric oxide to nitrous oxide. The enzyme nitrous oxide reductase helps to convert nitrous oxide to nitrogen gas, the final step in the nitrogen cycle. The denitrification process using the denitrifying bacteria is as follows[199]:

Nitrate (NO_3^-) → Nitrite (NO_2^-) → Nitric Oxide (NO) → Nitrous oxide (N_2O) → Nitrogen gas (N_2)

It makes sense not to apply excessive nitrogen fertilizer, particularly when the soil is waterlogged. When there are excessive nitrates, plants do not take them up because they already have enough, and the nitrates may be converted into nitrous oxide. This is important because nitrous oxide, a potent greenhouse gas, may not be entirely removed during denitrification, as we saw above. Nitrogen gas by itself is harmless and is not a greenhouse gas.

To summarize, ammonia can be converted into nitrates by nitrifying bacteria in the nitrification process. Plants can absorb ammonium (ammonium is the abbreviation for ammonium ions) and nitrates (abbreviation for nitrate ions) to produce proteins. Fertilizers are frequently applied because the production of nitrates by nitrifying bacteria is usually insufficient. In anaerobic conditions, denitrifying bacteria can convert nitrates into intermediate products during denitrification, depending on soil pH. In the denitrification process, although the final product is nitrogen gas, the undesired intermediate product can be nitrous oxide. Nitrous oxide is a very potent greenhouse gas. Hence, nitrogen fertilizers must be applied prudently to avoid excessive nitrate levels.

16.3 The Haber-Bosch Process to Make Fertilizers: Earth-Shattering Importance

A major nitrogen fertilizer used worldwide is ammonia, with the chemical formula NH_3. The nitrogen for ammonia is harvested from the atmosphere through a chemical process developed by Fritz Haber. Haber did it in a small tube after many years of research.[200]

Haber's work was an earth-shattering discovery. The fruits of his research work are a breakthrough of tremendous consequence, as nitrogen gas is readily available in the atmosphere, but it is hard to harvest the nitrogen atoms. Nitrogen is a highly unreactive inert gas owing to the strong bonding between the two atoms. Hence, the process requires high temperature and pressure to break the strong bonding between the two nitrogen atoms in nitrogen gas molecules, thereby harvesting the nitrogen atoms.

Breaking the bond between nitrogen atoms enables them to be released and react with hydrogen atoms to form ammonia. Without breaking the bond between the nitrogen atoms in the nitrogen gas, the nitrogen atoms cannot react with the atoms of other elements, such as the hydrogen atoms. Carl Bosch further developed the engineering process to produce ammonia on a larger scale.

The whole engineering process for industrial production of ammonia is known as the Haber-Bosch process. In the Haber-Bosch process, hydrogen is produced by a chemical reaction between methane and water. The source of methane comes from natural gas. Methane, a potent greenhouse gas, makes up about 70-90% of natural gas. During this chemical reaction, hydrogen and carbon monoxide are produced:

$$CH_4 + H_2O \longrightarrow 3H_2 + CO. \qquad (16.9)$$

- CH_4: methane
- H_2O: water
- H_2: hydrogen gas
- CO: carbon monoxide

Additional hydrogen is generated in the second stage:

$$CO + H_2O \longrightarrow H_2 + CO_2. \qquad (16.10)$$

The Haber-Bosch process uses nitrogen gas from the air and hydrogen primarily from methane. Nitrogen and hydrogen then react in the Haber-Bosch process under high pressure and temperature, aided enormously by a catalyst to produce anhydrous ammonia (NH_3):

$$3H_2 + N_2 \rightleftharpoons 2NH_3 \qquad (16.11)$$

"Anhydrous" means without water.

For more technical details on the Haber-Bosch process, readers may refer to Clark[201] and Modak (2002)[202].

Anhydrous ammonia is converted into liquid form for use as a fertilizer. Liquid ammonia is transported to the farmer by compressing it or refrigerating it at a specific temperature. When liquid ammonia is injected into the soil at the farm, it reacts with water to form ammonium ions ($NH4^+$), i.e., $NH_3 + H_2O \leftrightarrow NH_4^+ + OH^-$. OH^- is called the hydroxide ion. Ammonium ions are absorbed by plants to meet their nitrogen requirements.

Ammonium ions are an ingredient in the formation of glutamate, an amino acid. Under certain soil conditions, nitrifying bacteria can convert ammonium ions into nitrates, a process called nitrification. As stated earlier, there are two types of nitrifying bacteria: ammonia-oxidizing bacteria and nitrite-oxidizing bacteria.

Ammonium ions are converted to nitrite by ammonia-oxidizing bacteria. The nitrites formed are then converted to nitrates by nitrite-oxidizing bacteria. Nitrification occurs in well-aerated and well-drained soils. Plants then absorb the nitrates.

The Haber-Bosch process is an extremely important breakthrough that has led to the production of nitrogen fertilizers at an economical cost. The application of fertilizers enables a much larger annual crop harvest, given that soil nitrogen is limited. The higher yields from croplands have led to a larger population on Earth. For example, in 2015, the world population stood at 7.38 billion. It is estimated that the availability of fertilizers enabled the feeding of 3.54 billion people, about half of the world's population.[203]

Before the Haber-Bosch process, natural fertilizers were grossly insufficient for a growing population. It was clear to many that the Haber-Bosch process was a revolutionary invention, and the Nobel Committee recognized that. Though Haber was awarded the Nobel Prize in 1918, many opposed his award owing to his involvement in chemical warfare and his support for Germany during World War I.[204]

To produce fertilizers such as ammonium nitrate fertilizer, ammonia is engineered to react with nitric acid (HNO_3) to produce ammonium nitrate (NH_4NO_3). Ammonium nitrate can also be used as an explosive. Ammonium nitrate is highly soluble in water. When applied to soils, ammonium nitrate dissociates in water into ammonium ions (NH_4^+) and nitrate ions (NO_3^-). The plant roots then absorb these ions for nitrogen.

16.4 The Harmful Effects of Fertilizer Production and Excessive Fertilizer Usage

The downsides of using fertilizers include significant carbon dioxide emissions from the production of nitrogen fertilizers, nitrous oxide (N_2O) emissions from fertilizer application, pollution of fresh water from excessive nitrates, atmospheric pollution from ammonia, and eutrophication. Fertilizers used to increase crop yields to feed farm animals are contributing to more greenhouse gas emissions.

The Haber-Bosch process for manufacturing ammonia fertilizer under high pressure and temperature requires a significant energy input.[205] The considerable energy input comes from using lots of fossil fuels, and the process consumes about 1.8% of the world's total energy production in 2018.[206]

The carbon dioxide emitted by the Haber-Bosch process accounts for about 1.8% of global anthropogenic emissions, or about 500 million tons of carbon dioxide equivalent. Worldwide, about 96% of the hydrogen used in the Haber-Bosch process is derived from fossil fuels. 90% of the ammonia produced is derived from fossil fuels.[207]

The increasing trend in nitrogen fertilizer use since the mid-20th century shows no signs of slowing down. Along with this trend, nitrous oxide emissions have also increased. Nitrous oxide accounts for about 6.2% of total global greenhouse gas emissions, measured in carbon dioxide equivalents. It is about 300 times more potent than carbon dioxide as a greenhouse gas, and it eats up the ozone layer.

Natural sources of nitrous oxide account for about 62% of total emissions, and anthropogenic sources account for the remaining 38%. Natural sources include soils under natural vegetation, oceans, and atmospheric oxidation of ammonia. Human-caused sources include agriculture, fossil fuel combustion, biomass burning, and atmospheric deposition.

Farming accounts for about two-thirds of the global human-caused nitrous oxide emissions. Denitrification is the primary source of nitrous oxide emissions from soils.

Nitrous oxide emissions are increasing. Nitrous oxide emissions from agriculture result from excessive application of synthetic fertilizers, animal urine, and manure. Finding the right balance in fertilizer use is crucial to reducing nitrous oxide emissions. For nitrous oxide to be produced as part of the nitrogen cycle, nitrates are needed, so it is important to ensure the optimal amount of fertilizer is applied. Perhaps Artificial Intelligence can be used to achieve the optimal amount.

When there are excessive nitrates in the soil from the overuse of ammonia fertilizers, plants are not absorbing these excess nitrates. Ammonia is converted to ammonium ions in the presence of water. The ammonium ions are then converted to nitrites by ammonia-oxidizing bacteria. The nitrites formed are then converted to nitrates by nitrite-oxidizing bacteria.

While nitrogen gas, which is the end product of denitrification, may be formed, nitrous oxide or nitric oxide (NO) may be released into the atmosphere under certain conditions. Factors affecting denitrification include soil microbes, soil oxygen supply, soil pH, soil water content, nitrate levels in the soil, soil temperature, and the amount of organic matter.[208] [209]

16.5 Animal Waste from Animal Farming Adds to the Problem

As much as 50% - 80% of the nitrogen in animal feed is excreted in the form of animal waste (urine and manure) instead of being absorbed into the animal bodies. A significant source of nitrogen in pastureland soil is livestock urine.[210] In fact, livestock urine may contain much more nitrogen than nitrogen from fertilizers. It has been estimated that a urine patch can contain about 1,000 kg of nitrogen per hectare, compared with about 30-50 kg from fertilizers per hectare.

About 60% - 80% of the nitrogen in livestock urine is in the form of urea. Urea reacts with an enzyme in livestock faeces to form ammonia. Ammonia formed in this way is an issue if there is too much. Ammonia is converted to ammonium ions in the presence of water. The nitrifying bacteria then convert the ammonium ions into nitrates. The nitrates may be converted to nitrous oxide under certain conditions, as described earlier.

Animal manure can lead to various types of pollution. Pollution from animal manure, including ammonia, nitrates, and nitrous oxides, is a major concern. Similar to urine, manure is a source of ammonia. Nitrogen in manure can be converted into ammonia through bacterial degradation.

The ammonia may dissolve in moist soil to form ammonium ions and, through the processes described earlier, produce nitrates as the end product. Or, the ammonia may be released into the atmosphere and react with nitric acid and sulfuric acid to form ammonium nitrate or ammonium sulfate. Both ammonium nitrate and ammonium sulphate are major components of the fine particulates $PM_{2.5}$. These fine particulates are very harmful to human health.

The overabundance of nitrates leads to eutrophication, which is an excessive enrichment of a body of water with nutrients. Nitrates are soluble in water, and this substance may run off to streams, lakes, or reservoirs. The overabundance of nitrates in the soil results from excessive fertilizer use, animal urine, and manure. The resulting algal proliferation is a serious problem that adversely affects marine and freshwater organisms.

The sudden, expansive blooms of algal growth can lead to high levels of dissolved oxygen during the daytime due to photosynthesis. But at night, due to the algae's respiratory activity, dissolved oxygen levels in the water are reduced. These low levels deprive other organisms of oxygen, and some may die. If nutrient flows in the form of nitrates decline, the algal blooms will die, and the microbes that decompose them will consume oxygen. The decomposition process sucks up oxygen, and this could lead to suffocation and death of other organisms.

Nitrates may enter freshwater intended for human consumption. Excessive nitrate levels are harmful to human health and lead to respiratory and reproductive diseases, kidney, spleen, and thyroid issues in children and adults. Nitrates are particularly harmful to infants.

What we have seen in this chapter is that fertilizers and uncontrolled run-offs containing animal wastes have also contributed to various forms of pollution, including nitrous oxide, a very potent greenhouse gas. Manure that does not receive oxygen will produce nitrous oxide under anaerobic conditions.

Excessive application of inorganic nitrogen fertilizers (i.e., synthetic fertilizers) results in elevated soil nitrate levels, which compound the problems caused by animal wastes. Urine and animal manure from animal farming also result in the formation of nitrates. Nitrates are an input for the production of nitrous oxide through microbial activities. Not all are specifically targeted to fertilize the soil.

The animal waste washed away is not treated and cannot be controlled, leading to atmospheric pollution from ammonia and nitrous oxide, and freshwater pollution from nitrates and algal blooms. Widespread adoption of a vegan diet helps address the problems arising from animal waste.

PART IV. THE WAY FORWARD

17 The Way Forward: Recommendations and Further Research

I wish to provide several suggestions to governments, medical associations, medical schools, universities, schools, education authorities, corporations, and the general public on what we can all do for our health and our environment. International agencies, such as those under the United Nations, could work with governments, universities, corporations, etc., to educate the general public about a vegan diet and to implement research projects.

My suggestions on educating the public about a vegan diet are as follows:

a. It is time for governments to recognize that a vegan diet is healthy. Governments could allocate funding to raise awareness of this diet among the general public. I do not think this will cost much, as they could prepare brief notes that can be uploaded to a website for users to download. Governments could compile a list of past research on a vegan diet and use it to inform their citizens and residents. There is, of course, no need to print on paper.

   Governments will have an incentive to do so, as the workforce's productivity will likely increase as fewer workers take sick leave. The health care budget will be reduced. The healthcare system can breathe easier with fewer patients suffering from chronic diseases in the future.

b. Medical associations could upload, say, a short leaflet for general practitioners to inform their patients about the benefits of a vegan diet for health, listing the past research on vegan diets and testimonials from those who are vegans. They are welcome to incorporate relevant excerpts of what I have written here.

c. Universities worldwide could also participate and inform their students about the benefits of a vegan diet for health and the environment. A vegan diet is a powerful tool in combating climate change and for their students' overall health. Most universities and large corporations have been actively incorporating environmental, social, and governance concerns into their mission statements and daily operations. These criteria are grouped under the Environmental, Social, and Governance (ESG) umbrella.

   ESG standards are a set of criteria a company may wish to follow in its business activities. There is no universal set of criteria for organizations to follow. There are varying levels of commitment, and different organizations use different criteria. Some organizations may choose not to follow specific criteria that other corporations earnestly pursue.

   An example of the environmental criteria for a company is its commitment to environmental protection. Some may wish to lower or offset their carbon dioxide emissions in the future. At the same time, other companies may go to the extent of using technologies and other measures to remove all the carbon dioxide they have produced for decades since their incorporation.

   The environmental, social, and governance (ESG) standards can be further strengthened if organizations, including universities, promote a vegan diet on their premises. A vegan diet benefits the environment, and ESG's environmental standards are inseparably linked to a vegan diet. As stated earlier, a vegan diet can lead to a drastic reduction in greenhouse gas emissions.

d. We can start from a young age. The education authorities and schools have a role to play in informing students about the benefits of a vegan diet for health and the environment.

   To convey what constitutes a well-balanced diet, education authorities and schools do not have to include meat, seafood, dairy and eggs in the food pyramid. Based on past research findings, these food items are not necessary for a person to be healthy. The food pyramid should not include any guidance that a meat-based diet is healthy.

   The authorities will want another food pyramid that is plant-based and lists all the vegetables, fruits, and nuts that form a well-balanced diet. Vegan Vitamin B-12 should be included, and possible allergies to certain nuts, etc., should be listed. Let the readers and parents judge whether this diet is healthy.

   They will want to inform students and parents that a well-balanced plant-based diet is healthy, based on past research. It is important to educate students that they may need vegan sources of vitamin B-12 and vitamin D.

   Those living in the tropics can get vitamin D from sunlight. Still, those living further north or south of the equator may not get sufficient sunlight during fall, winter, and spring. So, supplements may be necessary.

e. Corporations and financial institutions will want to inform their employees about the benefits of vegan diets for health and the environment. The ESG standards mentioned previously are inseparably linked to the vegan diet lifestyle. I firmly believe a healthier workforce will be a bonus to all firms.

f. The general public has a role to play. Humans are responsible people who want to play their part in preserving the environment for future generations. When it comes to the environment, we all want to leave behind a better legacy for our descendants, our children, grandchildren, great-grandchildren, etc.

g. Medical schools should include a course on nutrition and invite experts to show how a vegan diet can serve as a preventive tool for various chronic diseases. This course could be offered to both practicing doctors, specialists and students. They may advise their students that a vegan diet is a powerful tool for preventive medicine.

More medical research on a vegan diet is needed. Medical schools could initiate the following research projects, with funding possibly from the government and the private sector:

i. Follow the sample of babies and children who are on a vegan diet well into their adult life and look at their health progression, controlling for factors such as alcohol intake, smoking, etc. The privacy of individuals must be respected.

ii. Study the effects of a vegan diet and a meat-based diet on certain neurological disorders such as Parkinson’s Disease and Alzheimer's Disease.

iii. Study the effects of a meat-induced free radicals and reactive oxygen species on gene (a segment or specific sequence of DNA responsible for a particular function, trait, or facial feature) damage, and other damages in cells of various organs and tissues, and compare with the outcome from a vegan diet. But do this without involving human and animal trials, as we do not want anyone to be harmed. Perhaps conduct the studies using biochemical assays and experiments involving, e.g., dead tissues and cultures, and not involving humans or animals.

iv. Study the effects of a meat-induced free radicals and reactive oxygen species on fertility (e.g., sperm quality), and compare with the outcome from a vegan diet.

v. Study the effects of the possibility of correlation between gene damage in reproductive cells (sperm and egg cells), which can lead to, e.g., autism and attack by free radicals induced by meat eating.

vi. Do more research on the composition of plant-based infant formula and come up with an affordable infant formula that will be able to meet the dietary requirements of babies and growing children.

vii. Work with certain international agencies to do more research on a daily vegan diet makeup that is nutritious and affordable, taking into consideration the different cultural backgrounds of societies across the globe.

viii. Engage nutritionists and doctors to come up with targeted compositions of vegan diets tailored for those suffering from heart-related ailments, chronic kidney diseases, certain cancers, etc.

ix. Research the factors, e.g., physiological factors, that lead to iron deficiency for those who are on a vegan diet.

x. Research the combination of plant-based foods that can fix the iron deficiency problem that some people, particularly women, face when they are on a vegetarian or vegan diet.

xi. Research if some people could be prone to suffering from certain nutritional deficiencies when they are on a vegan diet.

xii. Research the affordability of vegan diets for those in the lower-income groups in different countries.

xiii. Research cheaper ways to produce the food items that constitute a balanced vegan diet.

xiv. Research how to make a vegan diet more accessible, particularly in developing nations, etc.

Our descendants want a healthier environment. Those adopting a vegan diet are doing environmental charity every day. A small step by an individual to adopt a vegan diet, when summed across billions worldwide, is powerfully significant.

18 To Wrap It All Up

When I began my meat-free diet, I thought there was a possibility that I would become sick. Instead, I have enjoyed many years of good health since then. I would rate going vegan as one of the most critical decisions in my life. Of course, our family and our well-being, including financial security, are most important, and all these should rank at the top of one's priorities. Next in importance is the decision to go vegan. If you are not yet on a well-balanced vegan diet, I encourage you to explore further and weigh the pros and cons. To me, it is a happy and healthy diet.

Some who are on a vegan diet do, however, suffer from certain chronic diseases; again, factors like how long one has been on a vegan diet, the composition of the diet, genetic make-up, the environment, etc., are crucial to consider too. The good news is that there are more testimonials from vegans. Articles published in recent years in medical and nutrition journals show that the risk of developing certain chronic diseases is significantly reduced among those on a vegan diet. That is a strong reason to go vegan.

I have provided the scientific basis for health based on research from our very eminent researchers in this field. I am amazed by the ingenuity of our doctors, nurses, medical researchers, engineers, scientific researchers, and pharmacists in working toward good health for all, including the development of appropriate diagnostic methods. I appreciate the efforts of various health professionals and engineers who have cared for patients and developed treatments, medical tests, machines, and instruments to improve diagnosis. Those in the health and health-related sectors are outstanding professionals who have contributed to human well-being.

Our bodies work very hard for us without us even knowing it. Cellular metabolism takes place naturally, miraculously, and 24/7 all day and night, without us directing or commanding the cells, tissues, and muscles, nervous system, etc., to do so. I value and appreciate the incredible efforts of my organs and cells. I try my best to keep them working efficiently and optimally.

I believe that a vegan diet is the best diet for helping our organs, nervous system, tissues, muscles, and cells carry out their various roles to the best of their ability. Most researchers are on the same page as me on this, and I have cited their research in this area. There are, of course, other research articles I have not read, but which are also extremely important.

It has taken me many years to adopt a vegan diet. I hope that, after reading this book, those who wish to go on a vegan diet but are unsure whether it is healthy will not have to wait that long. They have to decide for themselves as to whether the diet is appropriate for them. Other factors, including behavioral and psychological factors, are also very important.

For good health, I strongly recommend a vegan diet as a crucial component. Still, other critical ingredients include a war-free environment, clean air and water, and income to buy food. We all know too well the ravages of war – possible famine, food shortages, unavailability of medical care, heavy psychological toll on mental well-being, spread of diseases, poverty, deaths, injuries, etc.

I hope that more and more people are aware that going meat-free can be healthy, as long as a vegan diet is well balanced. To those who are not yet on this diet, do read about its benefits and give it a try, but do so under medical advice and supervision if necessary. The diet must be well balanced and supplemented with vegan vitamin B-12. Vegan Vitamin D may also be necessary.

Parents can feed their newborns a vegan diet, as several brands of vegan baby formula are now available. It is healthy to raise newborn babies and young children on a vegan diet. Parents have a role in presenting choices and information to their children about meat- and plant-based diets. Those in their teens have their own social circles, and it is not easy at all for teenagers to adopt a vegan diet.

I hope to see more discussion about a vegan diet. It is challenging for those already used to a meat-based diet to adopt a vegan diet. I strongly advocate that individuals collect more facts and conduct more research on this diet. Parents who are on a vegan diet and want their children to adopt this diet need to be patient. One should not push aggressively. It may take years of conversation before your children sign on to a vegan diet. A very important factor, too, is individuals' mental well-being.

There are testimonials from those who have been on a vegan diet since birth. Currently, research articles on a vegan diet, testimonials from vegans, and advice from doctors and nutritionists advocating a vegan diet are readily available. We can use all these sources of information to inform children.

I do support health insurance companies adjusting the health insurance premiums for those who are on a vegan diet. Given research on lower probabilities of contracting chronic diseases (non-genetically related) such as some cancers, diabetes, and heart-related ailments, factoring a person's vegan diet into lowering the health insurance premium is welcome. The scientific basis for a vegan diet supporting good health is very strong.

Some people may find that they will also enjoy inner peace, in addition to good health. As for what inner peace is, it is best left to the individual to describe. My feeling of inner peace is about minimizing harm to animals. In summary, a well-balanced vegan diet is good for better health and the environment. Inner peace is a bonus.

APPENDICES

Appendix 1. Heart Anatomy, How the Heart Works, and Bronchial Circulation

This appendix presents simplified explanations of how the heart works. After reading this appendix, I hope readers will have a better understanding of the terms I introduced earlier, such as atrial fibrillation and arrhythmia, and why researchers are recommending a vegan diet or one that is mostly plant-based. After knowing what the term “atria” is (discussed more below), readers will know that atrial fibrillation is a specific type of arrhythmia that is confined to the atria. An arrhythmia is an irregular heartbeat that can be uncoordinated, too slow, or too fast.

I marvel at all the human organs working for us 24/7, without complaints. The heart is one of those organs. Every organ has its functions, and this story about the heart's functions serves as an example of the myriad tasks each organ must perform in a human being. Another reason is to better understand some common cardiovascular diseases (CVD). CVDs are the leading cause of death globally, with about 17.9 million deaths each year.[211]

A better understanding of the intricate functions of the heart, albeit simplified here, and its coordination with other organs, provides helpful information on the preventive measures against CVD. The heart works tirelessly and very hard for us by itself, without us controlling it or telling it what to do. I find it beneficial to know the ways to help the heart work as well as possible.

For a picture to illustrate how the heart functions and how the heart is linked to the pulmonary or respiratory system, refer to Betts et al. (2022).[212] I strongly suggest that readers refer to the picture as they read this appendix.

A1.1 Basic Structure of the Heart

The circulation of blood, driven by the pumping of the heart, enables blood to flow into and out of the heart. The heart has four chambers: two on the upper side and two on the lower side. The two chambers on the left are separated from the two chambers on the right. The right atrium and left atrium are separated and are in the upper chambers. The right ventricle and left ventricle are separated and are in the lower chambers. The right atrium and right ventricle are on the right side of your body, like your right hand is on the right side of your body.

The right atrium and the right ventricle are connected by a valve called the tricuspid valve. Similarly, the left atrium and the left ventricle are connected by the mitral valve, also known as the bicuspid valve.

The tricuspid and mitral valves operate like a keeper. These valves keep blood flowing in one direction only — from the atria to the ventricles — and prevent backflow from the ventricles to the atria.

There are two other valves. The pulmonary valve separates the right ventricle from the pulmonary artery. The aortic valve is between the left ventricle and the aorta. Their functions are described below.

A1.2 Cardiac Cycle

The cardiac cycle involves both the right and left heart chambers. For convenience, let us suppose the cardiac cycle begins with atrial diastole. During the atrial diastole, both the right and left atria relax almost simultaneously, and blood enters the atria from the large veins connected to the atria.

A1.3 The Right Chambers of the Heart in the Cardiac Cycle

A1.3.1 Deoxygenated blood flows to the right atrium

Focusing on the right chambers in the heart, the superior vena cava and inferior vena cava veins are connected to the right atrium. The deoxygenated blood flows from the superior vena cava and inferior vena cava veins to the right atrium. The superior vena cava vein carries blood from the upper body, i.e., the head, neck, arms, and chest, excluding the heart, while the inferior vena cava vein carries blood from the lower body, i.e., the abdomen, pelvis, and lower limbs. There is a third vein to the right atrium called the coronary sinus vein that carries deoxygenated blood from the heart muscles to the right atrium.

During atrial diastole, blood flows into the right atrium from the veins due to a pressure difference: the large veins connected to the right atrium are under greater pressure than the relaxed right atrium. Blood flows almost continuously from the large veins into the right atrium. The atrium is never empty of blood.

A1.3.2 Tricuspid valve opens, right ventricle fills up

As deoxygenated blood enters the right atrium from the veins, the right atrium fills, and its pressure increases, forcing the tricuspid valve to open because the pressure in the right atrium is greater than that in the right ventricle. The opening of the tricuspid valve allows the blood to flow into the right ventricle. There is a period during which the right atrium and the right ventricle relax at the same time. Blood flows from the right atrium to the right ventricle during this "joint" diastole period.

The diastolic phase is the period when the ventricles relax. The term, diastole, generally refers to the ventricular diastole phase, though there is an atrial diastole phase. We will use the term *diastole* to refer to the period during which the ventricles relax. The right atrium relaxes for most of diastole, and it contracts toward the end of diastole, a process called atrial systole. Atrial systole is the final kick to pump the remaining blood into the right ventricle. The tricuspid valve is open, and the pulmonary valve is closed during this stage.

Note that the atrial systole marks the end of the ventricular diastole phase. Though there is a period during diastole when both the right atrium and the right ventricle are relaxed and filling with blood, the period when they do not relax together is when the right atrium, during atrial systole, contracts to push blood into the right ventricle.

A1.3.3 The right ventricular systole's initial phase

After the right ventricle is filled with blood at the end of the atrial systole, the pressure in the right ventricle increases to the point that the pressure in the right ventricle is greater than that in the right atrium. The tricuspid valve then closes, while the pulmonary valve remains closed during the isovolumetric ventricular contraction phase. The isovolumic ventricular contraction phase is the initial phase of ventricular systole. The isovolumic ventricular contraction is so named because the volume of blood in the right ventricle remains constant, with no blood entering from the right atrium and none leaving for the pulmonary arteries.

The pulmonary valve remains closed as the pressure in the right ventricle is not high enough. As pressure in the right ventricle builds during contraction, the pulmonary valve opens, signaling the end of the isovolumic contraction phase. Note that during the phase after the tricuspid valves close and the right ventricle has been filled up, the right atrium is in atrial diastole as blood flows into the right atrium from the veins.

A1.3.4 The right ventricular systole's phase: blood ejects into the pulmonary artery

The right ventricle then contracts to pump deoxygenated blood to the lungs via the main pulmonary artery (also called the pulmonary trunk), which splits into the left and right pulmonary arteries. The left pulmonary artery carries deoxygenated blood to the left lung, and the right pulmonary artery carries deoxygenated blood to the right lung. Note that the ventricular systole consists of the isovolumic contraction phase and the phase in which blood is ejected into the arteries (the ejection phase). The heart systole is generally referred to as the ventricular systole, not the atrial systole.

Not all the blood in the right ventricle is ejected when it contracts, as some remains behind at the end of ventricular systole; the same is true of the left ventricle. The pulmonary valve is open to allow blood to flow into the pulmonary arteries, and the tricuspid valve between the right atrium and right ventricle is closed during the ventricular systole phase.

A1.3.5 End of the right ventricular systole

As the right ventricle contracts to eject blood, pressure in the ventricle initially rises, then drops as more blood is ejected and the volume remaining in the right ventricle declines. At the end of the right ventricular systole, the right ventricle begins to relax. At this late stage of systole, the pressure in the right ventricle drops, and the pulmonary valve closes; note that the tricuspid valve is also closed. The tricuspid valve opens up when the pressure in the right atrium is greater than that in the right ventricle.

Throughout the ventricular systole, the right atrium is relaxed and in atrial diastole, receiving blood from the veins. That is why the duration of the atrial diastole is longer than the duration of the ventricular diastole phase, because there is a period in which the right atrium is filling with blood as the right ventricle goes into the systole phase. The atrial diastole lasts for about 0.7 seconds, while the ventricular diastole is about 0.5 seconds in duration.

A1.3.6 Beginning of the right ventricular diastole

The period between the point at which both the pulmonary and tricuspid valves close and the point at which the tricuspid valve opens is called the isovolumic ventricular relaxation phase. During the isovolumic ventricular relaxation phase, the volume of the blood in the right ventricle is the same, as no blood flows into the pulmonary artery and no blood is flowing into the right ventricle from the right atrium, and the tricuspid valve and the pulmonary valve remain closed.

A1.3.7 The right ventricular diastole - initial phase ends, filling phase, and end phase

The ventricular diastole phase for the right ventricle consists of the isovolumic ventricular relaxation phase and the phase in which the right ventricle remains relaxed to allow the blood to flow into the right ventricle with the tricuspid valve open. There is rapid filling, followed by slower filling (i.e., diastasis).

The ventricular diastole phase ends with the final kick of the atrium contraction, which pumps the last bit of blood into the right ventricle, just before the right ventricle begins to contract in systole.

A1.4 The Left Chambers of the Heart in the Cardiac Cycle

A1.4.1 Oxygenated blood flows into the left atrium

After deoxygenated blood flows from the pulmonary arteries into the tiny blood capillaries in the lungs, oxygenation occurs. Oxygenation of the deoxygenated blood takes place within the pulmonary circulation. The air we breathe in flows to the trachea, which is a tube in the thorax from the voice box to the bronchi, which are the left and right bronchi. The bronchus ultimately branches out into bronchioles, and the bronchioles lead into the alveoli. The alveoli are tiny air sacs in the lungs.

The oxygenation of the blood is a result of the gas exchange in the alveoli in the lungs, where the carbon dioxide and other wastes in the deoxygenated blood are expelled via the tiny walls of the blood capillaries and diffuse into the alveoli, and the oxygen from air breathed in diffuses via the tiny walls of the alveoli and then enters the blood capillaries. There is a very thin membrane between the alveoli and the blood capillaries through which the diffusion of gases takes place. The oxygen then binds to the hemoglobin in the blood and is carried to the heart.[213] The oxygenated blood then flows to the heart.

Oxygenated blood from the lungs flows into the left atrium via the pulmonary veins. For most people, four pulmonary veins connect to the left atrium individually: two from the left lung and two from the right lung, carrying oxygenated blood from the lungs. There are, however, anatomical variations, including cases of people having three to five pulmonary veins.[214] The pressure in the left atrium is lower than that in the pulmonary veins, which are carrying the oxygenated blood, so blood enters the left atrium. Blood flows almost continuously into the left atrium through the pulmonary veins.

A1.4.2 Mitral valve opens, left ventricle fills up

When the pressure inside the left ventricle drops below that of the left atrium, blood from the left atrium forces the mitral valve to open, allowing blood to flow into the left ventricle. As the left atrium continues to fill up with blood, the mitral valve remains open, and the blood continues to flow into the left ventricle.

The mitral valve is open during the ventricular diastole phase to allow the blood to flow into the left ventricle, and the aortic valve is closed during this phase. The left atrium then contracts during atrial systole, forcing the remaining oxygenated blood into the relaxed left ventricle through the mitral valve. During the period in which the mitral valve is open, the left atrium is in atrial diastole most of the time, allowing blood to flow into the left atrium and then into the left ventricle. Then, during the left atrial systole, the mitral valve remains open. After the atrial systole kicks in and the ventricular systole begins, the mitral valve is closed. Similar activities are happening at the right side of the heart at almost the same time.

A1.4.3 The left ventricular systole's initial phase

The left ventricle is now full after the atrial systole process. After the left ventricle fills, pressure rises, and the mitral valve closes. There is a period between the mitral valve's closure and just before the aortic valve opens, called the isovolumetric contraction period. During the isovolumetric contraction period, the aortic valve is closed.

During the isovolumetric contraction period, the pressure in the left ventricle rises. Still, the oxygenated blood has not left the ventricle for the aorta, and no blood is flowing into the left ventricle from the left atrium. The mitral valve is closed, and the aortic valve remains closed.

A1.4.4 The left ventricular systole's phase: blood ejects into the aorta

Eventually, as pressure builds further in the left ventricle, it exceeds that of the aorta, and the aortic valve opens, allowing rapid ejection of blood from the left ventricle into the aorta. When the aortic valve is at the point of opening, that is the end of the isovolumic contraction period.

The blood flows to the rest of the body via the aorta and the smaller arteries that branch off the aorta. The ventricular systole phase includes the isovolumic contraction phase and the phase during which the ventricle contracts and ejects blood. The left atrium relaxes to allow blood to flow into the left atrium from the pulmonary veins, as the left ventricle contracts. The pressure in the ventricle rises to its peak, then declines as more blood is ejected from the left ventricle. The blood remaining in the left ventricle is reduced, and the pressure in the left ventricle at the end of the contraction phase becomes lower.

A1.4.5 End of the left ventricular systole

At the end of the systole, the aortic valve closes, and blood is not ejected anymore.

A1.4.6 Beginning of the left ventricular diastole

The left ventricle relaxes, and isovolumetric relaxation begins when the aortic valve closes, with the mitral valve still closed. The isovolumic relaxation ends when the mitral valve opens.

During the isovolumic relaxation, the pressure in the left ventricle falls without a change in the blood volume in the left ventricle. No blood leaves for the aorta, and no blood is entering the left ventricle from the left atrium.

A1.4.7 The left ventricular diastole - initial phase ends, filling phase, and end phase

The cycle repeats as oxygenated blood fills the left atrium. Similar to what happens to the right chambers, when the pressure inside the left ventricle drops further below that of the left atrium, blood from the left atrium forces the mitral valve to open and allows blood to flow into the left ventricle.

The ventricular diastolic phase consists of the isovolumic relaxation phase, followed by the phase in which the left ventricle relaxes, pressure drops further, and allows blood to flow into the left ventricle when the bicuspid valve opens. The ventricular diastole phase ends when the left atrium contracts to push the last bit of blood into the left ventricle, and this contraction of the left atrium is known as the atrial kick. The cycle repeats as described above.

A1.5 Almost Simultaneous Actions on the Right and Left Sides of the Heart

Atrial kicks in the right and left atria occur almost simultaneously. This means that the right and left atria contract almost simultaneously.

During the ventricular systole phase for both the right and left ventricles, contractions of the right and left ventricles occur in a coordinated fashion, almost simultaneously, with a 6 ± 8 milliseconds delay. The onset of contraction of the left ventricle is an instant before that of the right ventricle.[215] [216]

The diastole phase of the right and left ventricles occurs almost simultaneously. During this phase, both the right and left ventricles relax and fill with blood.

The diastole phase of the right and left atria occurs almost simultaneously. Here, “diastole” refers to the atria, not the ventricles.

Note the actions on the left and right sides of the heart occur “almost” simultaneously, owing to the electrical impulses that pass via specialized pathways in the heart. The electrical impulse originates in the sinoatrial node (SA node), which is located in the right atrium.

The tricuspid and the mitral valves, also called the atrioventricular valves, close at nearly the same time. This closing of the atrioventricular valves generates the “lub” sound.

The pulmonary and aortic valves, also called the semilunar valves, close at nearly the same time. This closing of the semilunar valves generates the “dub” sound.

The opening actions of the atrioventricular and semilunar valves do not create a sound. The “lub” sound is slightly louder than the “dub” sound, and these sounds are separated by about 0.3 seconds. The 0.3-second period corresponds to the ventricular systole. The ejection phase takes about 0.25 seconds, and the isovolumetric contraction period lasts for about 0.05 seconds.

A1.6 The heartbeat and measurements of blood pressure

Regarding the definition of a heartbeat, some may define it as referring only to the ventricular systole phase. To be complete, a heartbeat consists of the ventricular systole and ventricular diastole, with atrial systole included. A heartbeat is also known as the cardiac cycle. The "lub" and "dub" sounds are part of the heartbeat.

When the ventricles are contracting, i.e., are in systole, the atria are receiving blood at the same time. When the ventricles are in diastole or relaxing, they are filling with blood. Atrial kicks occur toward the end of ventricular diastole, i.e., the atria contract and pump the last bit of blood into the ventricles, as discussed above.

For blood pressure, the systolic and diastolic pressures are recorded. Systolic pressure is the blood pressure when the ventricles are contracting at peak pressure, ejecting blood into the arteries. The diastolic pressure refers to the minimum blood pressure recorded when the ventricles are relaxing just before the next ventricular contraction. Systolic and diastolic pressure are not the "lub" and "dub" sounds from the heart.

Blood pressure is measured in mmHg. "mm” refers to millimeters, and “Hg” is the symbol for mercury.

A systolic pressure of 120 mmHg refers to the pressure pressing against the artery walls as the ventricles contract to push out blood into the arteries and 120 mmHg refers to the height of the mercury column raised by that blood pressure, i.e., the height of the mercury column is equal to 120 mm exerted by a certain pressure that is the same as the blood pressure pressing against the artery walls. The systolic pressure is the top number in a blood pressure reading.

Diastolic pressure is the pressure against the arterial walls when the ventricles are relaxing and filling with blood from the atria. It is the lower number in the blood pressure reading.

If the blood pressure reading is 120/80 mmHg, 120 mmHg is the systolic pressure, and 80 mmHg is the diastolic pressure. The normal blood pressure for an adult is less than 120 mmHg for systolic pressure and less than 80 mmHg for diastolic pressure.

A1.7 Bronchial Circulation

Lung cells also need to undergo metabolic activities. The bronchial circulation refers to the blood that flows from the heart to the lung cells and from the lung cells to the heart. The bronchial circulation network is essential for lung cell metabolism, and it has nothing to do with pulmonary circulation. Recall that the primary function of pulmonary circulation is to facilitate gaseous exchange at the alveoli. The lung cells require oxygen to break down glucose and release energy. Waste products and carbon dioxide are removed from the lung cells during metabolic activities. The lung cells get oxygen from the bronchial arteries.

Bronchial arteries have their origin in the aorta. As for the removal of waste products and carbon dioxide from the lung cells, the bronchial veins carry them away from the cells. The bronchial veins are divided into the right superficial bronchial veins, the left superficial bronchial veins, and the deep bronchial veins. The superficial bronchial veins are so named as they are located closer to the surface of the lungs.

The right superficial bronchial veins on the right side of the lungs carry deoxygenated blood from the surface of the lungs to the azygos vein. The azygos vein originates in the lumbar region and runs through up to the thoracic cavity on the right side of the vertebral column. The left superficial bronchial veins on the left side of the lungs carry deoxygenated blood from the surface of the lungs to the accessory hemiazygos vein or the left superior intercostal vein. See Figure 20.36 in Betts et al. (2025) for the azygos venous system.[217]

Blood from the accessory hemiazygos vein flows into the azygos vein. The intercostal veins are on the left and right sides of the body and are found within the rib cage. “Intercostal” here refers to being located within the ribs. The left superior intercostal vein is a vein (only one) that collects blood from certain intercostal veins on the left side of the body. The left superior intercostal vein drains blood into the left brachiocephalic vein. The left brachiocephalic vein carries deoxygenated blood from the head, neck, and arms and empties into the superior vena cava.

“Azygos” refers to a vein. The azygos venous system carries deoxygenated blood and lies on either side of the vertebral column (the bones that make up the backbone). It consists of the azygos vein, which branches into the hemiazygos vein and the accessory hemiazygos vein. This means that blood from the hemiazygos and accessory hemiazygos veins ultimately flows into the azygos vein.

The blood in the azygos vein drains into the superior vena cava (SVC). As noted earlier, the superior vena cava carries deoxygenated blood from the upper part of the body, including the head, neck, upper limbs, and parts of the chest (not all of the chest). The SVC flows into the right atrium of the heart. The azygos vein is a single vein that runs on the right side of the back of one’s thorax and is located near the spine. The thorax, or chest cavity, is situated between the neck and the abdomen. The thorax houses the heart and the lungs.

The deoxygenated blood from lung cell metabolism, which is carried by the deep bronchial veins, drains ultimately into the pulmonary veins. The deep bronchial veins carry deoxygenated blood from the terminal bronchioles and other deeper lung tissues as part of the bronchial circulation. As explained earlier, the pulmonary veins carry oxygenated blood to the left atrium. So, deoxygenated blood from the deep bronchial veins mixes with oxygenated blood from the pulmonary veins. As a result of this mixing, the blood returning to the left atrium is 95% oxygenated, rather than 100% before mixing.[218] [219]

A1.8 Respiration and Gaseous Exchange at the Alveoli

The respiratory system is, of course, very much related to the cardiovascular system. When we breathe in, air flows into the airways. Finally, it flows into the alveoli in the following sequence: into the nose or mouth, pharynx (below the mouth), larynx (in the middle of the neck), trachea (below the larynx), left and right bronchi (bronchus is the singular term), primary bronchus, secondary bronchus, tertiary bronchus, bronchiole, and terminal bronchioles. These are the conducting airways, where air is transported without gaseous exchange, and they branch just before the respiratory bronchioles.

The terminal bronchioles are the final branches of the conducting airways. “Conducting” here refers to the transport of air without gaseous exchange. The terminal bronchioles then branch into a number of respiratory bronchioles.

As for the respiratory zone, or the zone through which gaseous exchange occurs in the lungs, it comprises, in the following sequence, the respiratory bronchioles, alveolar ducts, and alveolar sacs. The alveolar sacs contain the alveoli. The respiratory bronchioles form the initial part of the respiratory zone, where gaseous exchange occurs, and also serve a dual role: transporting air and performing some gaseous exchange. There are some alveolar sacs attached to the sides of the respiratory bronchioles. Each respiratory bronchiole then divides at its end into two to eleven alveolar ducts. Each alveolar duct divides into five to six alveolar sacs.[220]

Gaseous exchange occurs when oxygen and carbon dioxide move between the air and blood, and between the blood and cells across cell membranes in the alveoli of the lungs. The alveolar ducts and the respiratory bronchioles together account for about 10% of gas exchange, with the remaining 90% carried out by the alveoli. The alveolar ducts and the respiratory bronchioles have some alveoli (not as dense as in alveolar sacs) budding off their walls.

During gas exchange, cells take in oxygen and expel carbon dioxide. The oxygen we breathe in flows into the respiratory bronchioles from the terminal bronchioles. The air then moves into the alveoli. Oxygen is transported across the membranes of the alveoli into the alveolar bloodstreams by simple diffusion.

On the discharge of carbon dioxide and other wastes, the veins, except for the pulmonary veins, carry deoxygenated blood from the cells in our human body into the superior vena cava, the inferior vena cava, and also the coronary sinus vein into the right atrium, then into the right ventricles. As noted previously, the coronary sinus drains deoxygenated blood from the heart muscle. The pulmonary arteries carry deoxygenated blood from the right ventricles to the lungs, where it flows into the capillaries surrounding the alveoli for the discharge of carbon dioxide via diffusion from the blood into the airways. Carbon dioxide is then expelled when we breathe out.

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Appendix 2. The Atomic Structure, Chemical Bonding, and Free Radicals

This appendix briefly reviews atomic structure, the electron configuration of an atom, and bonding in molecules, before describing the unpaired-electron structure in free radicals. Having the foundation knowledge in atomic structure and molecular bonding makes it easier to understand how free radicals can harm the human body.

I also describe why saturated fats are worse than unsaturated fats. There is also a brief discussion as to why unsaturated fats are more susceptible to attacks by free radicals than saturated fats. The last subsection examines how antioxidants help to reduce oxidative stress in the human body.

A2.1 What is a free radical?

A free radical, or simply a radical, is an atom, molecule, or ion that has at least one unpaired valence electron in its outermost shell. The free radical also must be highly reactive. “Reactive” in chemistry refers to how readily a substance undergoes a chemical reaction either on its own or with other atoms or molecules. Let us look at the structure of the atom first, with a discussion on valence electrons, “orbitals”, and other items related to the atom and molecules to follow.

A2.2 Basic Structure of an atom

An atom consists of a nucleus surrounded by a certain number of electrons. The atom is electrically neutral and has a certain number of protons, electrons, and neutrons (if present). The lightest atom is the hydrogen atom with one proton, one electron, and no neutrons. The proton in the hydrogen atom is in the nucleus. The only atom with no neutrons is hydrogen. Other atoms have neutrons, protons, and electrons. In general, neutrons and protons can be found in the nucleus of the atom.

The shape of the nucleus of a particular atom can change with time. What is currently known is that many nuclei are roughly spherical or ellipsoidal and can also exhibit other shapes. The nucleus may change shape under certain conditions, such as nuclear vibrations or collisions.

The shape of the proton is not stable. A proton consists of quarks, and a quark is known to be an elementary particle. A neutron also includes quarks. The quark is an elementary particle, as it cannot be broken further into other constituents, given what we know as of the date of this publication. The electron is an elementary particle, i.e., it cannot be broken further, and is almost perfectly spherical in shape in the form of a cloud of negative charge.[221]

All types of matter, including body tissues, cells, and physical substances such as wood, plastics, liquids, and gases, are made up of atoms. Matter has weight and takes up space, including the commonly known states of matter—liquids, solids, and gases. There are other states of matter, such as plasma and Bose-Einstein condensates, and we will not discuss them further.

In the early days, before quantum mechanics was a field in its own right, classical mechanics was used to study the behavior of atoms. Classical mechanics, which studies the motion of large objects such as cars and planets, could not explain the behavior of subatomic particles. Quantum mechanics is about the study of the behavior of light, atoms, and what is inside the atom, including subatomic particles such as electrons, protons, neutrons, and quarks.

The birth of quantum mechanics is attributed to Werner Heisenberg, Max Born, Wolfgang Pauli, Prince Louis de Broglie, Erwin Schrödinger, Paul Dirac, Max Planck, Albert Einstein, Neil Bohr and other prominent scientists. Although Bohr's planetary theory of the atom, which postulates that electrons orbited at fixed distances from the nucleus, was not accurate, he laid the foundation for further progress in physics and chemistry with his contributions, including the concept of quantized energy levels, as discussed later. As quantum mechanics is broad, this appendix is limited to examining the existence of valence electrons in free radicals and their interactions with other atoms or molecules.

Atoms have energy, and we will look at the types of energy subatomic particles possess: potential and kinetic energy. Protons and neutrons vibrate and move within the nucleus. The neutrons and protons cannot move from one atom to another. The neutrons and protons reside in the nucleus. The nucleus is a tightly knit structure that is not easily broken apart, except through nuclear fission. The protons could reside in the nucleus, despite their positive charge, because the nuclear force within the nucleus is stronger than the electromagnetic force.

The electromagnetic force within the nucleus is the force that causes repulsion between the positively charged protons in the nucleus. Outside the nucleus, the electromagnetic force is the force of attraction between the electrons and the protons in the nucleus. We can safely say the electrons are located outside the nucleus.

Nuclear force is the force that holds protons and neutrons together within the nucleus. Positively charged protons should be repelling one another owing to the electromagnetic force, but they are held together by the nuclear force within the nucleus.

Protons, neutrons, electrons, light, and other subatomic particles exhibit wave-particle duality in accordance with quantum mechanics.[222] Wave-particle duality is briefly described in this appendix to help explain the energy of an electron.

Light exhibits wave-particle duality. Once thought to be only a wave, light also behaves like a stream of particles, technically known as photons. Photons are discrete packets of energy. Electrons, which were once modelled as particles only, also exhibit some (but not all) wave-like characteristics.

The wave-like behavior of the electron is not precisely a physical wave. We can talk about the probability of the electron being found at a certain location as modelled by a wave function in quantum mechanics. There is no way to pinpoint the location of the electron with accuracy. Electrons can bend and spread out like waves when passed through a very tiny opening, as evidenced in experiments.

Experiments were conducted in which electrons were fired at a screen with two slit-holes. Wave-like patterns were formed on the other side of the screen, similar to what one would observe when two or more waves meet and overlap in the ocean. However, an electron is not physically a water wave that we observe when we go to the sea. For example, electrons can travel through a vacuum. Water waves are generated through a medium, i.e., water. Electrons do not need a medium to travel.

As particles, electrons are shown to have mass and to be packets of energy. Electrons have some mass, though much smaller than the mass of the proton or neutron. That is how we can justify the fact that electrons can behave as particles, since they have mass and charge. There is much about the wave-particle duality of subatomic particles that we still do not know. While it is widely accepted that subatomic particles exhibit wave-particle duality, we do not understand how or why this occurs.

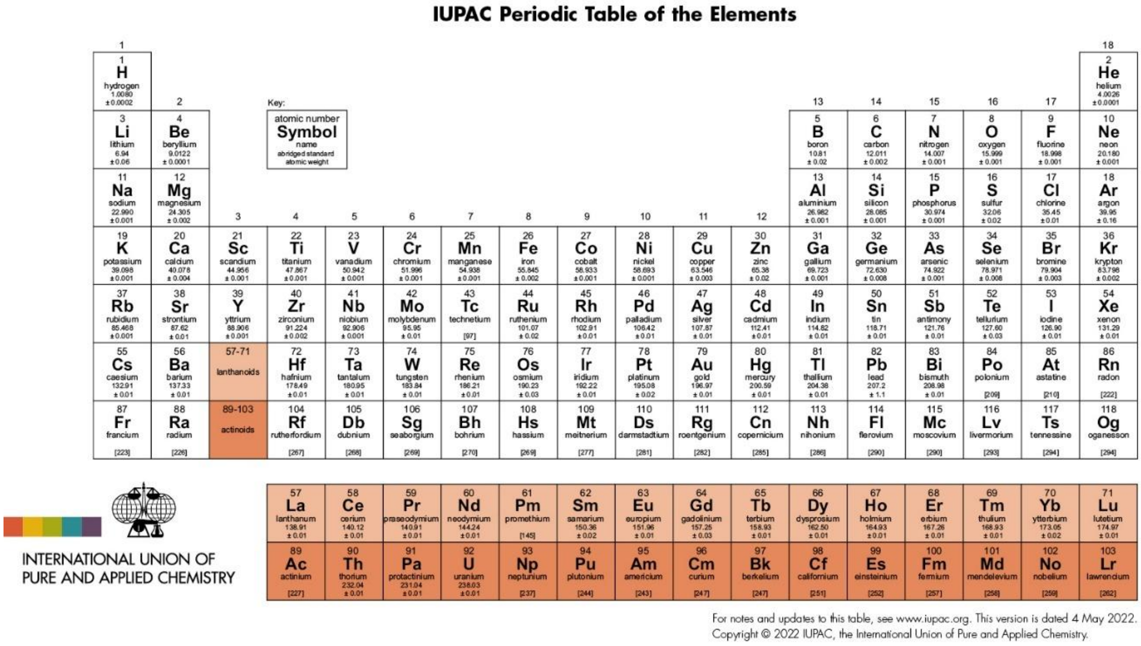
While neutrons and protons do not move from one atom to another, the nuclei and electrons of different atoms interact as they approach each other. The electrons of atoms are crucial to how chemical bonds form, but note that the positively charged nuclei are attracted to the electrons of different atoms.

Chemical bonds can occur when electrons of an atom move to another atom or molecule, are shared with another atom or molecule, and are delocalized and become mobile within the material. While it is true that the electrons of different atoms repel one another, electrons of an atom are attracted to the protons (in that sense, the nuclei) of another atom.

A2.3 The Elements and Periodic Table

Elements are materials that cannot be broken down further via chemical reactions and are the most fundamental building blocks. For example, the hydrogen atom is an element as it cannot be transformed into another element via chemical reactions. To provide another example, like atoms of other elements, Carbon-12 (C-12) is an element that cannot be broken down further into other substances via chemical reactions.

As of August 2025, the total number of elements that have been discovered is 118, and all known elements are listed in the periodic table below:



Source: The International Union of Pure and Applied Chemistry

The atomic number refers to the number of protons and has nothing to do with the number of neutrons or electrons in the atom. For example, in the periodic table above, hydrogen's atomic number is 1 as it has one proton. Carbon's atomic number is 6, as it has 6 protons. The symbol of an element is unique to that element. For example, the symbols for hydrogen and carbon are "H" and "C", respectively. The name of an element is spelled out above in the periodic table.

Atomic mass refers to the mass of a single atom of a specific isotope of the element, and it should theoretically include the mass of protons, neutrons, and electrons. The atomic mass, however, does not usually include the mass of electrons, as the mass of electrons is minuscule. Theoretically, the mass of electrons could be included.

Atomic weight is the average weight of all isotopes of an element, weighted by their natural abundance. The atomic weight of the hydrogen isotopes listed in the periodic table, which is an average weight, is 1.0080 ±0.0002 atomic mass unit (amu or u). Atomic mass is the mass of a single, specific atom or isotope, while atomic weight is the average mass of all the naturally occurring isotopes of an element.

One amu is equal to 1.67 x 10^{-24} grams. One atomic mass unit (amu) is defined as exactly one-twelfth (i.e., 1/12) the mass of a carbon-12 isotope, and no other isotopes of carbon are considered in getting this mass. A carbon-12 atom has 6 protons, 6 neutrons, and 6 electrons. The atomic mass of a carbon-12 atom is 12 amu.

The atomic mass unit (amu) is standardized against carbon-12, not hydrogen, because the carbon-12 isotope is relatively abundant and stable. The atomic weight of each atom, which also considers the weight of the isotopes of the same element in the periodic table above, is expressed in terms of amu. The weight of the hydrogen isotope with one proton and one electron is equal to approximately 1.007825 amu. Isotopes refer to atoms of the same element with different numbers of neutrons.

A2.4 Molecules and Compounds

Molecules are combinations (or groups) of atoms of the same element or of different elements formed via chemical bonding. Compounds are groups of atoms held together by chemical bonding between atoms of various elements. For example, oxygen gas (O_2) is a molecule, as is water (H_2O). H_2O is a compound as it contains different elements, but O_2 is not a compound as it is formed from two atoms of the same element. Compounds are molecules, but a molecule is not necessarily a compound.

A2.5 Shells, Sub-shells and Orbitals

Each atom has a definite number of outer shells, *n*, that surround the nucleus, say n = 1, 2, 3, 4, … 7, which is known as the principal quantum number. Each outer shell consists of subshells, s, p, d, f.

The number of orbitals for each subshell:

Subshell *s* contains one orbital, designated by s.
Subshell p contains three orbitals, i.e., p_x, p_y, and p_z.
Subshell d contains five orbitals, designated by d_{xy}, d_{yz}, d_{xz}, d_{x2-y2}, and d_{z2}.
Subshell f contains seven orbitals, designated by $f_{x(x2-3y2)}$, $f_{y(3x2-y2)}$, f_{xyz}, f_{z3}, f_{yz2}, f_{xz2}, $f_{z(x2-y2)}$

The maximum number of subshells in an outer shell is equal to the principal quantum number, *n*. The first outer shell has one subshell, s. The second outer shell can have at most 2 subshells: s and p. The third outer shell can have at most 3 subshells: s, p, and d. The fourth outer shell can have at most 4 subshells: s, p, d, and f.

It is worthwhile to know the Azimuthal quantum number because it determines how electrons occupy orbitals and which orbitals are at higher energy levels. The Azimuthal quantum number, ℓ, begins with 0 and ends with *n*-1, where *n* is the principal quantum number. The Azimuthal quantum numbers, ℓ, which are 0, 1, 2, 3, refer to the orbitals s, p, d, and f, respectively. The Azimuthal quantum number 0 relates to s, 1 refers to p, 2 refers to d = 2, and 3 refers to f.

How do we know the number of orbitals in the s, p, d, and f subshells? The number of orbitals in a certain subshell is equal to 2(ℓ) + 1. For the *s* subshell, 2(ℓ) + 1 = 2(0) + 1 = 1. For the *p* subshell, 2(ℓ) + 1 = 2(1) + 1 = 3. For the *d* subshell, 2(2) + 1 = 2(2) + 1 = 5. For the *f* subshell, 2(3) + 1 = 2(3) + 1 = 7.

Each orbital, e.g., $3p_y$, is occupied by a maximum of 2 electrons.

The maximum number of electrons of an atom in an electron shell follows the rule that the number of electrons is equal to $2^*(n)^2$, where n = 1 (the innermost electron shell), 2, 3, etc. If the atom has one shell, the maximum number of electrons is 2. If the atom has two shells, the maximum number of electrons in the second shell = $2^*(2)^2 = 8$.

If the atom has three shells, the maximum number of electrons in the third shell = $2^*(3)^2 = 18$, but this is the maximum number. It does not mean that 18 electrons must occupy the third shell, as the number of electrons in a certain outer shell depends on the element. Some elements have more electrons, while some have fewer. We should know that the maximum number of electrons in the n^{th} shell given by the formula, $2^*(n)^2$, is consistent with and based on what has been discussed previously. Based on the points below, we can also obtain the maximum number of electrons in each shell:

- The maximum number of subshells in the n^{th} outer shell is equal to the principal quantum number, n.
- The number of orbitals in a certain subshell is equal to $2(\ell) + 1$, where ℓ is the corresponding Azimuthal quantum number for a certain subshell (s, p, d, or f).
- A maximum of 2 electrons occupy each orbital.

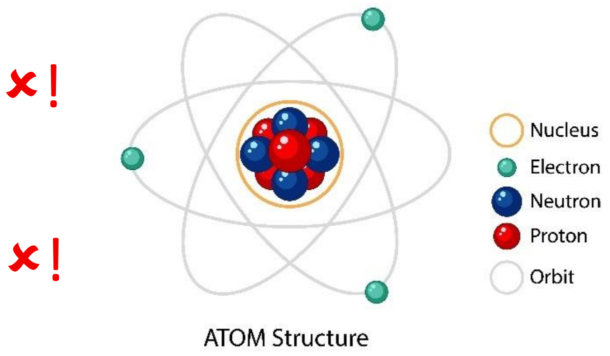
E.g., if the atom has three outer shells, the maximum number of electrons in the third shell is calculated in the following way. There are 3 subshells: s, p, and d. The number of orbitals in s, p, and d subshell is equal to 2(0) + 1, 2(1) + 1, and 2(2) + 1, respectively, which are 1, 3, and 5 (maximum). Since each orbital can hold a maximum of 2 electrons, the total number of electrons is 2 + 6 + 10 = 18, the same value obtained from the formula $2^*(n^2)$.

An orbital is a region in which one could find the electrons. We can talk about the probability of electrons being located within certain regions of an orbital; i.e., we know it is impossible to pinpoint the exact location of electrons as they move within an orbital in a probabilistic sense.

The Heisenberg Uncertainty Principle states that the more we wish to know the exact position of a subatomic particle, the less we know about its momentum. Examples of subatomic particles are electrons or photons. The Uncertainty Principle applies in the quantum world of particles. It does not apply to large objects such as cars and aeroplanes, as we can locate their positions. Owing to the Heisenberg Uncertainty Principle, both the exact position and momentum of an electron are not known simultaneously. The uncertainty increases as the mass of a subatomic particle decreases.

The orbitals where electrons can be found come in different shapes. See LibreTexts for the shapes of the s, p, d, and f orbitals.[223]

The orbitals are not elliptical or circular in shape, and the electrons do not orbit around the nucleus along an elliptical or circular line. It is wrong to think that electrons orbit along a definite track, as depicted in some pictures on the internet. The example below is an incorrect depiction of electron movement around the nucleus:



WRONG! Electrons do not orbit along the path show in the diagram.

Source: Freepik.

Let us take a look at the 2s and 2p orbitals. The 2s and 2p orbitals belong to the second outer shell with a quantum number of 2. The s orbital is of a lower energy level than the p orbital.

Rest energy is the intrinsic or inherent energy an electron possesses even when it is not moving. Rest energy is given by $E=mc^2$, where m is mass and c is the speed of light. Though an electron has rest energy, this energy is ignored when we discuss changes in the energy of an electron in an orbital. The energy of the electron is due to its position and motion within the atom. What matters is the electron's potential and kinetic energy, and quantum mechanics recognizes these types of energy.

When we talk about the energy level of an orbital, we are referring to the energy of the electrons in that orbital. The energy of an electron is equal to its potential energy and kinetic energy, and the discussion of these types of energy in this section is based on quantum mechanics at a very introductory level.

The potential energy of an electron is very much related to its position within an atom, and the pull of the electron to the protons in the nucleus. This force of attraction is called electrostatic attraction. The nearer the electron is to the nucleus, the less the potential energy. The further the electron is away from the nucleus, the greater the potential energy.

We can explain the increase in potential energy as electrons move away from the nucleus using an analogy related to gravitational pull. An object that is higher above ground has greater potential energy compared to an object closer to the ground. When dropped to the ground, the object higher above ground will have greater energy compared to an object closer to the ground. Note that we need energy to move the object above the ground.

Kinetic energy is related to the energy of the electron in motion. Kinetic energy cannot be negative. In general, the kinetic energy of electrons decreases with an increase in the distance from the nucleus.

Electrons exist in orbitals, and we can talk about the probability of finding an electron within an orbital, with some regions having a higher probability. Electrons do not move along fixed orbits.

For electrons close to the nucleus, the electron is confined to a smaller space. According to Heisenberg's Uncertainty Principle (which aligns with quantum mechanics), if there is more certainty on the location of the electron, there is more uncertainty on the momentum of the electron, and vice versa. The higher uncertainty in the momentum is brought about by a higher level of kinetic energy. A higher level of kinetic energy increases the magnitude of the momentum of the electron. The Heisenberg Uncertainty Principle explains why electrons do not collapse into the nucleus – they exhibit wave-particle duality. If an electron gets too close to the nucleus, there is less uncertainty in its location, but there is a higher level of uncertainty about its momentum. There is a heightened increase in momentum, which means its kinetic energy increases.

The electron does not fall into the nucleus, so it is always moving. The kinetic energy of the electron near the nucleus is very high and serves to counteract the very strong electrostatic attraction between the electron and the nucleus in the proximity of the nucleus.

It is also noteworthy to point out that each orbital (with its electrons) has its own energy level, with orbitals further away from the nucleus having higher energy levels. Here, when we talk about the energy level of an orbital, we are referring to the energy level of the electron. This means that when potential energy becomes very negative (imagine a large negative number) in a specific orbital, there is an increase in kinetic energy (with a large positive number). Also importantly, the electron cannot just be viewed solely as a particle owing to its wave-particle duality. We can, however, discuss the probability that the electron is in a given region.

It is again important to emphasize that electrons in a particular orbital have specific, discrete energy levels, and not at any energy value in between. The term "quantum" in quantum mechanics refers to an electron's energy that is quantized: electrons in a particular orbital have specific, discrete energy levels. This is analogous to a ball resting on a staircase step, not between steps.

For example, it is well known that the ground state energy level of the electron in the hydrogen atom is -13.6eV. It takes 13.6eV to remove the electron from the atom.[224] *eV* stands for electron volt, and eV is approximately equal to $1.602*10^{-19}$ joules. The ground state is the lowest possible energy state for an electron. The negative sign indicates that the electron is attracted to the nucleus, and it takes energy to remove the electron from the atom.

Note that there is a difference between momentum and velocity. Momentum = mass*velocity. For example, if the mass of the car is 2,000 kg and the speed of the car is 10m/s, its momentum is 2,000 kg*10 = 20,000 kg · m/s.

Electrons occupying the 2p orbitals have more energy than the electrons in the 2s orbital. This higher energy of the 2p electrons makes them more likely to be involved in chemical bonding than the electrons in the 2s orbital.

The energy level of the electrons in a specific orbital depends on the net influence of the following factors: distance of electrons from the nucleus, electrons in a certain orbital shielded by electrons in another orbital, repulsion between the electrons in a particular orbital, and shape of the orbital.

Generally, electrons closer to the nucleus are more strongly attracted to the protons in the nucleus. This relates to the electromagnetic force, which is the force of attraction between electrons and protons. The electrons in the outer orbital are less bound to this force, and they are freer to move. Hence, electrons in an outer orbital have more energy.

About electrons in a certain orbital shielded by electrons in another orbital, electrons in the inner shells shield the electrons in the outer shells from the force of attraction between the protons and the electrons. Orbitals that are being shielded more and have higher energies will be filled later. This follows the principle that electrons will fill the lower-energy levels first.

About the repulsion between electrons, electrons repel each other as they are of like negative charge. To minimize repulsion between electrons, electrons spread out singly into different orbitals within a given subshell, such as the *p* subshell, before pairing in a particular orbital. This relates to Hund's Rule, which we will discuss later.

A pair of electrons in a certain orbital repel each other. As electrons repel each other, energy is raised. However, electrons are attracted to the protons in the nucleus. The force of attraction between the electron and the nucleus lowers the energy of an electron, but the repulsion between electrons raises their energy.

The shape of the orbital also affects the energy level of the orbital. E.g., the s orbitals have lower energy levels than the p orbitals. This is because the shape of the s orbitals is more effective in letting the electrons be more tightly bound or closer to the nucleus (with a higher likelihood) than the shape of the p orbitals. The attraction of electrons in the s orbital to the nucleus is stronger than the p orbitals and results in a lower energy state.

Molecules and atoms are more stable when their electrons are paired, particularly in the outermost valence shell. The valence shell is the outermost shell of an atom, molecule, or ion. The outermost shell may have several orbitals. If the outermost orbital contains only one electron and the atom is highly reactive, it is a free radical.

Suppose there is an unpaired electron in the p_z orbital of a highly reactive free radical, this electron will actively pursue to pair with an electron from another atom or molecule.

Each orbital of a certain subshell, i.e., p_x, p_y, and p_z, for a quantum number, e.g., 2, has the same energy level and is about the same distance from the nucleus. E.g., all three orbitals in the *p* subshell for a certain shell, say n = 2, have the same energy level and are about the same distance from the nucleus. Orbitals having the same energy level are known as degenerate orbitals.

Each atom or ion has a fixed number of electrons. The hydrogen atom has one unpaired electron in the 1s orbital and is a free radical as it is highly reactive.

A2.6 The order in which electrons occupy the orbitals depends on the element

The electrons of most elements occupy the orbitals in accordance with the Aufbau Rule, the Pauli exclusion principle, Hund's Rule, and Madelung's Rule. Certain elements do not obey these rules for their electron configurations. The rules are discussed below:

Aufbau Principle: Electrons fill the lowest-energy levels first, progressively filling orbitals of higher energy levels.

The Pauli Exclusion Principle: Each orbital holds a maximum of 2 electrons, and if there are two electrons, the electrons have opposite spins. The spins of the electrons are not the same as the spinning of tops that some children play with.[225] With paired electrons, there is no creation of a magnetic field as the opposite spin direction cancels each other out.

All the atoms of wood have paired electrons. That is why wood has no attraction toward magnets. Iron is attracted to a magnet because the outermost orbitals of the atoms of iron have some unpaired electrons, which generate tiny magnetic fields.

Hund's Rule: The electrons individually occupy each of the orbitals in the other subshells before progressively adding more electrons to the orbitals, with each orbital having two electrons at most. This means that each orbital is singly occupied first. If all orbitals are already occupied by one electron, the remaining electrons will occupy the relevant orbitals, with at most two electrons in each orbital. Using the analogy of two enemies brought together, but who do not want to be together, we can visualize why electrons spread out singly into separate orbitals. This is to avoid interactions among the electrons, and the electrons become more stable before pairing up in a particular orbital.

The individual electrons in each orbital will have the same spin direction. The same spin direction for all the electrons in singly occupied orbitals is also called parallel spin. Parallel spins give rise to a magnetic field, though tiny. But with a larger number of atoms with parallel spins aligned in a certain material, the magnetic field increases.

Madelung's Rule: The Rule states that orbitals are filled with electrons in order of increasing $n + \ell$, i.e., an orbital with a smaller value for $n + \ell$ is filled first, and then electrons fill in the next orbital with a higher value for $n + \ell$. n is the principal quantum number, 1, 2, 3, 4, … 7. ℓ is the Azimuthal number, 0, 1, 2, 3, which refers to the orbitals s, p, d, and f, respectively. For elements with the same $n + \ell$, the electrons fill in the orbital with the lower n first.

E.g., look at the sum, $n + \ell$, for an element's 4s orbital and 3d orbital. As 4s has a lower value for $n + \ell$, the 4s orbital has a lower energy level than the 3d orbital, with exceptions to this rule for certain elements.

For elements that do not violate this rule, $n + \ell$ for 4s $= 4 + 0 = 4$. For 3d, $n + \ell = 3 + 2 = 5$. Hence, 4s is of lower energy than 3d. The electrons fill the 4s orbital first, before occupying the 3d orbitals, if any.

Electrons in higher energy levels are much less pulled to the nucleus and have higher potential energy, but have lower kinetic energy. An electron's potential energy is higher as it moves away from the nucleus. The total energy of an electron is the sum of its potential energy and kinetic energy.

The potential energy of the electron is zero at an infinite distance from the nucleus, i.e., the electrostatic force is zero. The distance is theoretically the situation in which the electrostatic attraction is zero, and is not about the exact distance between the electron and the nucleus. The potential energy of the electron is very negative near the nucleus and much less negative the further the electron is from the nucleus. That means the potential energy is lower near the nucleus, and higher the further it is from the nucleus.

The electrostatic attraction between electrons and protons for electrons further away from the nucleus is much less. Further away from the nucleus, there is greater uncertainty about the electron's location because it is less tightly bound to the nucleus. However, there is less uncertainty about the momentum of the electron, which translates into lower kinetic energy, according to the Heisenberg Uncertainty Principle.

The repulsive force between the electrons across the orbitals and between paired electrons within an orbital increases the potential energy of an electron. The repulsive force is positive. An analogy to this situation – two enemies (or electrons) coming together within a particular space. It takes a lot of energy to put two enemies together. The potential energy increases as two electrons are brought closer together.

The total energy of the electron is the sum of its potential energy and kinetic energy (Total energy = potential energy + kinetic energy). In general, as electrons move farther from the nucleus, their total energy increases. Note that the repulsive force between electrons in a shared orbital and across orbitals is part of the potential energy in the total energy equation.

Overall, the positive repulsive force between paired electrons in a shared orbital and across orbitals is less intense compared to the stronger electrostatic attraction between the electrons and the protons - the net effect is that the electron's overall total energy is still negative.[226] The dominant force is still the electrostatic attraction. The opposite spins of the paired electrons enable the electrons to tolerate each other's presence in the same space or orbital and allow them to stay together in the same orbital, though the electrons still repel each other.[227]

About the repulsion of electrons across orbitals, electrons spread out across orbitals to minimize interactions with one another. This is in accordance with the Pauli Exclusion Principle. The repulsion between electrons across orbitals is weak compared to the attraction between electrons and the nucleus.

The energy of an atom and the energy of an electron are different. From the above discussion, we know that the energy of an atom comprises the potential energy and kinetic energy of the electrons in their orbitals relative to the nucleus (with positively-charged protons), and the potential energy from binding together the protons and the neutrons, which are within the nucleus.

We can ignore the rest energy of the atom, given by $E = mc^2$, as the rest energy is released during highly controlled reactions, e.g., nuclear fission and nuclear fusion. Nuclear fission refers to the splitting of the nucleus brought about by a force. Nuclear fusion refers to the process in which an atom's nucleus and the nucleus of another atom fuse or combine to form a heavier nucleus, releasing a large amount of energy in the process.

In $E = mc^2$, E is energy, m is the mass, and c is the velocity of light. Yes, rest energy involves the velocity of light, though the atom is not moving. Using the example of a nuclear fission to illustrate $E = mc^2$, the mass, m, is the difference between the mass of the reactants, e.g., one Uranium-235 atom and the neutron fired into the Uranium-235 atom before fission takes place, and the fission products, including barium-139, krypton-94, and neutrons. The atomic mass (amu or u) of the reactants is greater than that of the fission products by about 0.2 u. So, m = 0.2 u approximately. This missing atomic mass of approximately 0.2 u gives rise to the energy in E. Energy released = (0.2 u)*c^2.

Though rest energy is released in controlled reactions, such as nuclear reactions, we recognize that mass and energy are equivalent, and that a small amount of mass can be converted into an enormous amount of energy. While it is true that only a few elements, such as uranium-235, uranium-233, and plutonium-239, can undergo nuclear fission, rest energy is a fundamental principle in physics, as all elements have rest energy. Fission is a specific process where mass is converted into a significant amount of energy, as given by $E = mc^2$.

A2.7 Applications and Violations of Madelung's Rule

In this section, we will look at the applications of the Aufbau Rule, Pauli exclusion principle, Hund's Rule, and Madelung's Rule, and briefly discuss the violations of Madelung's Rule by some elements toward the end of this section.

Let us look at the p-subshell. Three orbitals p_x, p_y and p_z, are in subshell p. Each of the orbitals p_x, p_y and p_z takes one electron first, and if there are more electrons to be occupied, we add an electron to an orbital, p_x. p_x now will have two electrons. Once the number of electrons reaches a maximum of two in that orbital, any electrons remaining to be filled in will go to the next orbital, p_y, in the sub-shell. For the s orbital, two electrons will occupy that orbital first before other electrons occupy the p-orbitals, if applicable.

The electrons occupy the shells and the orbitals depending on the element's atomic number. Let us look at the oxygen atom, which has an atomic number equal to 8. The oxygen atom has 8 electrons. Next, we examine how electrons occupy the orbitals. The electrons for each atom or isotope are distributed in the orbitals based on the rule that the first orbital, 1s, will have 2 electrons. The next shell is n=2. The 2s orbital will have 2 electrons. We have 4 electrons, which will be occupied by the $2p_x$, $2p_y$, and $2p_z$ orbitals. A possible configuration is that $2p_x$ has 2 electrons, and the $2p_y$ and $2p_z$ orbitals have 1 electron each. The electron configuration for the oxygen atom is $1s^2 2s^2 2p^4$.

This means that the oxygen atom has two unpaired electrons in the $2p_y$ and $2p_z$ orbitals. Free radicals have unpaired electrons in their outermost shell or subshell. The oxygen atom has two unpaired electrons and is highly reactive. Hence, the oxygen atom is a free radical.

For all elements, the electrons occupy part of or all of the orbitals 1s, 2s, 2p, 3s, 3p, depending on the number of electrons. For the first 18 elements in the periodic table, i.e., elements with one to eighteen electrons, the electrons occupy part or all of these orbitals in this order, 1s, 2s, 2p, 3s, 3p, i.e., 1s (2 electrons), 2s (2 electrons), 2p (a total of 6 electrons in the p sub-shell, with 2 each in the p_x, p_y and p_z orbitals), 3s (2 electrons), 3p (6 electrons). For the argon element [Ar] with atomic number 18, the electron configuration is commonly written as $1s^2 2s^2 2p^6 3s^2 3p^6$.

For the element potassium (atomic number 19), the electron configuration is $1s^2 2s^2 2p^6 3s^2 3p^6 4s^1$. For calcium (atomic number 20), the electron configuration is $1s^2 2s^2 2p^6 3s^2 3p^6 4s^2$. These elements follow Madelung's Rule. For potassium, the sum n + ℓ for the 4s orbital is 4 + 0 = 4. The sum n + ℓ for the 3p orbital is 3 + 1 = 4. Both the n + ℓ values are equal to 4. Since both values are equal, we go for the rule that electrons fill in the orbital with the lower n first, which is 3 in this case. So, 3p is filled first, followed by 4s.

The electron configuration for potassium can be expressed as [Ar] $4s^1$ for brevity. Instead of writing $1s^2 2s^2 2p^6 3s^2 3p^6 4s^1$, given the electron configuration of [Ar] of $1s^2 2s^2 2p^6 3s^2 3p^6$, potassium's electron configuration may be expressed as [Ar] $4s^1$.

Notice that the potassium atom is not a free radical. The potassium atom has an unpaired valence electron, which means that there is an unpaired electron in its valence shell (the outermost shell). Though it has one unpaired valence electron in its outermost orbital, the potassium atom is not considered a free radical, as potassium readily loses its unpaired electron to form the potassium ion or cation.

Lithium, in its neutral atomic state, is also not a free radical. The electron configuration of lithium (Li), which has 3 electrons, is $1s^2 2s^1$. Lithium has one valence electron in 2s, but it readily loses this electron to form a positive ion (Li+), like potassium and sodium (explained below).

The potassium cation, K^+, is stable as the third outer shell has eight electrons with no unpaired electrons. The electron configuration for potassium (K) is $1s^2 2s^2 2p^6 3s^2 3p^6 4s^1$, and the electron configuration for the potassium cation (K^+) is $1s^2 2s^2 2p^6 3s^2 3p^6$. Looking at the electron configuration in the third outer shell for the potassium cation, K^+, it is clear that it has no unpaired electrons. The potassium cation is stable because it follows the octet rule, which states that an outer shell with 8 electrons is stable. The potassium cation bonds easily with, e.g., the chloride ion, Cl^-, to form potassium chloride.

The octet rule certainly does not apply to the hydrogen gas molecule, which is stable, or to the helium (He) atom. A He atom, which has 2 electrons and an electron configuration of $1s^2$, is stable and unreactive. There are violations of the octet rule in other cases.[228]

Do note, however, there are violations of the Madelung's Rule.[229] [230] [231] Approximately 20 elements beyond Calcium (element number 20) do not follow the Madelung's Rule.

A2.8 Chemical Bonds

Chemical bonds occur when the attractions between the positively charged nuclei and electrons are sufficiently strong, and if each atom in the bonding has room in its valence orbitals (also referred to as outermost orbitals) to accommodate the valence electrons. The avenues for chemical bonds to occur include:

- The affected electron(s) could move from one atom to another atom. This will result in ionic bonding. One may also say that an atom is donating electron(s) to another atom.
- The affected electrons of an atom may be shared with another atom. This will result in covalent bonding.
- The affected electrons are delocalized and shared among many atoms. This is known as metallic bonding. Delocalized electrons are mobile electrons in atoms that can move freely within a metal structure, e.g., a copper wire. This movement is known as electron flow.

- Hydrogen bonding is a type of intermolecular bonding. An example of hydrogen bonding is between water molecules. The water molecule is formed via covalent bonding, and there is also interaction between water molecules via hydrogen bonding. More details are discussed below.

An example of ionic bonding is sodium chloride, or table salt. The atomic number of sodium is 11 with an electron configuration of $1s^2 2s^2 2p^6 3s^1$. The atomic number of the chlorine atom is 17, with an electron configuration of $1s^2 2s^2 2p^6 3s^2 3p^5$.

The sodium atom has an unpaired electron, but it is not a free radical as it readily donates an electron to the chlorine atom. The chlorine atom has become an anion or negatively charged ion with 6 electrons in the 3p orbital after getting an electron from sodium, and the new electron configuration is $1s^2 2s^2 2p^6 3s^2 3p^6$. The sodium atom, after donating its electron, has become a cation or positively charged ion with an electron configuration of $1s^2 2s^2 2p^6$. The octet rule, which explains how atoms strive to achieve a stable electron configuration, is in play here for the sodium ion. The result is a stable electron configuration of eight electrons in the valence (outermost) shell for the sodium ion in this chemical bond.

The positively charged sodium cations (Na^+) and the negatively charged chloride anions (Cl^-) form a stable ionic bond owing to the electrostatic attraction, as these ions attract each other:

$$Na + Cl \rightarrow Na^+ + Cl^- \qquad \text{Eq. A2.1}$$

See the figure in Encyclopedia Britannica for an illustration of ionic bonding[232]. Though the symbol for sodium chloride is typically written as NaCl, this is for convenience, as sodium chloride does not exist in discrete molecules. Sodium chloride exists as an ionic bond – think of sodium chloride or table salt as a lattice of ions, not individual molecules. The structure of sodium chloride differs from that of water. Water exists as separate molecules, not a lattice.

The positively charged sodium cations and the negatively charged chloride anions are found, e.g., in human blood, not in the solid table salt form but as freely moving ions in a dissolved state in the body's fluids. They are essential for maintaining electrolyte balance in the human body and for nerve function, muscle movement, and fluid and blood pressure regulation. The simple example provided is intended to illustrate the basics of ionic bonding that occurs in the human body.

An example of covalent bonding is the formation of the oxygen molecule. As noted previously, the electron configuration for the oxygen atom is $1s^2 2s^2 2p^4$. There are two unpaired electrons in each oxygen atom. Two oxygen atoms share electrons and form an octet in the valence shell, together with the 2s subshell, which has two electrons. Note that the oxygen atom is a free radical, as stated previously. The human body does not produce oxygen.

Another example of covalent bonding and hydrogen bonding is the water molecule. As noted earlier, the oxygen atom has two unpaired electrons in the $2p_y$ and $2p_z$ orbitals, while two electrons occupy the 2px orbital. The hydrogen atom has one unpaired electron in its 1s shell.

Two hydrogen atoms, each with one unpaired electron, share their unpaired electrons with one oxygen atom, which has two unpaired electrons – this results in covalent bonding:

$H_2 + O \rightarrow H_2O$ Eq. A2.2

The oxygen atom has now achieved a stable electron configuration with an octet of eight electrons in its outermost shell (the second outer shell) through covalent bonding. The human body produces water as a by-product of metabolic processes, accounting for about 5-10% of the water it needs daily.

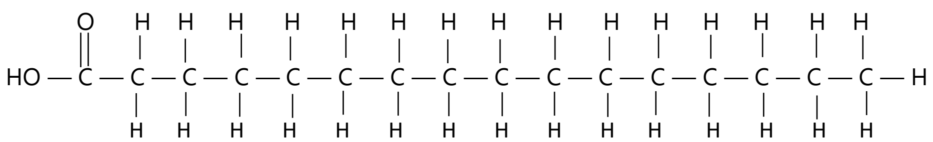
Hydrogen bonding is an intermolecular force that determines the strength of the attraction between adjacent water molecules. When the hydrogen atom shares its electron with the oxygen atom, the oxygen atom attracts the shared electron more strongly than the hydrogen atom does. Hence, the hydrogen atom is now slightly positively charged, and the oxygen atom slightly negatively charged. The hydrogen atom of one water molecule will then form a weak bond with the oxygen atom of another water molecule, thereby forming hydrogen bonding.[233]

A2.9 The Structure of Saturated and Unsaturated Fatty Acids

Free radicals damage the unsaturated fatty acids, particularly the polyunsaturated fatty acids. Fatty acids are essential components of human cells. Saturated and unsaturated fatty acids are components of human cells, but the proportions of these fatty acids vary depending on cell type. I will describe the structure and bonding of the fatty acids. Free radicals typically do not damage saturated fatty acids.

Fatty acids are made of carbon, hydrogen, and oxygen. Fatty acids are “acids” owing to the carboxyl group. Acids are defined by their ability to donate a proton, but the carboxyl group is the defining feature of fatty acids. Unsaturated fatty acids differ from saturated fats (also made of carbon, hydrogen, and oxygen) in that unsaturated fatty acids have one or more double bonds, but saturated fats only have single carbon-carbon bonds. Monounsaturated fats have one carbon-carbon double bond, with the rest being single carbon-carbon bonds.

Saturated fats are so named because the hydrocarbon chains have the maximum number of hydrogen atoms. The unsaturated fats do not have the maximum number of hydrogen atoms. See the figure below for an example of a simplified structure of a saturated fatty acid. Please note that the drawings below are simplifications of the molecular structures of fatty acids, intended to show the elements that make up fatty acids — single and double bonds — and not the actual three-dimensional structures. Malik (2025) presents approximate three-dimensional structures of fatty acids.[234]



Palmitic acid, a saturated fatty acid.

Palmitic acid is a saturated fatty acid with a 16-carbon chain, all single C—C bonds. The term "saturated" in saturated fatty acids means the fatty acid is completely saturated with hydrogen atoms.

The carboxyl group (as mentioned earlier) is on the left in the above diagram. The chemical formula for the carboxyl group is COOH. The carbon atom is double-bonded to one oxygen atom and is single-bonded to the hydroxyl group (HO). We will see this carboxyl group in all the illustrations for the fatty acids below.

The electron configuration of the carbon atom is $1s^2$, $2s^2$, $2p^2$. The 2 electrons in the p-orbitals fill the $2p_x$ and $2p_y$ orbitals, with an electron in each orbital. Given that to be stable, carbon should share electrons to form an octet of electrons in the 2nd outer shell. The carbon atom is hence reactive because it has not achieved an octet in its second outer shell.

The carbon atom cannot form four covalent bonds based on the configuration of $2s^2$, $2p^2$. In the configuration $2s^2$, $2p^2$, if two electrons were to remain in the 2s orbital, we cannot have four covalent bonds, given there are only two electrons in the p-orbitals. Something else must happen. That something else is hybridization. Hybridization of orbitals occurs when the s- and p- orbitals, e.g., mix to form sp orbitals, so that the number of bonds can be achieved in a molecule. This will result in four hybrid sp^3 orbitals on the carbon atom, with four single bonds in palmitic acid (except for the carbon atom in the carboxyl group, which has a double bond).

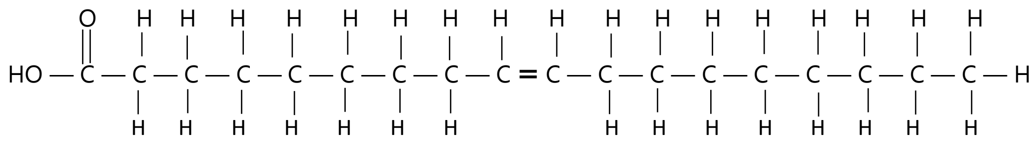
In the saturated fatty acid chain above, an intermediate carbon atom, say the third carbon atom from the left of the carboxyl group, has four covalent bonds. These are called sigma bonds. This is achieved through hybridization (or mixing) of one s- and three p- orbitals in the second outer shell. Different hybrid orbitals have different shapes. Experiments using spectroscopy have confirmed that hybridization takes place.

Hybridization enables bonding in molecules, forming electron pairs. Without hybridization, the bonding in the fatty acids will not occur. It does require some energy input to promote an electron from the 2s orbital to the empty 2p orbital. The energy released more than compensates for the initial energy input. The resulting structure is more stable.

The bonds are explained below:

- An electron in a sp^3 orbital of the carbon atom shares its electron with an electron from a hydrogen atom. There are two hydrogen atoms. Each hydrogen atom contributes an electron to share with the electron from the carbon atom (e.g., the third carbon atom). Now we have two covalent bonds.
- An electron in a sp^3 orbital of the third carbon atom shares its electron with an electron from an adjacent carbon atom. There are two adjacent carbon atoms for the third carbon atom. Similarly, the adjacent carbon atoms will also have four sp^3 orbitals. We now have two covalent bonds.
- There are now altogether eight electrons in the valence shell for the third carbon atom. A stable octet structure is achieved.

Monounsaturated fatty acids are characterized by a single carbon-carbon double bond, as shown below. An example of a monounsaturated fatty acid is oleic acid with 18 Carbon atoms:



Oleic acid, a monounsaturated fatty acid

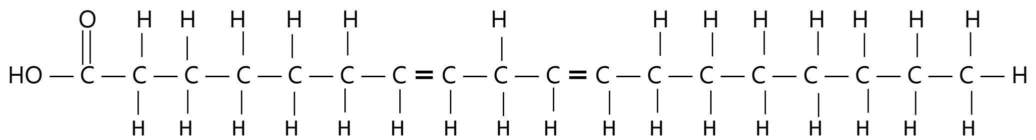
The double bond is at the 9^{th} carbon atom, counted from the first carbon atom of the carboxyl group (on the left of the figure above). The carboxyl group (- COOH) consists of a carbon atom double-bonded to an oxygen atom and single-bonded to a hydroxyl group. Notice there is one double C ═ C bond, hence the name “mono”.

In the carbon-carbon double bond, C ═ C, the carbon atom linked via the double bond, e.g., the 9^{th} carbon atom counted from the carbon atom in the carboxyl group, forms three sp^2 hybrid orbitals and has one p unhybridized orbital. An unhybridized orbital does not undergo any hybridization.

- The electron in the sp^2 hybrid orbital of the 9^{th} carbon atom shares an electron from the sp^2 hybrid orbital of the 10^{th} carbon atom. The name for this bond is called the sigma σ bond.
- The 9^{th} carbon atom shares its electron in the unhybridized p-orbital with the electron from the unhybridized p-orbital of the 10^{th} carbon atom. This bond is called the pi π bond. The pi bond is weaker than the sigma bond.[235]
- The 9^{th} carbon atom shares an electron in its sp^2 orbital with an electron contributed by the hydrogen atom to form the covalent sigma bond.
- The 9th carbon atom shares an electron in its sp^2 orbital with an electron from the sp^3 orbital of the 8^{th} carbon atom. This forms the covalent sigma bond.

There are now altogether eight electrons in the valence shell of the 9^{th} carbon atom. A stable octet structure is achieved.

An example of a polyunsaturated fatty acid is linoleic acid. Linoleic acid has 18 carbon atoms in its chain structure. There are two double carbons. The explanations for the double-bonded structure are the same as those for the monounsaturated fatty acid.

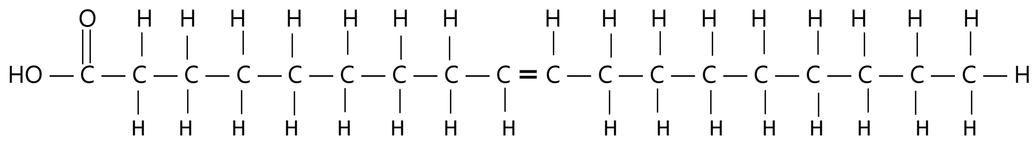


Linoleic acid, a polyunsaturated fatty acid. Note that there are two C ═ C double bonds.

Trans fats are a type of trans-unsaturated fat, but they are much more unhealthy than unsaturated fats. It can raise the bad cholesterol, LDL, and lower the good cholesterol, HDL. Trans fat behaves like saturated fats.

An example of trans fat is elaidic acid. Elaidic acid with 18 carbon atoms is an isomer of oleic acid, as both have the same chemical formula, the same number of carbon, oxygen, and hydrogen atoms, but the arrangement of the atoms is different. An isomer is a molecule that has the same molecular formula as another molecule, but with a different structural arrangement of the atoms.

The hydrogen atoms at the 9th and 10th carbon atoms, counted from the carboxyl group, are *on opposite sides* (also termed as on the trans side) of the double bond:



Elaidic acid, trans unsaturated fatty acid.

The chemical and physical properties of elaidic acid are different from those of oleic acid owing to the hydrogen atom arrangements at the double bond. The word “trans” means “across” in Latin. Trans fats are created industrially through partial hydrogenation, which creates the trans structure. In the partial hydrogenation process, hydrogen is added to liquid unsaturated vegetable oils to make them more solid. Partial hydrogenation means that not all the carbon atoms are bonded to the hydrogen atoms. Full hydrogenation is the case when all carbon atoms have the maximum number of hydrogen atoms.

Regarding the effects on health from consuming saturated, unsaturated, and trans fats, the chemical structure of these fats plays a role. The unsaturated fats, as discussed, have one or more (if applicable) double C ═ C bonds, while the saturated fats have single bonds. The reason why saturated fats are more unhealthy than unsaturated fats is related to the single C — C bonds of saturated fats. The double C ═ C bond, with one sigma bond and one pi bond, is not twice as strong as a single sigma bond. This means that a double bond is weaker than the combined strength of two single bonds. Of course, a double bond is stronger than a single bond.

The double bond in unsaturated fats makes them less tightly packed together than saturated fats. Unsaturated fats are liquid at room temperature because of their double bonds. Saturated fats are solid at room temperature.

The fact that unsaturated fats are less tightly packed is due to the weaker intermolecular forces between the molecules, and so less energy is required to keep them in a liquid state. The melting point of unsaturated fats is lower than that of saturated fats. A substance with a lower melting point melts at a lower temperature. A higher melting point means the substance requires a higher temperature to melt, typically requiring more energy input.

The double bond makes it easier for the unsaturated fats to break down than the saturated fats. It is less likely for arteries to be clogged by consuming unsaturated fats than saturated fats.[236] [237]

The semi-solid or solid state of trans fat at room temperature is attributed to its trans structure. In the trans structure, the hydrogen atoms are on opposite sides of the carbon-carbon double bond, C ═ C, as illustrated above. Not all countries have banned or restricted trans fats in foods. Countries that ban or limit the use of trans fat include the USA, Canada, and EU countries. Limits can be expressed as a maximum of 2% of trans fat in total fats.

Most saturated fats come from animal sources. Most unsaturated fats are from plants. Coconut flesh and palm oil contain saturated fats. Fish, a popular dish, contain both unsaturated fats and saturated fats. But the proportion of saturated fats in fish is not as high as that in other animal products.

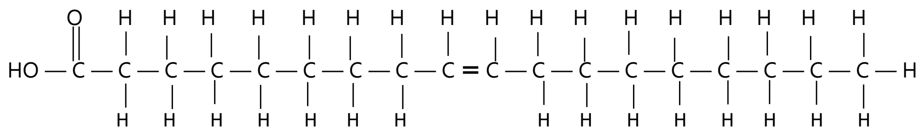
Triglycerides are formed when glycerol reacts with fatty acids:

Glycerol + fatty acids → Triglycerides + $3H_2O$ Eq. A2.3

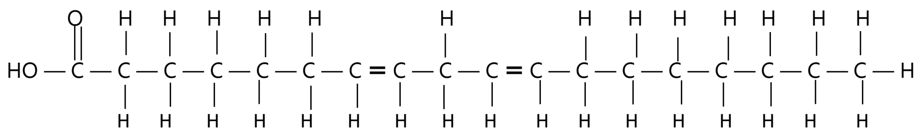
The chemical formula for glycerol is $C_3H_8O_3$ with three hydroxyl groups (OH).

For example, suppose the fatty acids are:

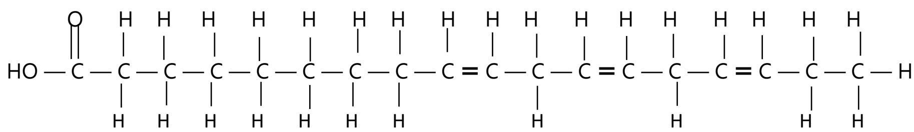
Oleic acid



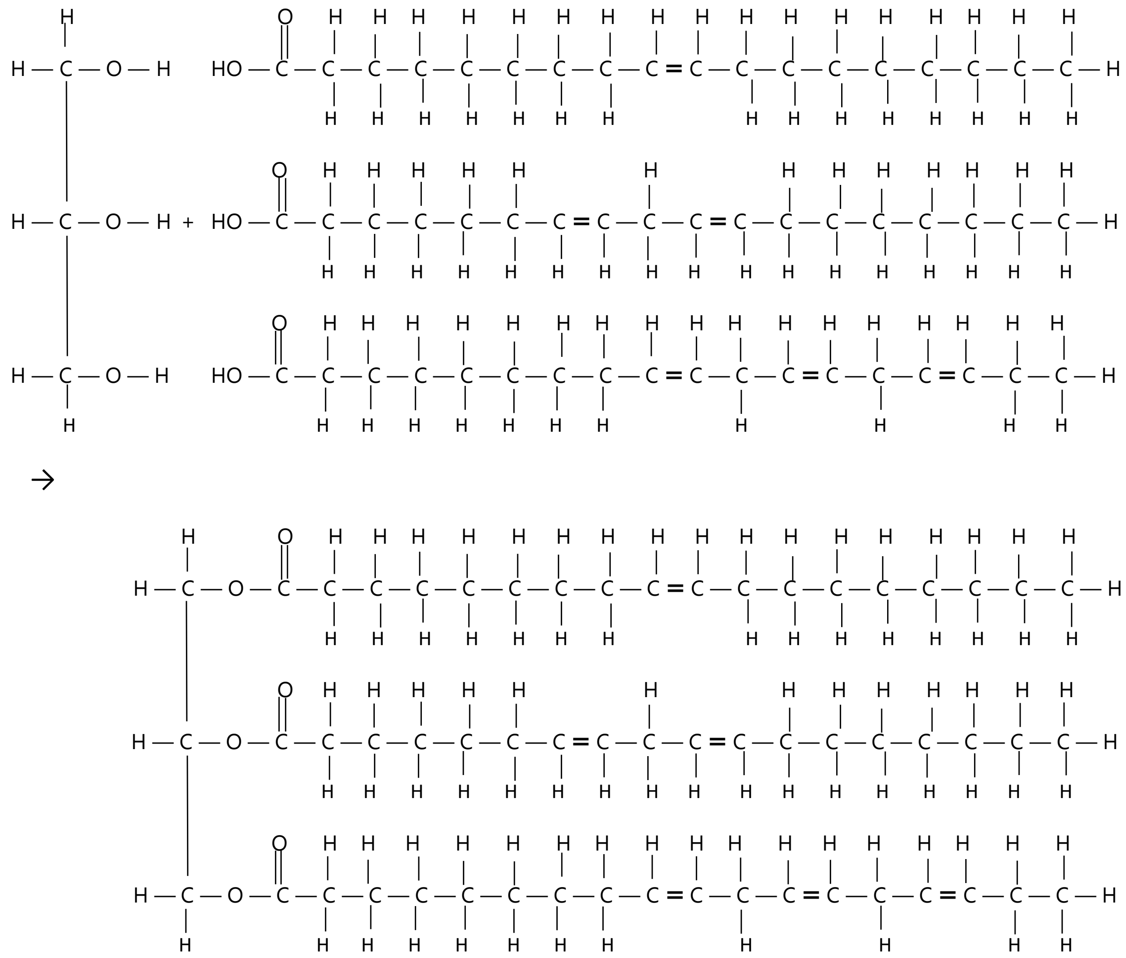
Linoleic acid



Linolenic acid



Glycerol reacts with the fatty acids:



+ $3H_2O$

Eq. A2.4

A2.10 Redox Reactions: Reduction and Oxidation, and the Rusting Process of Iron

Oxidation is about an atom or molecule losing one or more electrons. Oxidation, in the past, referred to iron being oxidized when it reacts with oxygen in the presence of water, forming rust. However, the definition of oxidation, as understood after the discovery of electrons, refers to an atom or molecule losing one or more electrons.

The rusting process of iron best explains the oxidation process. The electron configuration for iron (FE) is [Ar] $3d^6\ 4s^2$. The chemical reactions for iron rusting involve multiple steps. The purpose here is not to cover the various pathways in detail but to illustrate the basics of oxidation, redox reactions, and the gain or loss of electrons during rusting.

In the presence of water and oxygen, iron loses its electrons more quickly than if there were no oxygen and water.

A possible way to illustrate the basics of oxidation is listed below.

In the rusting process, oxidation takes place when iron comes into contact with water and loses its electrons,

$Fe \rightarrow Fe^{2+}(aq) + 2e^-$ Eq. A2.5

$Fe^{2+}(aq)$ refers to the ferrous ion in aqueous form. The electron configuration for the ferrous ion (Fe^{2+}) is [Ar] $3d^6$.

As oxidation refers to a substance losing its electrons, the net electrical charge of the iron atom has increased from 0 in the neutral state to 2+. If iron is being oxidised, iron is the reducing agent as it loses electrons to another substance. Reducing agents are substances that donate electrons.

As iron is being oxidized, the oxygen molecules in the presence of water accept the electrons. Hydroxide ions (OH^-) are produced:

$O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$ Eq. A2.6

An oxidant (also known as an oxidizing agent) is a substance that accepts electrons from another substance in a chemical reaction. Oxygen is an oxidant. The hydroxide ion (OH^-) so formed is stable.

The electron configuration of the neutral oxygen atom is $1s^2 2s^2 2p^4$, with six electrons in its outer shell. After the extra electron is accepted owing to the formation of the hydroxide ion in Eq. A2.6, the oxygen atom has formed an octet of eight electrons, together with an electron from the hydrogen atom and the extra electron accepted during the process. The hydroxide ion now has, in its outer shell, six electrons from the oxygen atom, one from the shared bond with hydrogen, and one extra from the negative charge accepted in the oxidation process. The octet rule is satisfied, and the negatively charged hydroxide ion is stable.

The reduction process refers to the gain of electrons by a substance; in this case, oxygen is the substance undergoing reduction. If oxygen atoms gain electrons, the oxygen atoms have been reduced. The oxygen atoms have been reduced because the net electrical charge of oxygen decreases from 0 as oxygen accepts electrons to form the hydroxide ion. In the reactions above, we observe both reduction and oxidation activities, which are part of the redox reaction. Oxygen atoms have been reduced, and iron atoms have been oxidized. If oxidation occurs, a simultaneous reduction process must also take place.

The oxygen gas molecule accepting the electrons in Eq. A2.6 is related to its molecular orbital structure.[238] An oxygen gas (O_2) molecule has partially filled molecular orbitals, and it can hence readily accept electrons.[239] A molecular orbital is similar to an atomic orbital in that they both are regions of space where electrons are likely to be found. Still, a molecular orbital differs from an atomic orbital in that the molecular orbital is associated with the entire molecule.

Not all oxidants are free radicals, as some oxidants do not have unpaired electrons. Some free radicals act as oxidants, and others act as reducing agents.[240]

The ferrous ions in aqueous form ($Fe^{2+}(aq)$) react with the hydroxide ions to form ferrous hydroxide ($Fe(OH)_2$), a solid:

$Fe^{2+}(aq) + 2OH^{-}(aq) \rightarrow Fe(OH)_2$ Eq. A2.7

The ferrous ion ($Fe^{2+}(aq)$) also reacts with the hydrogen ions in water and oxygen to produce ferric ion ($Fe^{3+}(aq)$) and water:

$4Fe^{2+}(aq) + 4H^{+}(aq) + O_2(aq) \rightarrow 4Fe^{3+}(aq) + 2H_2O(l)$ Eq. A2.8

The ferric ions (Fe^{3+}) react with the hydroxide ions to form ferric hydroxide ($Fe(OH)_3$), also known as iron (III) hydroxide (solid state):

$Fe^{3+} + 3OH^{-} \rightarrow Fe(OH)_3$ Eq. A2.9

The hydrated ferric hydroxide ($Fe(OH)_3$) can dehydrate, which means that it can release water to form ferric oxide (Fe_2O_3), the main component of rust:

$2Fe(OH)_3 \rightarrow Fe_2O_3{\cdot}xH_2O + (3-x)H_2O$ Eq. A2.10

We can say that ferric oxide (Fe_2O_3) is undergoing hydration.

Suppose x = 1, so the chemical equation becomes:

$2Fe(OH)_3 \rightarrow Fe_2O_3{\cdot}H_2O + 2H_2O$ Eq. A2.11

Note that e^{-} is electron. The formula for ferric oxide is Fe_2O_3. Hydrated ferric oxide is rust. Water molecules can associate with the surface of ferric oxide. The surface of ferric oxide refers to the external layer of the compound. This external layer interacts with its surroundings and, in this case, can associate with water molecules. The formula for hydrated ferric oxide is $Fe_2O_3{\cdot}xH_2O$, where x represents the number of water molecules attached to one molecule of ferric oxide. x, the composition of water molecules, is not fixed and is dependent on conditions such as the temperature and concentration of the reactants.

A2.11 Free Radicals and the Damage to the Human Body

A free radical has an unpaired electron and is highly reactive. The chlorine atom is an example of a free radical. A chlorine atom has an atomic number of 17, and the electron configuration is $[Ne]3s^2 3p^5$. The chlorine atom is a highly unstable free radical because it has one unpaired electron in its outermost $3p$ orbital, i.e., $3p_x$ has two electrons, $3p_y$ has two electrons but $3p_z$ has an unpaired electron. When the highly reactive chlorine atoms combine to form a chlorine molecule, each shares its single unpaired valence electron with the other, forming a bond quickly.

Free radicals may accept, share, or donate electrons.

We will look at examples of free radicals that accept electrons and cause damage to cells in the human body. For example, we see how the hydroxyl free radical, in the process of abstracting a hydrogen atom from unsaturated fatty acids, essentially accepts an electron as well.

About free radicals sharing electrons, two free radicals can share an electron each to form a stable, non-radical molecule – we saw this earlier when two chlorine atoms bond to form the chlorine molecule. Two free radicals in the human body can react to form a stable, non-radical molecule. We will see this later when we look at the termination of free radicals.

An example of how the superoxide radical ($O_2\bullet^-$ donates an electron is discussed later in this subsection when we see that $O_2\bullet^-$ can donate an electron to ferric ions (Fe^{3+}). The dot (•) in the radical signifies that the atom or molecule has a single, unpaired electron.

Free radicals that cause harm to the human body include hydroxyl radical (HO•), superoxide anion radical ($O_2^-\bullet$), and nitric oxide radical (NO•). The "•" symbolizes the unpaired electron for free radicals. Note that free radicals can benefit the human body by fighting against pathogens, provided they are not excessive.

A2.11.1 How free radicals operate

As discussed earlier, meat can induce the production of free radicals. The heme iron in meat contains iron. The ferrous ion (Fe^{2+}) is released from the heme iron with the aid of an enzyme, heme oxygenase. Ferrous ions may then participate in a chemical reaction to produce a free radical.

The chemical reactions are as follows[241]:

The released ferrous ion (Fe^{2+}) can react with hydrogen peroxide to produce ferric iron (Fe^{3+}), hydroxyl radical (HO•), and the negatively charged hydroxide ion. The hydroxyl radical, a neutral form of the hydroxide ion (OH^-), can harm the human body.

$$Fe^{2+} + H_2O_2 \rightarrow Fe^{3+} + OH^- + HO\bullet \qquad \text{Eq. A2.12}$$

Hydrogen peroxide is produced in the human body as a by-product of metabolic activities. From the chemical equation above, it is abundantly clear that a free radical is produced when iron from heme iron (found in animal byproducts) reacts with hydrogen peroxide, which is produced in the human body. That free radical is the hydroxyl radical (HO•), a highly potent and extremely reactive molecule which is also a member of the reactive oxygen species (ROS).

ROS are substances that are highly reactive, and they contain one or more oxygen atoms in their molecular structure. ROS is an oxidising agent, and some ROS contain unpaired electrons, which make them free radicals. Superoxide and hydroxyl radicals contain unpaired electrons and oxygen, and they are ROS. The hydroxyl radical (HO•) is, in fact, the most reactive member of ROS.

Not all ROS are free radicals. An example of a ROS that contains oxygen atoms and does not contain unpaired electrons is hydrogen peroxide (H_2O_2).[242]

The equation in Eq. A2.12 is balanced. Notice that there are two hydrogen atoms and two oxygen atoms on the left-hand side. On the right-hand side, there are also two hydrogen atoms and two oxygen atoms. The ferrous ion (Fe^{2+}) is a double positively charged cation. On the right-hand side, the Fe^{3+} is a +3 ion, and the hydroxide ion is a -1 ion. The net total positive and negative charges on both sides are equal.

Note that the hydroxyl radical (HO•) is a molecule with one oxygen atom and one hydrogen atom. The oxygen atom has 6 electrons in its outermost shell, and the hydrogen atom has one electron in the 1s shell. Given the discussion above on free radicals, this molecule is highly unstable because it is not an octet and has an unpaired electron. The hydroxyl radical is extremely short-lived (a very minute fraction of a second) and actively seeks to achieve stability.

In the human body, hydroxyl radicals damage DNA, disrupt cell protein structure, and initiate lipid peroxidation. Lipids are organic compounds that are generally insoluble in water and include fats, components of cell membranes, steroids such as cholesterol, oils, and waxes. Peroxidation is a type of oxidation, and it is more serious than just simple oxidation. It is a type of oxidation that can trigger a chain reaction and cause more serious damage to human cells and extensive tissue damage. The ROS radicals generated primarily target the unsaturated fatty acids that make up the cell membrane.[243 244]

The superoxide radical is $O_2{\bullet}^-$. The superoxide radical is made up of O_2 and has a single unpaired electron and a net negative charge. The superoxide anion radical ($O_2{\bullet}^-$) is formed in the body primarily as a by-product of mitochondrial respiration and by enzymes. Mitochondria are special subunits within a cell responsible for producing energy. The oxygen molecule accepted one extra electron as a result of an electron leak during the mitochondrial activities:

$$O_2 + e^- \rightarrow O_2{\bullet}^- \qquad \text{Eq. A2.13}$$

Though the superoxide radical is highly reactive, it is not necessarily bad in small amounts. It helps, e.g., with the body's defense mechanisms and cell regulation. Cell regulation is about cells interacting with other cells and themselves, and cell death.

The superoxide radical produced reacts with hydrogen peroxide to generate more hydroxyl radicals:

$$O_2{\bullet}^- + H_2O_2 \rightarrow O_2 + OH^- + HO{\bullet} \qquad \text{Eq. A2.14}$$

Note that the equation is balanced in terms of the net electrical charge and in the number of atoms of the elements on both sides.

The superoxide radicals ($O_2^-{\bullet}$) can donate an electron to ferric ions (Fe^{3+}).

$$O_2^-{\bullet} + Fe^{3+} \rightarrow O_2 + Fe^{2+} \qquad \text{Eq. A2.15}$$

As in Eq. A2.12, Fe^{2+} then reacts with hydrogen peroxide (H_2O_2) to form the hydroxyl radical ($HO{\bullet}$), and hydroxide ion (OH^-):[245]

$$Fe^{2+} + H_2O_2 \rightarrow Fe^{3+} + OH^- + HO{\bullet} \qquad \text{Eq. A2.16}$$

Given its unpaired electron, the hydroxyl radical ($HO{\bullet}$) can abstract or accept electrons from other compounds in the cells of the human body. The molecule that has lost an electron can become a new free radical. This attack by free radicals can trigger a chain reaction that damages cells in the human body. When cells are damaged due to electron loss, cellular functions are disrupted, and harmful substances such as ROS are produced. Cell death may also occur.

A2.11.2 Chain Reaction in the Production of Free Radicals

The chemical reactions involving the hydroxyl radical ($HO{\bullet}$), including the chain reaction, are as follows:

In the initiation stage, the hydroxyl radical attacks the polyunsaturated fatty acid (discussed in more detail below). The polyunsaturated fatty acid is denoted simply as RH. The "R" in RH refers to the "rest of" and, in this example, it relates to the rest of the fatty acid that does not include a hydrogen atom (H) that is to be abstracted by the free radical.

$$HO\bullet + RH \rightarrow R\bullet + H_2O \qquad \text{Eq. A2.17}$$

A hydrogen atom is abstracted from RH, and a fatty acid free radical (R•) and water are formed. In Eq. A2.17, the hydroxyl radical abstracts a hydrogen atom from the unsaturated fatty acid, which, in essence, is accepting an electron belonging to the hydrogen, to form a stable water molecule. On the product side of the reaction, we note that the fatty acid radical product has an unpaired electron.

In the propagation stage of the production of free radicals, the following reactions take place. Free radicals formed can initiate further free radical generation during the propagation stage.

- The fatty acid radical (R•) reacts with oxygen molecules to form the fatty acid peroxyl radicals (ROO•):

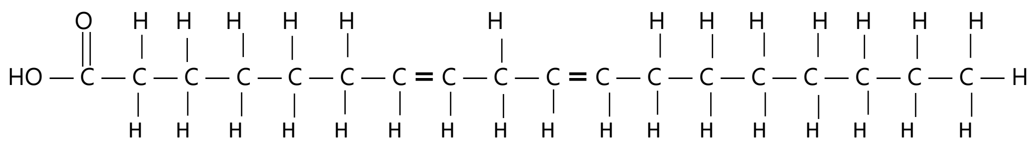
$$R\bullet + O_2 \rightarrow ROO\bullet \qquad \text{Eq. A2.18}$$

- The fatty acid peroxyl radical (ROO•) can further react with the polyunsaturated fatty acid (RH) to generate the fatty acid radical (R•) and lipid hydroperoxides (ROOH):

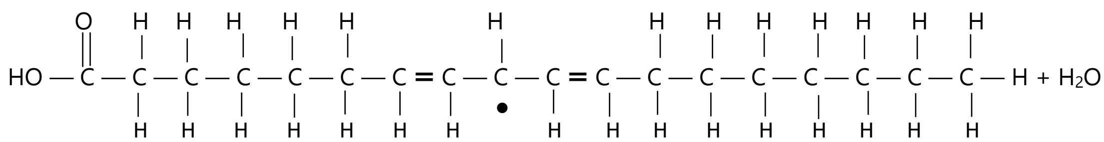
$$ROO\bullet + RH \rightarrow R\bullet + ROOH \qquad \text{Eq. A2.19}$$

Note that one hydrogen atom is removed from the polyunsaturated fatty acid (RH). The polyunsaturated fatty acid is said to be oxidized when the hydrogen atom is removed. The reactions go on and on, like a chain reaction, unless terminated.

Polyunsaturated fatty acids (PUFAs) are more susceptible to damage by free radicals than monounsaturated fatty acids (MUFAs) because they have two or more carbon-carbon double bonds. One of the hydrogen atoms in the C-H bond that is between the double bonds ($C = C$) is vulnerable to abstraction or removal by free radicals. See the figure below:



+ HO radical →



Eq. A2.20

Note that one of the hydrogen atoms in between the double bonds (at the 9th carbon atom) has been removed by the hydroxyl radical to form the fatty acid free radical (R•) and water. Either the top or bottom hydrogen atom may be removed.

In equation Eq. A2.17, the formation of the fatty acid free radicals is expressed in symbols. In this example, the fatty acid chain is illustrated to show precisely where the hydrogen atom is removed.

As noted previously, the 9^{th} carbon atom, before abstraction of the hydrogen atom, is stable with four covalent bonds, and the electrons of the carbon atom are paired with two hydrogen atoms and two adjacent carbon atoms. With the hydrogen atom removed by the free radicals, the electron of the hydrogen atom was also removed. The result is an unpaired electron for the carbon atom, i.e., a loss of a covalent bond.

This removal of the hydrogen atom means that the polyunsaturated fatty acid has become a free radical, which is highly reactive and eagerly seeks to bond with another molecule. As noted earlier, this process can trigger a chain reaction that produces excessive free radicals and oxidative stress, leading to cell damage.

Saturated fats are more resistant to attacks by free radicals owing to their bonding structure. Saturated fats comprise single C — C bonds which are all sigma bonds. Unsaturated fats have double C = C bonds, which have a sigma (σ) bond and a weaker pi (π) bond. The weaker π bond is more easily attacked and broken by free radicals.

Free radicals can also attack triglycerides with unsaturated fatty acid chains. As discussed earlier, triglycerides can be composed of saturated, unsaturated, and polyunsaturated fatty acids. Note that the polyunsaturated fatty acids within triglycerides, if present, are susceptible to attacks by free radicals.

Cell membranes are composed of both unsaturated and saturated fats. We can do nothing about the fact that unsaturated fats are a necessary and significant component of human cells. While the compositions of polyunsaturated and saturated fats of total fats in human cells vary from cell to cell and organ to organ, the percentages of unsaturated fats of total fats in human cells vary from 60 to 80%. Given the prominence of unsaturated fats in human cells and their susceptibility to free-radical attack, it is vital to reduce the potency of free-radical attacks. The choice of diet is, of course, crucial.

In the natural termination stage of the free radicals, i.e., without involving any antioxidants to terminate the chain reaction, a fatty acid radical can react with another fatty acid radical to generate a non-radical product. Examples include the following:

- The fatty acid free radical (R•) may also react with the fatty acid peroxyl radical (ROO•) to generate a non-radical product.
- The fatty acid peroxyl radical (ROO•) may also react with another fatty acid peroxyl radical (ROO•) to produce a non-radical product.

The basic principle is that both radicals have unpaired electrons and are highly reactive, eager to pair electrons to form a stable molecular structure. This termination process is very rare, as the likelihood of two radicals colliding is very small. Given these rare occurrences, antioxidants play a critical role, as discussed next.

A2.11.3 How Antioxidants Counteract Free Radicals

Antioxidants can help to terminate the free radical by donating an electron to the free radical, which is hungry to seek a pairing of electrons. When the free radicals are neutralized, the chain reaction stops. Damage to the molecules that make up the cells is delayed or prevented. This is very important so that healthy cells remain healthy and can carry out their metabolic functions. Cell damage is reduced.

When antioxidants are involved in terminating the propagation stage, we may refer to this as an antioxidant-induced termination of the free radicals. It is important to note that the human body needs a consistent supply of antioxidants to neutralize free radicals, and consuming foods rich in antioxidants, such as Vitamin C, E, and beta-carotene, is essential.

Antioxidants can interact with free radicals by donating electrons due to their molecular structure. Many antioxidants contain hydroxyl (-OH) groups, and these groups can readily lose a hydrogen atom, releasing the electron.[246] [247]

An example of an antioxidant containing the hydroxyl group is Vitamin E. Vitamin E reacts with the free radicals as follows. The process below, in which the antioxidant donates a hydrogen atom, is called hydrogen atom transfer:

$R_{Vit\,E}OH + R\bullet \rightarrow R_{Vit\,E}O\bullet + RH$ Eq. A2.21

$R_{Vit\,E}OH$ is Vitamin E, the antioxidant.
$R_{Vit\,E}$ is the rest of Vitamin E, without the hydroxyl group (OH).
OH is the hydroxyl group.
$R\bullet$ is the free radical.
$R_{Vit\,E}O\bullet$ is the oxidized product.
RH is a stable compound.

As shown above, the antioxidant vitamin E donates a hydrogen atom (via hydrogen atom transfer) to the free radical ($R\bullet$). When the hydrogen atom is donated, the electron is also donated to the free radical, which has an unpaired electron. When a hydrogen atom is bonded to the free radical, a stable compound, RH, is formed. $R_{Vit\,E}O\bullet$ is the oxidized product, but not as reactive as or much less reactive than the free radical.

Vitamin C, an antioxidant, can also donate the hydrogen atom to the free radical. The equation above can be applied using Vitamin C instead of Vitamin E. Vara and Pula (2014) use a figure to describe how the antioxidants Vitamins C and E help the human body counteract free radicals.[248]

It is worth discussing the bond dissociation energy to explain why this is the case. Bond dissociation energy is the energy required to break a particular bond in a molecule into separate fragments. For antioxidants with a hydroxyl group, the bond dissociation energy of the hydrogen bond within the hydroxyl group is low enough to enable the free radical to abstract the hydrogen atom, capturing its electron in the process. The result is a stable oxidised compound.

Though the antioxidant has lost an electron and become oxidised after losing the hydrogen atom, the oxidised compound is stable owing to its stable molecular structure, attributed to electron delocalisation. Electron delocalisation refers to the ability of a compound whose molecular structure allows electrons to spread across atoms, reducing electron-electron repulsion and lowering its overall energy.[249] A molecule with lower overall energy is more stable. You may think of a child with lots of energy running around actively, but when the child has less energy, the child returns to a more stable state.

Structural groups that define antioxidants include hydroxyl groups (-OH), amino groups, thiol groups, and isoprenoid groups. Antioxidants containing the -OH group include vitamins, flavonoids, phenols, and phenolic compounds found in plants. Phenol is a specific chemical compound with the formula C_6H_5OH.

A phenolic group contains at least one (one or more) hydroxyl (-OH) group attached to a benzene ring, and the hydroxyl group replaces a hydrogen atom that was initially part of the benzene ring. Polyphenols have *more than one* phenolic group. Phenolic compounds must have the "poly" (more than one) phenolic groups to be called a polyphenol. Hence, all polyphenols are phenolic compounds, but not all phenolic compounds are polyphenols.

There are certain synthetic antioxidants, such as butylated hydroxytoluene (BHT). BHT should not be consumed beyond the recommended intake, as excessive use may pose risks. BHT contains the hydroxyl groups.

In addition to the hydroxyl group feature, Charlton et al. (2023)[250] describe other structural groups, amino groups, thiol groups, and isoprenoid groups, that enable these antioxidants to have the ability (or power) to react with free radicals. The objective of these groups is to tame radicals, thereby minimizing or preventing cell damage. These other antioxidants are explained briefly below. For more details on amino groups, thiol groups, and isoprenoid groups, see Charlton et al. (2023).

Amino group antioxidants are nitrogen-based. An example of an amino group antioxidant is melatonin.

The defining feature of the thiol group antioxidant is the presence of a sulfhydryl (SH) group. An example of a thiol group antioxidant is glutathione.

The chemical structure of the isoprenoids is largely determined by the number of isoprene units that a particular isoprenoid has, but the ultimate (C) and (H) atom counts differ due to certain reactions and structural modifications. The basic isoprene unit has the chemical formula C_5H_8. An example of an isoprenoid antioxidant is beta-carotene, found in, e.g., carrots and oranges. Beta carotene has the chemical formula $C_{40}H_{56}$. The number of carbon atoms is 8*5 or 40, but the number of hydrogen atoms is not exactly 8*8 or 64, owing to the molecular structure of beta carotene.

Antioxidants can donate electrons in another mechanism called Single Electron Transfer (SET) to unstable free radicals because their molecular structure allows them to become stable after the donation. Some antioxidants, such as Vitamin C and Vitamin E, become oxidised antioxidants after donating an electron in SET reactions under certain conditions, such as the pH level. They remain tame and unreactive after donating the electron.[251] [252] [253] Some call oxidised antioxidants unreactive or tame “radicals” (notice the “”). A free radical, technically, is highly reactive. We do not say that antioxidants have become free radicals after donating an electron.

In SET, the antioxidant molecule donates a single electron to a free radical. The free radical accepts the electron, and in this situation, the free radical is the oxidising agent. The antioxidant that donates the single electron (to a free radical) is the reducing agent. The antioxidant, after losing the electron, has become a cation compound, and the free radical has become neutralized in the sense that it is no longer reactive:

$R_{Vit\ E}OH + R\bullet \rightarrow R_{Vit\ E}OH^{+} + R^{-}$ Eq. A2.22

$R_{Vit\ E}OH^{+}$: an antioxidant that has become a cation compound

R^{-}: Neutralized compound

The antioxidant can donate the electron as the energy required to remove the electron from the antioxidant is low, i.e., the antioxidant has a low ionisation potential. A low ionisation potential means that it takes very little energy for the atom or compound to lose its outermost electron. This is seized upon by the free radical that readily accepts the electron from the antioxidant. The Vitamins C and E antioxidants can participate in either hydrogen atom transfer or SET under certain conditions in the human body.[254 255]

Some antioxidants, such as transferrin, do not become oxidised. Transferrin, a protein found in the human body, helps to transport iron through the blood and acts as an antioxidant. But transferrin does not become oxidised. Transferrin can bind to ferric iron (Fe^{3+}), sequestering the ferric ion and making the ferric ion inactive so that the ferric ion does not get involved in chemical reactions to form ferrous ions.[256] In chemical terms, this ability of transferrin to sequester the ferric ion is called "chelating." We can think of chelation as "grabbing" in simple English. Transferrin can "grab", or chelate, the ferric ion to prevent it from causing harm.

Ferrous ion, shown earlier, can react with hydrogen peroxide, become oxidised, and form ferric iron and the hydroxyl radical. Transferrin helps prevent the production of free radicals, thereby minimizing or preventing cell damage. Cell damage, in general, can harm the human body and cause various problems.

To summarize, this appendix explains how free radicals can abstract hydrogen atoms from polyunsaturated fatty acids. This is akin to a person losing something or having something stolen – no one likes their belongings to be stolen. If the loot is bigger, the damage is heavier. Free radicals can steal hydrogen atoms from polyunsaturated fatty acids. Antioxidants play a significant role in counteracting free radicals. Plant-sourced antioxidants from the consumption of a variety of fruits, vegetables, and nuts can offer lots of assistance to the human body.

Appendix 3. Tests for Cholesterol

Doctors commonly request cholesterol tests. The tests are creative in that they use the indirect measurement of hydrogen peroxide produced to calibrate the cholesterol levels. This Appendix explains these technical details for those who are interested. The cholesterol tests include testing for high-density lipoprotein cholesterol (HDL), low-density lipoprotein cholesterol (LDL), and total cholesterol. The doctor usually recommends the triglyceride test alongside cholesterol tests.

A3.1 Tests for Total Cholesterol

To measure total cholesterol, it is not necessary to centrifuge or use a separation method to separate HDL from non-HDL or LDL from non-LDL, since the total cholesterol level is the goal. It is, however, necessary to remove cholesterol from cholesterol esters bound to fatty acids using an enzyme, cholesterol esterase.

$$\text{Cholesterol esters} + H_2O \xrightarrow{\text{cholesterol esterase}} \text{Cholesterol} + \text{fatty acid} \qquad \text{Eq. A3.1}$$

Cholesterol esters are briefly explained as follows. A cholesterol ester is made through an ester bond between the hydroxyl group of cholesterol and a fatty acid. An ester bond forms in cholesterol esters when a fatty acid's carboxyl group ($COOH$) reacts with the cholesterol's hydroxyl group (OH) in a process called esterification.

The carboxylic acid is characterized by the COOH group. Look at the fatty acid structure illustrated earlier, which has a carboxyl group. The fatty acid is a carboxylic acid. The OH in the COOH group is not a hydroxyl group, as the OH in the carboxyl group (COOH) is bonded to a carbon atom that is also double-bonded to oxygen.

The cholesterol removed from the cholesterol esters is added to the free cholesterol in the blood to obtain the total cholesterol count.

All of the cholesterol reacts with oxygen in the presence of an enzyme called cholesterol oxidase to produce cholest-4-en-3-one and hydrogen peroxide.

$$\text{Cholesterol} + O_2 \xrightarrow{\text{cholesterol oxidase}} \text{cholest-4-en-3-one} + H_2O_2 \qquad \text{Eq. A3.2}$$

The compound cholest-4-en-3-one is a cholesterol derivative (a cholestenone) and is no longer cholesterol.

The key to the test is that the hydrogen peroxide reacts with chemicals, such as phenol and a coupling agent, to produce a colored dye for testing. The hydrogen peroxide product reacts with phenol and a coupling agent (like 4-aminoantipyrine) in the presence of peroxidase to produce a colored dye (quinoneimine). The coupling agent's role is to react with hydrogen peroxide and phenol to produce the colored dye.

$$\text{hydrogen peroxide} + \text{phenol} + \text{4-aminoantipyrine} \xrightarrow{\text{Peroxidase}} \text{Quinoneimine} + \text{water}$$

Eq. A3.3

Phenol is an organic compound, and it is part of the reactions. Phenol acts as the coupling agent's partner to produce a chromogenic compound. If phenol is absent, no colored product will form. In this reaction, the chromogenic compound is the colored dye. The role of peroxidase is to facilitate this reaction, i.e., to act as a catalyst.[257 258 259]

Note that to produce the colored product, quinoneimine, both the coupling agent, 4-aminoantipyrine, and its partner, phenol, must be involved in the reactions. Otherwise, quinoneimine will not be produced. The higher the amount of hydrogen peroxide produced, the higher the quinoneimine concentration. The higher the quinoneimine concentration, the higher the total cholesterol level.

A3.2 Tests for HDL cholesterol

HDL cholesterol can be measured using either the centrifuge-precipitation or direct methods.

Briefly, the centrifuge-precipitation method uses specific reagents to aggregate and remove LDL and VLDL, yielding a sample containing only HDL. The reagents used can be phosphotungstic acid and magnesium chloride, which are used together as a precipitating reagent to selectively remove very-low-density and low-density lipoproteins (VLDL and LDL) from blood samples.

The VLDL and LDL sediments are removed after centrifugation, and the residual HDL lipoprotein sample then reacts with specific enzymes in chemical reactions to produce a colored product. A spectrophotometer can measure the intensity of the colored product to determine the concentration of HDL cholesterol.[260 261]

The enzymatic reactions involve cholesterol esterase and cholesterol oxidase, described earlier. Cholesterol esterase helps to remove cholesterol from cholesterol esters – see the chemical reactions in Eq A3.1. Cholesterol oxidase helps to produce hydrogen peroxide – see the chemical reactions in Eq A3.2. Hydrogen peroxide undergoes a chemical reaction similar to the reactions in Eq. A3.3 for producing the colored product. A higher intensity of the colored product correlates with a higher cholesterol level.

The direct method for measuring HDL cholesterol does not require a centrifuge to separate lipoproteins into HDL and non-HDL. One way is to use magnesium ions, dextran sulfate, and PEG-modified enzymes that are more active on HDL.[262]

PEG is used with dextran sulfate and magnesium ions. Dextran sulfate and magnesium ions create water-soluble complexes with the non-HDL lipoprotein. You can think of a complex as a molecule formed when two or more distinct substances bind together. These complexes, which include lipoproteins LDL and VLDL, then do not react with (i.e., are resistant to) the PEG-modified cholesterol esterase and cholesterol oxidase enzymes. The PEG-modified cholesterol esterase and cholesterol oxidase enzymes act on the cholesterol within the HDL lipoprotein.

The HDL lipoprotein does not form complexes with dextran sulfate. The HDL lipoprotein cholesterol measurements are in accordance with Eq. A3.1 and Eq. A3.2 (Step 2). The enzyme cholesterol esterase is used to release cholesterol from HDL cholesterol ester. There is also free cholesterol in HDL lipoproteins, which is then combined with cholesterol released from HDL cholesterol ester. All of the HDL cholesterol reacts with oxygen in the presence of cholesterol oxidase to produce hydrogen peroxide and cholestenone. The higher the hydrogen peroxide concentration, the higher the cholesterol level.

As for Eq. A3.3, it is up to the user to choose the manufacturer's kit, which contains reagents whose functions are similar to those in Eq. A3.3. The hydrogen peroxide generated reacts with certain chemicals, e.g., 4-aminoantipyrine, which is both a chromogenic reagent and coupling agent, and N-(3-sulfopropyl)-3-methoxy-5-methylaniline (chromogenic reagent), in the presence of an enzyme, peroxidase.

A chromogenic reagent undergoes a color change during a chemical reaction, producing a colored substance (in this case). Without the coupling agent, hydrogen peroxide cannot be detected, and no color is produced. The intensity of the colored product correlates with the amount of hydrogen peroxide produced and can be measured by a spectrophotometer.[263] [264] The intensity of the colored product reflects the concentration of HDL cholesterol.[265] [266]

The intensity of the colored product can also be measured using a colorimeter. There is technically a difference between the colorimeter and the spectrophotometer. The colorimeter uses only a few wavelengths of visible light, while the spectrophotometer, which is more expensive, advanced, and precise, measures the light absorbed over a broader wavelength range, e.g., 200-800 nm or beyond.

A3.3 Tests for LDL Cholesterol

The level of LDL cholesterol can be estimated indirectly from the total cholesterol and HDL cholesterol levels using the formula LDL = Total Cholesterol – HDL Cholesterol - (Triglycerides/5). The value, Triglycerides/5, is an estimate of the cholesterol from VLDL, and the amount of triglycerides is divided by 5 because the level of cholesterol in VLDL is approximately one-fifth of the level of triglycerides in VLDL.

To measure LDL cholesterol directly, the first step is to apply a specific surfactant (some manufacturers call it Detergent 1) to target and solubilize (or dissolve) non-LDL cholesterol, thereby breaking apart VLDL and HDL lipoproteins. For this case, a particular surfactant targets only non-LDL cholesterol, solubilizing it. Surfactants may include polyoxyethylene lauryl ether, polyoxyethylene cetyl ether, etc.[267]

Once broken down, the cholesterol esterase helps in extracting cholesterol from the cholesterol esters of non-LDL lipoproteins. The cholesterol that was released and oxygen react in the presence of the enzyme cholesterol oxidase to generate cholestenone (a colorless product) and hydrogen peroxide. Cholestenone is a colorless compound that *does not* interfere with the measurement of cholesterol from LDL. The hydrogen peroxide produced in this step is eliminated using the catalase enzyme:

$$\text{hydrogen peroxide} \xrightarrow{\text{catalase}} \text{water + oxygen} \qquad \text{Eq. A3.4}$$

Alternatively, a substance such as DSBmT is used in the presence of peroxidase to react with hydrogen peroxide. DSBmT is N,N-bis(4-sulfobutyl)-m-toluidine disodium with the chemical formula $C_{18}H_{26}N_2Na_2O_6S_2$.

DSBmT's primary role is as a chromogenic substrate that produces a colorless product upon reaction with hydrogen peroxide. "Chromogenic" describes something that can change in color.

A substrate is a material that is acted upon by another substance, such as an enzyme or reagent, to produce another product. The colorless product will not interfere with LDL cholesterol measurements. This means that the cholesterol from non-LDL lipoproteins has been eliminated, and there is no trace of hydrogen peroxide.

In the second step of the direct test for LDL cholesterol, the remaining cholesterol, which is derived only from LDL lipoproteins, is to be measured. The tests for the second step are in accordance with the reactions in Eq. A3.1, A3.2 and A3.3. Catalase from the first step of the test is inactivated by sodium azide (NaN_3).[268]

The cholesterol esters in LDL lipoproteins react with cholesterol esterase, releasing cholesterol from its ester form. Cholesterol then reacts with oxygen in the presence of cholesterol oxidase, producing hydrogen peroxide and cholestenone. Next, a colored product forms when peroxidase catalyzes the reaction between hydrogen peroxide and a chromogenic coupler (such as 4-aminoantipyrine), and a chromogenic reagent (such as N-ethyl-N-(2-hydroxy-3-sulfopropyl)-3-methylaniline, often abbreviated as TOOS). A coupler is a substance that links with another molecule to produce a colored product.

The more intense the color of the colored product, the higher the LDL cholesterol level. A spectrophotometer can be used to measure the cholesterol level.

It is interesting to note that cholesterol tests (HDL, LDL, and total cholesterol) indirectly measure the amount of hydrogen peroxide produced by the chemical reactions. This is indeed an ingenious method for testing cholesterol. The hydrogen peroxide reacts with certain chemicals in the presence of a catalyst or enzyme to produce a colored product. The amount of hydrogen peroxide indicates the level of cholesterol; the higher the hydrogen peroxide, the higher the cholesterol. The higher the intensity of the dye or colored product, the higher the cholesterol level, as measured by the spectrophotometer.

A3.4 Tests for Triglycerides

Triglycerides in blood can be estimated using the Glycerol Phosphate Oxidase (GPO) method.[269] The triglycerides, which are composed of glycerol and fatty acids, are first separated using an enzyme, lipase. The released glycerol reacts with adenosine triphosphate in the presence of the glycerol kinase enzyme to produce glycerol 3-phosphate and adenosine diphosphate. Subsequently, glycerol

3-phosphate reacts with oxygen in the presence of glycerol 3-phosphate oxidase (an enzyme), producing hydrogen peroxide as one of the products.

The hydrogen peroxide reacts with 4-chlorophenol and 4-amino-antipyrine (which functions as a coupling agent) in the presence of peroxidase to produce a colored dye product (i.e., Quinoneimine) and water. 4-chlorophenol is not the same phenol used for the cholesterol test. The intensity of the colored dye is proportional to the level of the hydrogen peroxide. The intensity of the colored dye, as measured by a spectrophotometer, is proportional to the level of triglycerides.

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References

(Readers may press Ctrl-click on the numbered hyperlink if they wish to find the location in this article that cites the corresponding reference.)

1 The World Counts. 2025. “Globally, we consume around 350 million tons of meat a year.” *TheWorldCounts.* https://www.theworldcounts.com/challenges/foods-and-beverages/world-consumption-of-meat. (26 July 2025, date last accessed).

2 Shahbandeh, M. 2022. “Meat Consumption Worldwide From 1990 to 2021, by Meat Type.” *Statista*, Apr 14. https://www.statista.com/statistics/274522/global-per-capita-consumption-of-meat/ (6 June 2022, date last accessed).

3 Jacobsen, Katherine. 2016. “Russia’s nuclear nightmare flows down radioactive river.” *AP News*, April 29. https://apnews.com/article/ba820f02074247fc8486b63b7c87d6cb (May 20, 2022, date last accessed).

4 PCRM. “Omega-3 Fatty Acids and Plant-Based Diets.” *Physicians Committee for Responsible Medicine.* https://www.pcrm.org/good-nutrition/nutrition-information/omega-3 (July 23, 2022, date last accessed).

5 American Dietetic Association and Dietitians of Canada. 2003. “Position of the American Dietetic Association and Dietitians of Canada: Vegetarian diet.” *Journal of the American Dietetic Association,* 103 (6): 748-65. https://pubmed.ncbi.nlm.nih.gov/12778049/.

6 Academy of Nutrition and Dietetics. 2016. “Position of the Academy of Nutrition and Dietetics: Vegetarian Diets.” *Journal of the Academy of Nutrition and Dietetics*, 116 (12). https://www.jandonline.org/article/S2212-2672(16)31192-3/fulltext.

7 Garone, Sarah. 2020. “Are Vegan Babies and Toddlers at Risk for Health Problems?” *Healthline,* November 30. https://www.healthline.com/health/baby/vegan-baby. (July 28, 2025, date last accessed).

8 Payton, William, 2020. “Can Too Much Garlic Upset Your Stomach?”, *Livestrong.com*, April 30. https://www.livestrong.com/article/480561-garlic-as-cause-of-diarrhea/ (May 18, 2022, date last accessed).

9 Ven Master Chin Kung. “The Art of Living: Part I and II.” *Buddha Dharma Education Association*. https://www.buddhistelibrary.org/library/view.php?adpath=33&msclkid=0daf53e3cef411ec9aa060fb5eadcc19. https://www.buddhistelibrary.org/library/download.php?aipath=59 (May 18, 2022, date last accessed).

10 Storoni, Mithu. 2018. “Stress and Your Diet: Can Certain Foods Affect Your Mood?” *Psychology Today*, February 15. https://www.psychologytoday.com/us/blog/the-stress-proof-life/201802/stress-and-your-diet-can-certain-foods-affect-your-mood.

11 Petre Alina. 2017. “Vegetarian Foods That Are Loaded with Iron.” *Healthline*, May 4. https://www.healthline.com/nutrition/iron-rich-plant-foods#TOC_TITLE_HDR_8 (May 18, 2022, date last accessed).

12 Shubrook, Nicola. 2019. “The best vegan calcium sources.” *BBC goodfood*, December 5. https://www.bbcgoodfood.com/howto/guide/best-vegan-calcium-sources (May 23, 2022, date last accessed).

13 David J. Sencer CDC Museum. 2025. “Outbreak in Hong Kong, 1997.” *Digital Exhibits, CDC Museum.* https://www.cdcmuseum.org/exhibits/show/influenza/avian-influenza/outbreak-hong-kong (July 26, 2025, date last accessed).

14 Danuta M. Skowronski, Caroline Astell, Robert C. Brunham, Donald E. Low, Martin Petric, Rachel L. Roper, Pierre J. Talbot, Theresa Tam, and Lorne Babiuk. 2005. “Severe Acute Respiratory Syndrome (SARS): A Year in Review.” *Annual Review of Medicine*, 56: 357-38. https://www.annualreviews.org/doi/10.1146/annurev.med.56.091103.134135.

15 Sean Ramos, Matthew MacLachlan, and Alex Melton. 2017. “Impacts of the 2014-2015 Highly Pathogenic Avian Influenza Outbreak on the U.S. Poultry Sector.” *United States Department of Agriculture*, December. https://www.ers.usda.gov/publications/pub-details?pubid=86281 (July 26, 2025, date last accessed).

16 WHO. 2022. “COVID-19 Cases, World.” *World Health Organization Coronavirus (COVID-19) Dashboard*, May 6. https://covid19.who.int/ (May 18, 2022, date last accessed).

17 Rigby, Jennifer. 2022. “COVID led to 15 million deaths globally, not the 5 million reported – WHO.” *Reuters*, May 6. https://www.reuters.com/legal/government/covid-led-15-million-deaths-globally-not-5-million-reported-who-2022-05-05/ (May 18, 2022, date last accessed).

18 Law, Violet. 2022. “COVID-19: The endless search for the origins of the virus.” *Aljazeera*, April 5. https://www.aljazeera.com/news/2022/4/5/covid-19-source-china-animal-or-lab (May 18, 2022, date last accessed).

19 John Elflein. 2023. “Coronavirus (COVID-19) cases, recoveries, and deaths worldwide as of May 2, 2023.” *Statista*, Aug 30. https://www.statista.com/statistics/1087466/covid19-cases-recoveries-deaths-worldwide/

20 Yuko Sato. 2022. “Bird flu is killing millions of chickens and turkeys across the US.” *The Conversation*, April 7. https://theconversation.com/bird-flu-is-killing-millions-of-chickens-and-turkeys-across-the-us-180299 (May 18, 2022, date last accessed).

21 Rust, Susanne and Karen Kaplan. 2025. “Killing 166 million birds hasn’t helped poultry farmers stop H5N1. Is there a better way?” *Los Angeles Times*, February 26. https://www.latimes.com/environment/story/2025-02-26/poultry-culling-hasnt-stopped-h5n1-bird-flu (July 26, 2025, date last accessed).

22 US Centers for Disease Control and Prevention (CDC). 2025. "H5 Bird Flu: Current Situation." *Centre for Disease Control Bird Flu Topic*, July 7. https://www.cdc.gov/bird-flu/situation-summary/index.html (July 26, 2025, date last accessed).

23 Kat Eschner. 2020. "A vegan world wouldn't keep diseases like COVID-19 from infecting humans." *Popular Science*, Mar 31 https://www.popsci.com/story/health/vegan-zoonotic-diseases-covid-coronavirus/ (May 18, 2022, date last accessed).

24 de Castro Cardoso Pereira, Paula Manuela, and Ana Filipa dos Reis Baltazar Vicente. 2013. "Meat nutritional composition and nutritive role in the human diet." *Meat Science*, 93 (3): 586-92. https://pubmed.ncbi.nlm.nih.gov/23273468/.

25 Binnie, Mary Ann, Karine Barlow, Valerie Johnson, and Carol Harrison. 2014. "Red meats: time for a paradigm shift in dietary advice." *Meat Science*, 98 (3): 445-51. https://pubmed.ncbi.nlm.nih.gov/25041653/.

26 McNeill, Shalene H. 2014. "Inclusion of red meat in healthful dietary patterns." *Meat Science*, 98 (3): 452-60. https://pubmed.ncbi.nlm.nih.gov/25034452/.

27 Wyness, Laura. 2016. "The role of red meat in the diet: nutrition and health benefits." *Proceedings of the Nutrition Society*, 75 (3): 227-32. https://pubmed.ncbi.nlm.nih.gov/26643369/.

28 Betts, J. Gordon, Peter Desaix, Eddie Johnson, Jody E. Johnson, Oksana Korol, Dean Kruse, Brandon Poe, James A. Wise, Mark Womble, and Kelly A. Young. 2022. *Anatomy and Physiology 2nd edition*. OpenStax. https://openstax.org/books/anatomy-and-physiology-2e/pages/1-introduction.

29 National Human Genome Research Institute. 2023. "Human Genomic Variation." February 1. https://www.genome.gov/about-genomics/educational-resources/fact-sheets/human-genomic-variation

30 Fraser, Carly. 2018. "Study: Vegan Diet and Lifestyle Changes Causes More Than 500 Genes to Change in 3 Months." *Live love fruit*, April 17. https://livelovefruit.com/vegan-diet-changes-500-genes-three-months/ (May 18, 2022, date last accessed).

31 Chandler, Jay. 2019. "Study Says: Vegan Diet Causes More Than 500 Genes to Change in Only 3 Months." *Medium*, October 20. https://medium.com/@jaychandler_30748/study-says-vegan-diet-causes-more-than-500-genes-to-change-in-only-3-months-1fbe27471caa (May 18, 2022, date last accessed).

32 Chaudhary, Priya, Anca Oana Docea, Balakyz Yeskaliyeva, Ahmad Faizal Abdull Razis, Babagana Modu, Daniela Calina, and Javad Sharifi-Rad. "Oxidative stress. 2023. Free radicals and antioxidants: potential crosstalk in the pathophysiology of human diseases." *Frontiers in Chemistry*, *Section: Medicinal and Pharmaceutical Chemistry,* 11. https://doi.org/10.3389/fchem.2023.1158198. https://www.frontiersin.org/journals/chemistry/articles/10.3389/fchem.2023.1158198/full.

33 George, Tammy. 2025. "Free Radicals and Antioxidants – What are They and Do You Need Them?" *Health Insurance Fund of Australia Limited (HIF)*. https://healthhub.hif.com.au/healthy-

living/free-radicals-and-antioxidants-what-are-they-and-do-you-need-them (September 29, 2025, date last accessed).

34 Yang, Jiaqi, Xiaona Na, Zhihui Li, and Ai Zhao. 2024. "Modification Role of Dietary Antioxidants in the Association of High Red Meat Intake and Lung Cancer Risk: Evidence from a Cancer Screening Trial." *Antioxidants* 13 (7): 799. https://doi.org/10.3390/antiox13070799 https://www.mdpi.com/2076-3921/13/7/799.

35 Macho-González, Adrián, Alba Garcimartín, María Elvira López-Oliva, Sara Bastida, Juana Benedí, Gaspar Ros, Gema Nieto, and Francisco José Sánchez-Muniz. 2020. "Can Meat and Meat-Products Induce Oxidative Stress?" *Antioxidants (Basel)*, 9 (7), Article 638. https://pmc.ncbi.nlm.nih.gov/articles/PMC7402184/

36 Ogun, Aminat S., Neena V. Joy, Menogh Valentine. 2023. "Biochemistry, Heme Synthesis." *in StatPearls Publishing*, May 1. https://www.ncbi.nlm.nih.gov/books/NBK537329/

37 Zhao, Guanghua. 2010. "Phytoferritin and its implications for human health and nutrition." *Biochimica et Biophysica Acta*, 1800 (8): 815-23. https://pubmed.ncbi.nlm.nih.gov/20100546/

38 Abdal Dayem, Ahmed, Mohammed Kawser Hossain, Soo Bin Lee, Kyeongseok Kim, Subbroto Kumar Saha, Gwang-Mo Yang, Hye Yeon Choi, and Ssang-Goo Cho. 2017. "The Role of Reactive Oxygen Species (ROS) in the Biological Activities of Metallic Nanoparticles." *International Journal of Molecular Sciences*, 18 (1): 120. https://doi.org/10.3390/ijms18010120 https://www.mdpi.com/1422-0067/18/1/120.

39 Chandimali, Nisansala, Seon Gyeong Bak, Eun Hyun Park, Hyung-Jin Lim, Yeong-Seon Won, Eun-Kyung Kim, Sang-Ik Park, and Seung Jae Lee. 2025. "Free radicals and their impact on health and antioxidant defenses: a review." *Cell Death Discovery*, 11, Article No. 19. https://doi.org/10.1038/s41420-024-02278-8 https://www.nature.com/articles/s41420-024-02278-8.

40 Harvard Medical School. 2019. "Understanding antioxidants". *Harvard Health Publishing*. January 31. https://www.health.harvard.edu/staying-healthy/understanding-antioxidants#:~:text=Your%20body%27s%20cells%20naturally%20produce,have%20antioxidant%20properties%20as%20well.

41 Narmin Hama amin Hussen, Sakar Karem Abdulla, Naza Mohammed Ali, Van Abdulqader Ahmed, Aso Hameed Hasan, and Eman Erfan Qadir. 2025. "Role of antioxidants in skin aging and the molecular mechanism of ROS: A comprehensive review." *Aspects of Molecular Medicine,* 5, Article 100063.
https://doi.org/10.1016/j.amolm.2025.100063.
https://www.sciencedirect.com/science/article/pii/S2949688825000012.

42 Tumilaar, Sefren Geiner, Hardianto, Ari, Dohi, Hirofumi, and Kurnia, Dikdik. 2024. "A Comprehensive Review of Free Radicals, Oxidative Stress, and Antioxidants: Overview, Clinical Applications, Global Perspectives, Future Directions, and Mechanisms of Antioxidant Activity of Flavonoid Compounds." *Journal of Chemistry,* 2024 (1).

https://onlinelibrary.wiley.com/doi/10.1155/2024/5594386#:~:text=*%20(1)%20Produced%20by%20the%20Fenton%20reaction,Fe+3%20+%20OH%E2%80%A2%20+%20OH%E2%88%92%20(fenton%20reaction).

43 Imran, Muhammad, Fereshteh Ghorat, Iahtisham Ul-Haq, Habib Ur-Rehman, Farhan Aslam, Mojtaba Heydari, Mohammad Ali Shariati, Eleonora Okuskhanova, Zhanibek Yessimbekov, Muthu Thiruvengadam, Mohammad Hashem Hashempur, Maksim Rebezov. 2020. "Lycopene as a Natural Antioxidant Used to Prevent Human Health Disorders." *Antioxidants (Basel)*, 9 (8), Article 706. https://pmc.ncbi.nlm.nih.gov/articles/PMC7464847/.

44 International Food Information Council. 2018. "What is Lutein?" December 18. https://ific.org/resources/articles/what-is-lutein/.

45 Adcock, Jacqui. 2018. "What are antioxidants? And are they truly good for us?" *The Conversation*, January 10. https://theconversation.com/what-are-antioxidants-and-are-they-truly-good-for-us-86062.

46 Carlsen, Monica H, Bente L Halvorsen, Kari Holte, Siv K Bøhn, Steinar Dragland, Laura. 2010."The total antioxidant content of more than 3100 foods, beverages, spices, herbs and supplements used worldwide." *Nutrition Journal*, 9 (3). https://doi.org/10.1186/1475-2891-9-3. https://nutritionj.biomedcentral.com/articles/10.1186/1475-2891-9-3.

47 Mayo Clinic. 2025. "Add antioxidants to your diet." *Mayo Clinic Health Library,* January 25. https://www.mayoclinic.org/healthy-lifestyle/nutrition-and-healthy-eating/in-depth/add-antioxidants-to-your-diet/art-20546814#:~:text=Plant%2Dbased%20foods%20are%20the,%2C%20isothiocyanates%2C%20and%20phenolic%20acids.

48 World Health Organization. 2015. "Cancer: Carcinogenicity of the consumption of red meat and processed meat, Q&A." *World Health Organization Newsroom*, October 26. https://www.who.int/news-room/questions-and-answers/item/cancer-carcinogenicity-of-the-consumption-of-red-meat-and-processed-meat (May 18, 2022, date last accessed).

49 The International Agency for Research on Cancer (IARC) & World Health Organization (WHO). 2015. "IARC Monographs evaluate consumption of red meat and processed meat." *IARC Monographs*, October 26. https://www.iarc.who.int/wp-content/uploads/2018/07/pr240_E.pdf (May 18, 2022, date last accessed).

50 Orlich, Michael J, Pramil N Singh, Joan Sabaté, Jing Fan, Lars Sveen, Hannelore Bennett, Synnove F Knutsen, W Lawrence Beeson, Karen Jaceldo-Siegl, Terry L Butler, R Patti Herring, and Gary E Fraser. 2015. "Vegetarian Dietary Patterns and the Risk of Colorectal Cancers." *The Journal of the American Medical Association (JAMA) Internal Medicine*, 175 (5): 767-76. https://pubmed.ncbi.nlm.nih.gov/25751512/.

51 Toniolo, Paolo, Elio Riboli, Fulvia Protta, Martine Charrel, and Alberto P. M. Cappa. 1989. "Calorie-Providing Nutrients and Risk of Breast Cancer." *Journal of the National Cancer Institute*, 81 (4): 278-

286. https://doi.org/10.1093/jnci/81.4.278. https://academic.oup.com/jnci/article-abstract/81/4/278/971336?redirectedFrom=fulltext&login=false.

52 Tantamango-Bartley, Yessenia, Synnove F Knutsen, Raymond Knutsen, Bjarne K Jacobsen, Jing Fan, W Lawrence Beeson, Joan Sabate, David Hadley, Karen Jaceldo-Siegl, Jason Penniecook, Patti Herring, Terry Butler, Hanni Bennett, and Gary Fraser. 2016. "Are strict vegetarians protected against prostate cancer?" *American Journal of Clinical Nutrition*, 103 (1): 153–160. https://pubmed.ncbi.nlm.nih.gov/26561618/.

53 Dong, Xiaocong, Mingjie Zhang, Jing Shu, Yunshan Li, Peishan Tan, Tianyou Peng, Jialin Lu, Yaojun Zhang, Xiali Zhong, and Aiping Fang. 2025. "The quality of plant-based diets and liver cancer incidence and liver disease mortality in the UK Biobank." *Clinical Nutrition ESPEN*, 67: 541-548. https://doi.org/10.1016/j.clnesp.2025.03.166. https://www.clinicalnutritionespen.com/article/S2405-4577(25)00258-X/abstract.

54 Brown, Julia. 2025. *"*Figure 15.5 Anatomy of the Kidney." In *"General Anatomy and Physiology,* K. Ernstmeyer and E. Christman (eds.). Open RN, WisTech Open. https://wtcs.pressbooks.pub/app/uploads/sites/49/2025/06/2610_The_Kidney.jpg.

55 Daniel, Carrie R, Yikyung Park, Wong-Ho Chow, Barry I Graubard, Albert R Hollenbeck, and Rashmi Sinha. 2013. "Intake of fiber and fiber-rich plant foods is associated with a lower risk of renal cell carcinoma in a large US cohort." *American Journal of Clinical Nutrition*, 97 (5): 1036–1043. https://pmc.ncbi.nlm.nih.gov/articles/PMC3628376/.

56 Davies, Alan, and Alwyn Scott. 2015. "Cardiac Anatomy and Electrophysiology." In *Starting to Read ECGs*, 1-15. Springer, London. https://thoracickey.com/cardiac-anatomy-and-electrophysiology/#Fig1. https://thoracickey.com/cardiac-anatomy-and-electrophysiology/.

57 Kauvery Hospital. 2016. "HDL and LDL. Do you know the difference?" Feb 23. https://www.kauveryhospital.com/blog/family-and-general-medicine/hdl-and-ldl-do-you-know-the-difference/.

58 Kamps, Arielle. 2018. "How Do LDL and HDL Differ Structurally and Functionally?" *Week&*, Dec 9. https://www.weekand.com/healthy-living/article/ldl-hdl-differ-structurally-functionally-18014488.php#%3A~%3Atext%3DThe%20main%20structural%20difference%20between%2Conly%2025%20percent%20is%20protein.%26text%3DLow-density%20lipoproteins%20contain%20proteins%2CA-I%20and%20A-II%20proteins.

59 McMillen, Matt. 2024. "Cholesterol Particle Size: What It Is and Why It Matters." *HealthCentral*, May 31. https://www.healthcentral.com/condition/high-cholesterol/cholesterol-particle-size.

60 Cleveland Clinic. 2024. "Cholesterol Levels." *Cleveland Clinic Health Library*, July 19. https://my.clevelandclinic.org/health/articles/11920-cholesterol-numbers-what-do-they-mean.

61 Ross AC, Taylor CL, Yaktine AL, et al., editors. 2011. "3 Overview of Vitamin D." In *Dietary Reference Intakes for Calcium and Vitamin D.* Institute of Medicine (US) Committee to Review Dietary Reference Intakes for Vitamin D and Calcium; Washington (DC): National Academies Press (US). https://www.ncbi.nlm.nih.gov/books/NBK56061/.

62 Papier, Keren, Georgina K. Fensom, Anika Knuppel, Paul N. Appleby, Tammy Y. N. Tong, Julie A. Schmidt, Ruth C. Travis, Timothy J. Key, and Aurora Perez-Cornago. 2021. "Meat consumption and risk of 25 common conditions: outcome-wide analyses in 475,000 men and women in the UK Biobank study." *BMC Medicine*, 19 (1): Article 53. https://bmcmedicine.biomedcentral.com/track/pdf/10.1186/s12916-021-01922-9.pdf. https://pubmed.ncbi.nlm.nih.gov/33648505/.

63 Alasmre, Faris A and Hammam A Alotaibi. 2020. "Plant-Based Diet: A Potential Intervention for Heart Failure." *Cureus*, 12 (5). https://pmc.ncbi.nlm.nih.gov/articles/PMC7317137/.

64 Landry, Matthew J., Katelyn E. Senkus, A Reed Mangels, Nanci S. Guest, Roman Pawlak, Sudha Raj, Deepa Handu, and Mary Rozga. 2024. "Vegetarian dietary patterns and cardiovascular risk factors and disease prevention: An umbrella review of systematic reviews." *American Journal of Preventive Cardiology*, 20. https://doi.org/10.1016/j.ajpc.2024.100868. https://www.sciencedirect.com/science/article/pii/S2666667724002368.

65 Storz, Maximilian Andreas and Paul Helle. 2019. "Atrial fibrillation risk factor management with a plant-based diet: A review." *Journal of Arrhythmia*, 35 (6): 781-788. https://pubmed.ncbi.nlm.nih.gov/31844466/.

66 Kuipers, M. F., Laurila, R., Remy, M. L., van Oudheusden, M., Hazlett, N., Lipsky, S., Reisner, L. L., McCall, D., de Groot, N. M. S., and Brundel, B. J. J. M. 2024. "Exploring Diet-Based Treatments for Atrial Fibrillation: Patient Empowerment and Citizen Science as a Model for Quality-of-Life-Centered Solutions." *Nutrients*, 16 (16). https://doi.org/10.3390/nu16162672. https://www.mdpi.com/2072-6643/16/16/2672.

67 Bai, Nina. 2025. "As fewer Americans die from heart attacks, more succumb to chronic heart disease." *Stanford Medicine*, Stanford School of Medicine, June 25. https://med.stanford.edu/news/all-news/2025/06/heart-attack.html.

68 Rapaport, Lisa. 2025. "Heart Attacks Have Become Less Deadly — Here's What's Killing Us Instead." *Everyday Health*, June 30. https://www.everydayhealth.com/cardiovascular-diseases/heart-attacks-have-become-less-deadly-heres-whats-killing-us-instead/#:~:text=%E2%80%9CMore%20are%20living%20with%20long%2Dterm%20heart%20issues%2C,heart%20conditions%20like%20heart%20failure%20and%20arrhythmias.%E2%80%9D.

69 Chiu, Tina H.T., Huai-Ren Chang, Ling-Yi Wang, Chia-Chen Chang, Ming-Nan Lin, and Chin-Lon Lin. 2020. "Vegetarian diet and incidence of total, ischemic, and hemorrhagic stroke in 2 cohorts in Taiwan." *Neurology,* 94 (11). https://doi.org/10.1212/WNL.0000000000009093. https://www.neurology.org/doi/10.1212/WNL.0000000000009093.

70 Baden, Megu Y., Zhilei Shan, Fenglei Wang, Yanping Li, JoAnn E. Manson, Eric B. Rimm, Walter C. Willett, Frank B. Hu, and Kathryn M. Rexrode. 2021. "Quality of Plant-Based Diet and Risk of Total, Ischemic, and Hemorrhagic Stroke." *Neurology*, 96 (15). https://www.neurology.org/doi/abs/10.1212/WNL.0000000000011713.

71 Mohammad Talaei, Ye-Li Wang, Jian-Min Yuan, An Pan, and Woon-Puay Koh. 2017. “Meat, Dietary Heme Iron, and Risk of Type 2 Diabetes Mellitus: The Singapore Chinese Health Study.” *American Journal of Epidemiology*, 186 (7), 824–833. https://academic.oup.com/aje/article/186/7/824/3848997?login=false.

72 Shahinfar, Hossein, Ahmad Jayedi, and Sakineh Shab-Bidar. 2022. “Dietary iron intake and the risk of type 2 diabetes: a systematic review and dose-response meta-analysis of prospective cohort studies.” *European Journal of Nutrition*, February 2. https://pubmed.ncbi.nlm.nih.gov/35107626/.

73 Li, Shu-Yi, Fan Wang, Xiao-Ting Lu, Rong-Huan Zhong, Jing-An Long, Ai-Ping Fang, and Hui-Lian Zhu. 2021. “Dietary iron intake and the risk of type 2 diabetes mellitus in middle-aged and older adults in urban China: a prospective cohort study.” *British Journal of Nutrition*, 126 (7): 1091-1099. https://pubmed.ncbi.nlm.nih.gov/33308344/.

74 Kim, Hyunju, Laura E. Caulfield, Vanessa Garcia-Larsen, Lyn M. Steffen, Morgan E. Grams, Josef Coresh, and Casey M. Rebholz. 2019. “Plant-Based Diets and Incident CKD and Kidney Function.” *Clinical Journal of American Society of Nephrology*, 14 (5): 682–691. https://pubmed.ncbi.nlm.nih.gov/31023928/.

75 NKF Patient Education Team. 2022. “Estimated Glomerular Filtration Rate (eGFR).” *National Kidney Foundation*, July 13. https://www.kidney.org/atoz/content/gfr (May 23, 2022, date last accessed).

76 Joshi Shivam, Sean Hashmi, Sanjeev Shah, and Kamyar Kalantar-Zadeh. 2020. “Plant-based diets for prevention and management of chronic kidney disease.” *Current Opinion in Nephrology and Hypertension*, 29 (1): 16-21. https://pubmed.ncbi.nlm.nih.gov/31725014/.

77 Cases, Aleix, Secundino Cigarrán-Guldrís, Sebastián Mas, and Emilio Gonzalez-Parra. 2019. “Vegetable-Based Diets for Chronic Kidney Disease? It Is Time to Reconsider.” *Nutrients*, 11 (6): 1263. https://pubmed.ncbi.nlm.nih.gov/31167346/.

78 McCarty, M F. 2001. “Does a vegan diet reduce risk for Parkinson's disease?” *Medical Hypotheses*, 57 (3): 318-23. https://pubmed.ncbi.nlm.nih.gov/11516224/. https://www.sciencedirect.com/science/article/pii/S0306987700913215?via%3Dihub.

79 Tresserra-Rimbau, Anna, Alysha S Thompson, Nicola Bondonno, Amy Jennings, Tilman Kühn, and Aedín Cassidy. 2023. “Plant-Based Dietary Patterns and Parkinson's Disease: A Prospective Analysis of the UK Biobank.” *Movement Disorders*, 38 (11): 1994-2004. https://movementdisorders.onlinelibrary.wiley.com/doi/10.1002/mds.29580. https://pubmed.ncbi.nlm.nih.gov/37602951/.

80 Kim, Hyunju, Casey M Rebholz, Sheila Hegde, Christine LaFiura, Madhunika Raghavan, John F Lloyd, Susan Cheng, and Sara B Seidelmann. 2021. “Plant-based diets, pescatarian diets and COVID-19 severity: a population-based case-control study in six countries.” *BMJ Nutrition Prevention and Health*, 4 (1): 257-266. https://nutrition.bmj.com/content/4/1/257.

81 Ray, Priyanka. 2021. “Impact of Vegan Diet on Visual Health”, *Vision Science Academy*, Mar 1. https://visionscienceacademy.org/impact-of-vegan-diet-on-visual-health/ (July 26, 2025, date last accessed).

82 Lazarus, Russel. 2021. “Healthy Eyes for Life: The 12 Best Vegetables.” *Optometrists Network*, October 6. https://www.optometrists.org/general-practice-optometry/guide-to-eye-health/eyes-the-windows-to-your-health/healthy-eyes-for-life-the-12-best-vegetables/ (May 18, 2022, date last accessed).

83 Wu, Juan, Eunyoung Cho , Walter C Willett, Srinivas M Sastry, and Debra A Schaumberg. 2015. “Intakes of Lutein, Zeaxanthin, and Other Carotenoids and Age-Related Macular Degeneration During 2 Decades of Prospective Follow-up.” *JAMA Ophthalmology*, 133 (12): 1415-24. https://pubmed.ncbi.nlm.nih.gov/26447482/.

84 Imelda, Eva, Rinaldi Idroes, Khairan Khairan, Rodiah Rahmawaty Lubis, Abdul Hawil Abas, Ade John Nursalim, Mohamad Rafi, and Trina Ekawati Tallei. 2022. "Natural Antioxidant Activities of Plants in Preventing Cataractogenesis" *Antioxidants* 11 (7), Article 1285. https://doi.org/10.3390/antiox11071285 https://www.mdpi.com/2076-3921/11/7/1285.

85 The University of Waikato. 2019. “Colours of light.” *Science Learning Hub Pokapū Akoranga Pūtaiao*, New Zealand Government. https://www.sciencelearn.org.nz/resources/47-colours-of-light

86 Cleveland Clinic. 2022. “Photokeratitis.” *Cleveland Clinic Health Library.* https://my.clevelandclinic.org/health/diseases/15763-photokeratitis (May 18, 2022, date last accessed).

87 Kierstan Boyd. 2021. “What Is a Pinguecula and a Pterygium?” *American Academy of Ophthalmology*, Nov. 22. https://www.aao.org/eye-health/diseases/pinguecula-pterygium (May 18, 2022, date last accessed).

88 Lee, Bo Ra, Yu Mi Ko, Mi Hee Cho, Young Ran Yoon, Seung Hee Kye, and Yoo Kyoung. 2016. “Effects of 12-week Vegetarian Diet on the Nutritional Status, Stress Status and Bowel Habits in Middle School Students and Teachers.” *Clinical Nutrition Research*, 5 (2): 102–111. https://pubmed.ncbi.nlm.nih.gov/27152300/.

89 Stephanie Eckelkamp. 2016. “The Surprising Reason You Shouldn't Chug Water with Your Meals.” *Prevention*, February 18. https://www.prevention.com/food-nutrition/healthy-eating/a20456813/why-you-shouldnt-drinking-water-with-meals/ (May 18, 2022, date last accessed).

90 Mayo Clinic. 2025. “Does drinking water during or after a meal help or harm digestion?” *Mayo Clinic Health Library,* March 7. https://www.mayoclinic.org/healthy-lifestyle/nutrition-and-healthy-eating/expert-answers/digestion/faq-20058348 (July 25, 2025, date last accessed).

91 Pandey, Kirti. 2021. “Hyponatremia or low sodium syndrome: Did you know drinking too much water can kill as electrolytes level dips?” *TimesNow*, June 2. https://www.timesnownews.com/health/article/hyponatremia-or-low-sodium-syndrome-did-you-

know-drinking-too-much-water-can-kill-as-electrolytes-level-dips/765247 (May 18, 2022, date last accessed).

92 Torborg, Liza. 2019. “Dairy milk, soy milk, almond milk — which is the healthiest choice for you (from Mayo Clinic News Network)?” *Lakeland Regional Health*, May 2. https://www.mylrh.org/dairy-milk-soy-milk-almond-milk-which-is-healthiest-for-you/ (July 26, 2025, date last accessed).

93 Thorning, Tanja Kongerslev, Anne Raben, Tine Tholstrup, Sabita S Soedamah-Muthu, Ian Givens, and Arne Astrup. 2016. “Milk and dairy products: good or bad for human health? An assessment of the totality of scientific evidence.” *Food and Nutrition Research*, Nov 22; 60. https://foodandnutritionresearch.net/index.php/fnr/article/view/954/3529.

94 Fraser, Gary E, Karen Jaceldo-Siegl, Michael Orlich, Andrew Mashchak, Rawiwan Sirirat, and Synnove Knutsen. 2020. “Dairy, soy, and risk of breast cancer: those confounded milks.” *International Journal of Epidemiology*, 49 (5): 1526–1537, https://doi.org/10.1093/ije/dyaa007.

95 Qin, Li-Qiang, Jia-Ying Xu, Pei-Yu Wang, Davaasambuu Ganmaa, Jue Li, Jing Wang, Takashi Kaneko, Kazuhiko Hoshi, Tomoyuki Shirai, and Akio Sato. 2004. “Low-fat milk promotes the development of 7,12-dimethylbenz(A)anthracene (DMBA)-induced mammary tumors in rats.” *The International Journal of Cancer*, March 15. https://doi.org/10.1002/ijc.20172. https://onlinelibrary.wiley.com/doi/full/10.1002/ijc.20172.

96 Qin, Li-Qiang, Jia-Ying Xu, Hideo Tezuka, Jue Li, Jun Arita, Kazuhiko Hoshi, and Akio Sato. 2007. “Consumption of commercial whole and non-fat milk increases the incidence of 7,12-dimethylbenz(a)anthracene-induced mammary tumors in rats.” *Cancer Detection and Prevention*, 31 (4): 339-43. https://pubmed.ncbi.nlm.nih.gov/17935906/.

97 Brahmkhatri, Varsha P., Chinmayi Prasanna, and Hanudatta S. Atreya. 2015. “Insulin-Like Growth Factor System in Cancer: Novel Targeted Therapies.” *Biomed Research International*, March 19, Article 538019.
https://pubmed.ncbi.nlm.nih.gov/25866791/.
https://onlinelibrary.wiley.com/doi/10.1155/2015/538019.

98 Bergman Daniel, Matilda Halje, Matilda Nordin, and Wilhelm Engström. 2013. “Insulin-Like Growth Factor 2 in Development and Disease: A Mini-Review.” *Gerontology*, 59: 240-249. https://www.karger.com/Article/Fulltext/343995.

99 Shanmugalingam, Thurkaa, Cecilia Bosco, Anne J. Ridley and Mieke Van Hemelrijck. 2016. “Is there a role for IGF-1 in the development of second primary cancers?” *Cancer Medicine*, 5 (11): 3353–3367. https://onlinelibrary.wiley.com/doi/full/10.1002/cam4.871. https://pubmed.ncbi.nlm.nih.gov/27734632/.

100 Danby, F William (Bill). 2009. “Acne, dairy and cancer: The 5α-P link.” *Dermato-Endocrinology*, 1 (1): 12–16. https://pubmed.ncbi.nlm.nih.gov/20046583/. https://www.tandfonline.com/doi/full/10.4161/derm.1.1.7124.

101 Yawitz, Kimberly. 2018. “IGF-1: Miracle Hormone or Health Hazard?” *Diet vs Disease*, November 28. https://www.dietvsdisease.org/igf-1-hormone-supplement/ (May 18, 2022, date last accessed).

102 Romo Ventura, Eugenia, Stefan Konigorski, Sabine Rohrmann, Harald Schneider, Guenter K Stalla, Tobias Pischon, Jakob Linseisen, and Katharina Nimptsch. 2020. "Association of dietary intake of milk and dairy products with blood concentrations of insulin-like growth factor 1 (IGF-1) in Bavarian adults." *European Journal of Nutrition*, 59 (4): 1413-1420. https://link.springer.com/article/10.1007/s00394-019-01994-7. https://pubmed.ncbi.nlm.nih.gov/31089868/.

103 Kakkoura, Maria G., Huaidong Du, Yu Guo, Canqing Yu, Ling Yang, Pei Pei, Yiping Chen, Sam Sansome, Wing Ching Chan, Xiaoming Yang, Lei Fan, Jun Lv, Junshi Chen, Liming Li, Timothy J. Key, and Zhengming Chen. 2022. "Dairy consumption and risks of total and site-specific cancers in Chinese adults: an 11-year prospective study of 0.5 million people." *BMC Medicine*, 20 (1): 134-147. https://bmcmedicine.biomedcentral.com/articles/10.1186/s12916-022-02330-3.

104 MK Manoylov. 2020. "What are cytokines?" *Live Science*, November 7. https://www.livescience.com/what-are-cytokines.html (May 18, 2022, date last accessed).

105 Dinarello, C A. 2000. "Proinflammatory cytokines." *Chest*, 118 (2): 503-8. https://pubmed.ncbi.nlm.nih.gov/10936147/.

106 Rahmani, Jamal, Alberto Montesanto, Edward Giovannucci, Hamid Zand, Meisam Barati, John J. Kopchick, Mario G. Mirisola, Vincenzo Lagani, Hiba Bawadi, Raffaele Vardavas, Alessandro Laviano, Kaare Christensen, Giuseppe Passarino, and Valter D. Longo. 2022. "Association between IGF-1 levels ranges and all-cause mortality: A meta-analysis." *Aging Cell*, 21 (2). https://onlinelibrary.wiley.com/doi/10.1111/acel.13540.

107 Gunnars, Kris. 2024. "9 Benefits of Eggs." *Healthline*, December 20. https://www.healthline.com/nutrition/10-proven-health-benefits-of-eggs#TOC_TITLE_HDR_2 (July 26, 2025, date last accessed).

108 Harvard T.H. Chan School of Public Health. 2020. "Eggs." *The Nutrition Source*, August. https://www.hsph.harvard.edu/nutritionsource/food-features/eggs/ (May 18, 2022, date last accessed).

109 Hu, F B, M J Stampfer, E B Rimm, J E Manson, A Ascherio, G A Colditz, B A Rosner, D Spiegelman, F E Speizer, F M Sacks, C H Hennekens, and W C Willett. 1999. "A prospective study of egg consumption and risk of cardiovascular disease in men and women." *JAMA*, 281 (15): 1387-94. https://pubmed.ncbi.nlm.nih.gov/10217054/.

110 Zhong, Victor W, Linda Van Horn, Marilyn C Cornelis, John T Wilkins, Hongyan Ning, Mercedes R Carnethon, Philip Greenland, Robert J Mentz, Katherine L Tucker, Lihui Zhao, Arnita F Norwood, Donald M Lloyd-Jones, and Norrina B Allen. 2019. Associations of Dietary Cholesterol or Egg Consumption with Incident Cardiovascular Disease and Mortality. *JAMA,* 321 (11):1081-1095. https://pubmed.ncbi.nlm.nih.gov/30874756/.

111 Harvard T.H. Chan School of Public Health. 2019. "Eggs and cholesterol back in the spotlight in new JAMA study." *The Nutrition Source*, March 18.

https://www.hsph.harvard.edu/nutritionsource/2019/03/18/eggs-and-cholesterol-back-in-the-spotlight-in-new-jama-study/ (May 18, 2022, date last accessed).

112 Rapier, Robert. 2021. "Highlights from the BP Statistical Review of World Energy 2021." *Forbes*, Jul 11. https://www.forbes.com/sites/rrapier/2021/07/11/highlights-from-the-bp-statistical-review-of-world-energy-2021/?sh=75aa40175bd6.

113 Rapier, Robert. 2020. "Fossil Fuels Still Supply 84 Percent of World Energy — And Other Eye Openers From BP's Annual Review." *Forbes*, Jun 20. https://www.forbes.com/sites/rrapier/2020/06/20/bp-review-new-highs-in-global-energy-consumption-and-carbon-emissions-in-2019/?sh=3d54ba8b66a1.

114 Ritchie, Hannah, Max Roser, and Pablo Rosado. 2020. "Renewable Energy." *Our World in Data.* https://ourworldindata.org/renewable-energy (5 July 2022, date last accessed).

115 Ritchie, Hannah, Max Roser, and Pablo Rosado. 2020. "CO_2 and Greenhouse Gas Emissions." *Our World In Data.* https://ourworldindata.org/greenhouse-gas-emissions (May 18, 2022, date last accessed).

116 *Food and Agriculture Organization of the United Nations* (FAO). 2017. *Livestock solutions for climate change*. https://www.fao.org/family-farming/detail/en/c/1634679/ (July 26, 2025, date last accessed).

117 Twine, Richard. 2021. "Emissions from Animal Agriculture—16.5% Is the New Minimum Figure." *Sustainability*, 13 (11), Article 6276. https://doi.org/10.3390/su13116276 https://www.mdpi.com/2071-1050/13/11/6276/htm.

118 Xiaoming Xu, Prateek Sharma, Shijie Shu, Tzu-Shun Lin, Philippe Ciais, Francesco N. Tubiello, Pete Smith, Nelson Campbell, and Atul K. Jain. 2021. "Global greenhouse gas emissions from animal-based foods are twice those of plant-based foods." *Nature Food,* 2, 724–732. https://www.nature.com/articles/s43016-021-00358-x. https://www.fao.org/3/cb7033en/cb7033en.pdf. https://openknowledge.fao.org/server/api/core/bitstreams/57aee0d5-0013-4182-abe7-55e1a817f553/content.

119 Ritchie, Hannah, Max Roser, and Pablo Rosado. 2024. "CO_2 and Greenhouse Gas Emissions." *Our World In Data*, January. https://ourworldindata.org/greenhouse-gas-emissions (October 13, 2025, date last accessed).

120 Lindsey, Rebecca. 2022. "Climate Change: Global Sea Level." *National Oceanic and Atmospheric Administration (NOAA)*, April 19. https://www.climate.gov/news-features/understanding-climate/climate-change-global-sea-level (May 18, 2022, date last accessed).

121 United Nations Climate Change. 2022. "The Paris Agreement." https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement (May 18, 2022, date last accessed).

122 Masson-Delmotte, Valérie, Panmao Zhai, Hans-Otto Pörtner, Debra Roberts, Jim Skea, Priyadarshi R. Shukla, Anna Pirani, Wilfran Moufouma-Okia, Clotilde Péan, Roz Pidcock, Sarah Connors, J. B. Robin Matthews, Yang Chen, Xiao Zhou, Melissa I. Gomis, Elisabeth Lonnoy, Tom Maycock, Melinda Tignor, and Tim Waterfield (eds.). 2018. “Global Warming of 1.5°C.” *Intergovernmental Panel on Climate Change.* https://www.ipcc.ch/sr15/ (May 18, 2022, date last accessed).

123 Abnett, Kate. 2021. “Explainer: What's the difference between 1.5°C and 2°C of global warming?” *Reuters*, November 10. https://www.reuters.com/business/cop/whats-difference-between-15c-2c-global-warming-2021-11-07/ (May 18, 2022, date last accessed).

124 Ritchie, Hannah, Max Roser, and Pablo Rosado. 2020. “CO_2 and Greenhouse Gas Emissions.” *Our World in Data*. https://ourworldindata.org/greenhouse-gas-emissions (May 22, 2022, date last accessed).

125 UNEP Press Release. 2019. “Cut global emissions by 7.6 percent every year for next decade to meet 1.5°C Paris target - UN report.” *United Nations Environment Programme*, November 26. https://www.unep.org/news-and-stories/press-release/cut-global-emissions-76-percent-every-year-next-decade-meet-15degc (May 18, 2022, date last accessed).

126 United Nations Framework Convention on Climate Change. 2022. “Global Warming Potentials (IPCC Second Assessment Report).” https://unfccc.int/process/transparency-and-reporting/greenhouse-gas-data/greenhouse-gas-data-unfccc/global-warming-potentials (May 18, 2022, date last accessed).

127 Center for Environmental Studies. 2023. “Radiation from the Sun.” in *Energy: The Driver of Climate*. Climate Science Investigations, Florida Atlantic University. https://www.ces.fau.edu/nasa/module-2/radiation-sun.php

128 Canon Science Lab. “Sunlight.”
https://global.canon/en/technology/s_labo/light/002/anigif/c002s001f003.gif
https://global.canon/en/technology/s_labo/light/002/01.html (October 14, 2025, date last accessed).

129 Aerological Observatory. 2005. “Observation of Infrared Radiation.” *Japan Meteorological Agency*. https://www.jma-net.go.jp/kousou/obs_third_div/rad/rad_ir-e.html (May 18, 2022, date last accessed).

130 Fecht, Sarah. 2021. “How Exactly Does Carbon Dioxide Cause Global Warming?” *Columbia Climate School*, February 25. https://news.climate.columbia.edu/2021/02/25/carbon-dioxide-cause-global-warming/ (May 18, 2022, date last accessed).

131 Betts, Richard. 2021. “Met Office: Atmospheric CO2 now hitting 50% higher than pre-industrial levels.” *Carbon Brief*, March 16. https://www.carbonbrief.org/met-office-atmospheric-co2-now-hitting-50-higher-than-pre-industrial-levels (May 18, 2022, date last accessed).

132 Salas, Erick Burgueño. 2025. “Average carbon dioxide (CO_2) levels in the atmosphere worldwide from 1959 to 2024.” *Statista*, Aug 7. https://www.statista.com/statistics/1091926/atmospheric-concentration-of-co2-historic/

133 Fred Pearce. 2016. "What would a global warming increase of 1.5C be like?" *Yale Environment 360*, June 16. https://e360.yale.edu/features/what_would_a_global_warming_increase_15_degree_be_like

134 Tans, Pieter and Kirk Thoning. 2020. "How we measure background CO2 levels on Mauna Loa." *National Oceanic and Atmospheric Administration (NOAA) Global Monitoring Laboratory*, September. https://gml.noaa.gov/ccgg/about/co2_measurements.html (May 22, 2022, date last accessed).

135 SciTechDaily. 2023. "How Heavy Is the Air? The Immense Weight of Earth's Atmosphere." October 18. https://scitechdaily.com/how-heavy-is-the-air-the-immense-weight-of-earths-atmosphere/#:~:text=By%20integrating%20the%20atmospheric%20pressure,the%20Great%20Pyramid%20of%20Giza! (October 14, 2025, date last accessed).

136 Nancy Harris and David Gibbs. 2021."Forests Absorb Twice as Much Carbon as They Emit Each Year." *World Resources Institute*, January 21. https://www.wri.org/insights/forests-absorb-twice-much-carbon-they-emit-each-year (May 18, 2022, date last accessed).

137 Planète Energies. 2025. "Forests & Oceans: Essential for the Climate." April 14. https://www.planete-energies.com/en/media/article/critical-role-played-forests-and-oceans

138 National Oceanic and Atmospheric Administration. 2022. "Increase in atmospheric methane set another record during 2021." April 7. https://www.noaa.gov/news-release/increase-in-atmospheric-methane-set-another-record-during-2021

139 Webb, Paul. 2021. "5.5 Dissolved Gases: Carbon Dioxide, pH, and Ocean Acidification." *Introduction to Oceanography*. Rhode Island. Roger Williams University. https://rwu.pressbooks.pub/webboceanography/chapter/5-5-dissolved-gases-carbon-dioxide-ph-and-ocean-acidification/ (May 18, 2022, date last accessed).

140 The University of Western Australia. 2011. "Researching ocean buffering." *The University of Western Australia*. https://www.uwa.edu.au/study/-/media/faculties/science/docs/researching-ocean-buffering.pdf (July 26, 2025, date last accessed).

141 Barker, Stephen and Andy Ridgwell. 2012. "Ocean Acidification." *Nature Education Knowledge*, 3 (10): Article #21. https://www.nature.com/scitable/knowledge/library/ocean-acidification-25822734/ (May 18, 2022, date last accessed).

142 NOAA Education. 2020. "Ocean acidification." *National Oceanic and Atmospheric Administration*, April 1. https://www.noaa.gov/education/resource-collections/ocean-coasts/ocean-acidification (May 18, 2022, date last accessed).

143 Planetary Technologies, Inc. 2023. "Detailed Community Response, Cornwall: Discussion and Emailed Q&A on Foundational Science." https://www.planetarytech.com/wp-content/uploads/2023/09/Community-Response_-Cornwall_-Discussion-and-Emailed-QA-on-Foundational-Science-2023.pdf

144 Rabiu, Kazeem O., Lidong Han, and Diganta Bhusan Das. 2017. "CO2 Trapping in the Context of Geological Carbon Sequestration." *Encyclopedia of Sustainable Technologies*, pp. 461-475. https://www.sciencedirect.com/science/article/pii/B9780124095489101241.

145 EPA. 2021. "Understanding the Science of Ocean and Coastal Acidification." *United States Environmental Protection Agency*, September 30. https://www.epa.gov/ocean-acidification/understanding-science-ocean-and-coastal-acidification (May 18, 2022, date last accessed).

146 Macnamara, Kelly. 2021 "Global Warming Is 'Fundamentally' Changing the Structure of Our World's Oceans." *ScienceAlert*, March 25. https://www.sciencealert.com/fundamental-changes-to-our-oceans-are-occurring-much-faster-than-we-thought (July 16, 2022, date last accessed).

147 Li, Guancheng, Lijing Cheng, Jiang Zhu, Kevin E. Trenberth, Michael E. Mann, and John P. Abraham. 2020. "Increasing ocean stratification over the past half-century." *Nature Climate Change*, 10, 1116–1123. https://doi.org/10.1038/s41558-020-00918-2. https://www.nature.com/articles/s41558-020-00918-2.

148 Snider, Laura. 2020. "Climate change is creating a significantly more stratified ocean, new study finds." *NCAR (National Center for Atmospheric Research) and UCAR (University Corporation for Atmospheric Research) News*, September 28. https://news.ucar.edu/132759/climate-change-creating-significantly-more-stratified-ocean-new-study-finds (July 16, 2022, date last accessed).

149 FAO. 2020. "The State of World Fisheries and Aquaculture 2020." *The State of the World Series.* Food and Agriculture Organization (FAO). http://www.fao.org/3/ca9229en/ca9229en.pdf https://openknowledge.fao.org/server/api/core/bitstreams/170b89c1-7946-4f4d-914a-fc56e54769de/content (July 26, 2025, date last accessed).

150 Riglen Victoria. 2021. "Climate smart fisheries: our new report." *Marine Conservation Society*, August 18. https://www.mcsuk.org/news/getting-climate-smart-our-new-fishery-report/ (May 18, 2022, date last accessed).

151 Broom, Douglas. 2020. "This small area of seagrass in Wales could be a big deal in the battle against climate change." *World Economic Forum*, Aug 31. https://www.weforum.org/agenda/2020/08/seagrass-restoration-carbon-climate-change/ (May 18, 2022, date last accessed).

152 Ahuja, Kiran. 2022. "Eating fish is destroying the planet." *Times of India*, April 22. https://timesofindia.indiatimes.com/blogs/voices/eating-fish-is-destroying-the-planet/ (May 18, 2022, date last accessed).

153 Greera, Krista, Dirk Zellerb, Jessika Woroniaka, Angie Coultera, Maeve Winchestera, M.L. Deng Palomaresa, and Daniel Paulya. 2019. "Global trends in carbon dioxide (CO2) emissions from fuel combustion in marine fisheries from 1950 to 2016." Marine Policy, 107, Article 103382. https://www.sciencedirect.com/science/article/pii/S0308597X1730893X.

154 Pimentel, David and Marcia Pimentel. 2003. "Sustainability of meat-based and plant-based diets and the environment." *The American Journal of Clinical Nutrition*, 78 (3): 660S–663S.

https://academic.oup.com/ajcn/article/78/3/660S/4690010?login=false (May 18, 2022, date last accessed).

155 Bittman, Mark. 2009. *Food matters: A guide to conscious eating with more than 75 recipes*. New York. Simon & Schuster.

156 Kannel, Charlie. 2010. “Conservation Tip #4: Eat Low on the Food Chain!!!.” *collegeconsumption*, November 24. https://collegeconsumption.wordpress.com/2010/11/24/conservation-tip-4/ (May 18, 2022, date last accessed).

157 Shahbandeh, M. 2022. “Number of chickens worldwide from 1990 to 2020.” *Statista*, Jan 21. https://www.statista.com/statistics/263962/number-of-chickens-worldwide-since-1990/ (July 2, 2022, date last accessed).

158 Shahbandeh, M. 2022. “Number of pigs worldwide from 2012 to 2022.” *Statista*, Apr 13. https://www.statista.com/statistics/263963/number-of-pigs-worldwide-since-1990 (July 2, 2022, date last accessed).

159 Foley, Jonathan A., Navin Ramankutty, Kate A. Brauman, Emily S. Cassidy, James S. Gerber, Matt Johnston, Nathaniel D. Mueller, Christine O’Connell, Deepak K. Ray, Paul C. West, Christian Balzer, Elena M. Bennett, Stephen R. Carpenter, Jason Hill, Chad Monfreda, Stephen Polasky, Johan Rockstro¨m, John Sheehan, Stefan Siebert, David Tilman, and David P. M. Zaks. 2011. “Solutions for a cultivated planet.” *Nature*, 478 (7369), 337–42. https://pubmed.ncbi.nlm.nih.gov/21993620/.

160 American Soybean Association. 2022. “Animal Agriculture.” *American Soybean Association*. https://soygrowers.com/key-issues-initiatives/key-issues/other/animal-ag/#:~:text=Animal%20agriculture%20is%20the%20soybean%20industry%E2%80%99s%20largest%20customer%2C,soybean%20meal%20goes%20to%20feed%20livestock%20and%20poultry (18 May 2022, date last accessed).

161 Turner, Laura. 2018. “How Eating Less Meat Can Reduce Poverty.” *The Borgen Project*, August 12. https://borgenproject.org/eating-less-meat-can-reduce-poverty/ (May 18, 2022, date last accessed).

162 Cassidy, Emily S, Paul C West, James S Gerber, and Jonathan A Foley. 2013. “Redefining agricultural yields: from tonnes to people nourished per hectare.” *Environmental Research Letters*, 8, Article 034015. https://iopscience.iop.org/article/10.1088/1748-9326/8/3/034015/pdf.

163 Cassidy, Emily S, Paul C West, James S Gerber, and Jonathan A Foley. 2013. “Redefining agricultural yields: from tonnes to people nourished per hectare.” *Environmental Research Letters*, 8, Article 034015. https://iopscience.iop.org/article/10.1088/1748-9326/8/3/034015/pdf.

164 Hunnes, Dana. “The Case for Plant Based.” *UCLA Sustainability.* https://www.sustain.ucla.edu/food-systems/the-case-for-plant-based/ (May 18, 2022, date last accessed).

165 Diet and Fitness Today. 2022. “Amount of Protein in Soybeans.” http://www.dietandfitnesstoday.com/protein-in-soybeans.php (May 18, 2022, date last accessed).

166 Fitprince. 2019. “Beef Protein per 100 Grams: Numbers, Alternatives, and Tips.” *Fitprince*, October 13. https://www.fitprince.com/beef-protein-per-100g/ (May 18, 2022, date last accessed).

167 Williams, Peter. 2007. “Nutritional composition of red meat.” *Journal of Dieticians Australia*, August 15. https://onlinelibrary.wiley.com/doi/full/10.1111/j.1747-0080.2007.00197.x.

168 Diet and Fitness Today. 2022. “Amount of Protein in Beef.” http://www.dietandfitnesstoday.com/protein-in-beef.php (May 18, 2022, date last accessed).

169 USDA. 2019. “Beef, ground, 80% lean meat / 20% fat, raw.” *FoodData Central*, US Department of Agriculture, April 1. https://fdc.nal.usda.gov/fdc-app.html#/food-details/174036/nutrients (May 18, 2022, date last accessed).

170 Diet and Fitness Today. 2022. “Amount of Protein in Cheddar Cheese.” http://www.dietandfitnesstoday.com/protein-in-cheddar-cheese.php (May 18, 2022, date last accessed).

171 FoodPrint. 2020. “The Water Footprint of Food.” August 11. https://foodprint.org/issues/the-water-footprint-of-food/#easy-footnote-bottom-5-1286 (May 18, 2022, date last accessed).

172 Katherine Boehrer. 2014. “This Is How Much Water It Takes to Make Your Favorite Foods.” *The Huffington Post*, Oct. 13. https://www.huffpost.com/entry/food-water-footprint_n_5952862 (May 18, 2022, date last accessed).

173 M Jalava, M Kummu, M Porkka, S Siebert, and O Varis. 2014. “Diet change—a solution to reduce water use?” *Environmental Research Letters*, 9, Article 074016. https://iopscience.iop.org/article/10.1088/1748-9326/9/7/074016.

174 Pacioglu, Octavian, Iris M.Tușa, Manuela E.Sidoroff, and Corina Ițcuș. 2021. “The Best Management Practices in Agriculture for Protection of Inland Water Ecosystems.” *ScienceDirect*, September 27. https://doi.org/10.1016/B978-0-12-819166-8.00042-6. https://www.sciencedirect.com/science/article/pii/B9780128191668000426.

175 Ritchie, Hannah and Max Roser. 2019. “Land Use.” *Our World in Data*, September. https://ourworldindata.org/land-use (May 18, 2022, date last accessed).

176 Poore, J. and T. Nemecek. 2018. “Reducing food’s environmental impacts through producers and consumers.” *Science*, 360 (6392), 987-992. https://www.science.org/doi/10.1126/science.aaq0216.

177 FAO, USAID, World Bank (coordinators).1997. “Livestock on grazing lands, Livestock & the Environment - Meeting the challenge”. *Food and Agriculture Organization of the United Nations, the United States Agency for International Development and the World Bank.* https://www.fao.org/3/x5304e/x5304e03.htm (May 18, 2022, date last accessed).

178 Anne Mottet, Ceesde Haan, Alessandra Falcucci, Giuseppe Tempio, Carolyn Opio, and Pierre Gerber. 2017. “Livestock: On our plates or eating at our table? A new analysis of the feed/food

debate." *Global Food Security*, 14: 1-8. https://www.sciencedirect.com/science/article/abs/pii/S2211912416300013.

179 National Farmers' Union. 2021. "Climate friendly farming: The facts about British meat." *National Farmers' Union*, c. https://www.nfuonline.com/media/sqhnllb3/the-facts-about-british-red-meat-and-milk.pdf (July 26, 2025, date last accessed).

180 Bell, Dan. 2009. "The methane makers." *BBC News*, October 28. http://news.bbc.co.uk/2/hi/uk_news/magazine/8329612.stm (May 18, 2022, date last accessed).

181 Badamasi, Hamza. 2022. "What is Permafrost and How is it Emitting Methane?" *Earth.org*, September 23. https://earth.org/data_visualization/what-is-permafrost/ (July 26, 2025, date last accessed).

182 National Geographic. 2025. "Glacier." *National Geographic Society Resource Library.* https://education.nationalgeographic.org/resource/glacier/ (July 28, 2025, date last accessed).

183 Horlings, Annika. 2022. "Crater Glacier: A story of renewal in the aftermath of destruction." *Cryospheric Sciences (CR) Division of the European Geosciences Union (EGU).* March 11. https://blogs.egu.eu/divisions/cr/2022/03/11/crater-glacier-a-story-of-renewal-in-the-aftermath-of-destruction/ (July 28, 2025, date last accessed).

184 IEA. 2020. "Methane Tracker 2020." *International Energy Agency*, March 2020. https://www.iea.org/reports/methane-tracker-2020 (May 18, 2022, date last accessed).

185 Levitt, Tom. 2021. "What's the beef with cows and the climate crisis?" *The Guardian*, October 27. https://www.theguardian.com/environment/2021/oct/27/whats-the-beef-with-cows-and-the-climate-crisis (May 18, 2022, date last accessed).

186 Struzik, Ed. 2020. "How Thawing Permafrost Is Beginning to Transform the Arctic." *Yale Environment 360*, January 21. https://e360.yale.edu/features/how-melting-permafrost-is-beginning-to-transform-the-arctic (May 18, 2022, date last accessed).

187 National Oceanic and Atmospheric Administration. 2022. "Increase in atmospheric methane set another record during 2021." April 7. https://www.noaa.gov/news-release/increase-in-atmospheric-methane-set-another-record-during-2021 (May 18, 2022, date last accessed).

188 Knoblauch, Christian, Christian Beer, Susanne Liebner, Mikhail N. Grigoriev, and Eva-Maria Pfeiffer. 2018. "Methane production as key to the greenhouse gas budget of thawing permafrost." *Nature Climate Change*, 8, 309–312. https://www.nature.com/articles/s41558-018-0095-z.

189 Kindy, David. 2021. "Permafrost Thaw in Siberia Creates a Ticking 'Methane Bomb' of Greenhouse Gases, Scientists Warn." *Smithsonian Magazine*, August 5. https://www.smithsonianmag.com/smart-news/ticking-timebomb-siberia-thawing-permafrost-releases-more-methane-180978381/ (May 18, 2022, date last accessed).

190 Lindsey, Rebecca. 2020. “Climate Change: Global Sea Level*.” Climate.gov, National Oceanic and Atmospheric Administration*, August 14. https://www.climate.gov/news-features/understanding-climate/climate-change-global-sea-level (May 18, 2022, date last accessed).

191 AFP. 2021. “Glacier melt is speeding up, raising seas – study.” *RTE News (Raidió Teilifís Éireann)*, Apr 28. https://www.rte.ie/news/2021/0428/1212696-glaciers-melting/ (May 18, 2022, date last accessed).

192 Smil, Vaclav. 2004. *Enriching the Earth: Fritz Haber, Carl Bosch, and the Transformation of World Food Production*. MIT Press. ISBN: 9780262194495.

193 QS Study. “Source of Oxygen during Photosynthesis.” In *Biology*. https://qsstudy.com/source-oxygen-photosynthesis/ (July 2, 2022, date last accessed).

194 Royal Society of Chemistry (RSC). “Nitrogen Cycle.”. https://edu.rsc.org/download?ac=12621 (July 2, 2022, date last accessed. Access for one article per month as a visitor).

195 American Water Works Association. 2002. “Nitrification.” *United States Environmental Protection Agency*, August 15. https://www.epa.gov/sites/default/files/2015-09/documents/nitrification_1.pdf (July 2, 2022, date last accessed).

196 Adrianne Jerrett. 2021. “How Do Plants Get Protein?” *Sciencing*, December 2. https://sciencing.com/how-do-plants-get-protein-13428186.html (July 2, 2022, date last accessed).

197 Bernhard, A. 2010. “The Nitrogen Cycle: Processes, Players, and Human Impact.” *Nature Education Knowledge,* 3 (10): 25. https://www.nature.com/scitable/knowledge/library/the-nitrogen-cycle-processes-players-and-human-15644632/ (July 2, 2022, date last accessed).

198 Giles, Madeline, Nicholas Morley, Elizabeth M. Baggs, and Tim J. Daniell. 2012. “Soil nitrate reducing processes – drivers, mechanisms for spatial variation, and significance for nitrous oxide production.” *Frontiers in Microbiology*, December 18. https://www.frontiersin.org/articles/10.3389/fmicb.2012.00407/full.

199 Schreiber Frank, Pascal Wunderlin , Kai M Udert, and George F Wells. 2012. “Nitric oxide and nitrous oxide turnover in natural and engineered microbial communities: biological pathways, chemical reactions, and novel technologies.” *Frontiers in Microbiology*, October 23, 3:372. https://pmc.ncbi.nlm.nih.gov/articles/PMC3478589/

200 Harford, Tim. 2017. “How fertiliser helped feed the world.” *BBC*, 2 January. https://www.bbc.com/news/business-38305504 (July 2, 2022, date last accessed).

201 Clark, Jim. “The Haber Process.” *Physical and Theoretical Chemistry*. LibreTexts. https://chem.libretexts.org/Bookshelves/Physical_and_Theoretical_Chemistry_Textbook_Maps/Supplemental_Modules_(Physical_and_Theoretical_Chemistry)/Equilibria/Le_Chateliers_Principle/The_Haber_Process

202 Modak, Jayant M. 2002. “Haber Process for Ammonia Synthesis.” *Resonance*, August, pp. 69 - 77. https://www.researchgate.net/publication/225769845_Haber_process_for_ammonia_synthesis

203 Our World in Data. "World population with and without synthetic nitrogen Fertilizers." *Our World in Data*. https://ourworldindata.org/grapher/world-population-with-and-without-fertilizer?country=~OWID_WRL (July 2, 2022, date last accessed).

204 Gilbert King. 2012. "Fritz Haber's Experiments in Life and Death." *Smithsonian Magazine*, June 6. https://www.smithsonianmag.com/history/fritz-habers-experiments-in-life-and-death-114161301/ (July 2, 2022, date last accessed).

205 Capdevila-Cortada, Marcal. 2019. "Electrifying the Haber–Bosch." *Nature,* 2, 1055. https://www.nature.com/articles/s41929-019-0414-4.

206 Policy Briefing Contributors. 2020. "Ammonia: zero-carbon fertiliser, fuel and energy store, policy briefing." *The Royal Society*, February. https://royalsociety.org/-/media/policy/projects/green-ammonia/green-ammonia-policy-briefing.pdf (July 2, 2022, date last accessed).

207 Ghavam, Seyedehhoma, Maria Vahdati, I. A. Grant Wilson, and Peter Styring. 2021. "Sustainable Ammonia Production Processes." *Frontiers in Energy Research*, March 29. https://www.frontiersin.org/articles/10.3389/fenrg.2021.580808/full (July 2, 2022, date last accessed).

208 IPNI. "Nitrification." *Nitrogen Notes 4, International Plant Nutrition Institute*. https://www.avocadosource.com/tools/useful_data/Nitrification.pdf (July 28, 2025, date last accessed).

209 Firestone, M. K., R. B. Firestone, and J. M. Tiedje. 1980. "Nitrous oxide from soil denitrification: factors controlling its biological production." *Science*, 208 (4445): 749-51. https://pubmed.ncbi.nlm.nih.gov/17771133/

210 AG Emissions Centre. "The science of nitrous oxide." New Zealand Agricultural Greenhouse Gas Research Centre. https://www.nzagrc.org.nz/domestic/nitrous-oxide-research-programme/the-science-of-nitrous-oxide/ (July 2, 2022, date last accessed).

211 World Health Organization. "Cardiovascular diseases." https://www.who.int/health-topics/cardiovascular-diseases#tab=tab_1

212 Betts, J. Gordon, Peter Desaix, Eddie Johnson, Jody E. Johnson, Oksana Korol, Dean Kruse, Brandon Poe, James A. Wise, Mark Womble, and Kelly A. Young. 2022. "Figure 19.4 Dual System of the Human Blood Circulation, 19.1 Heart Anatomy, Chapter 19 The Cardiovascular System: The Heart". in *Anatomy and Physiology, 2nd edition."* OpenStax. https://openstax.org/apps/image-cdn/v1/f=webp/apps/archive/20250522.165258/resources/38bde48e307e339036f8a4b50a1874aa6bdcb0d8.

213 Brodkey, Frank D. 2024. "Gas exchange." *MedlinePlus*, National Library of Medicine, US Government, July 15. https://medlineplus.gov/ency/anatomyvideos/000059.htm#:~:text=The%20walls%20of%20the%20alveoli%20share%20a%20membrane%20with%20the,travel%20back%20to%20the%20heart.

214 Cleveland Clinic. 2022. "Pulmonary Veins." Cleveland Clinic Health Library, June 2. https://my.clevelandclinic.org/health/body/23242-pulmonary-veins (September 22, 2025, date last accessed).

215 Leeper, Barbara and Darlene Legge. 2003. "Congestive Heart Failure." *Critical Care Nursing Clinics of North America*. https://www.sciencedirect.com/topics/medicine-and-dentistry/heart-left-ventricle-contraction (September 22, 2025, date last accessed).

216 UCSF. 2025. "How the Heart Works." *University of California San Francisco Thoracic Surgery, Department of Surgery*. https://thoracicsurgery.ucsf.edu/condition/how-heart-works (September 22, 2025, date last accessed).

217 Betts, J. Gordon, Peter Desaix, Eddie Johnson, Jody E. Johnson, Oksana Korol, Dean Kruse, Brandon Poe, James A. Wise, Mark Womble, and Kelly A. Young. "20.5 Circulatory Pathways." in *Anatomy and Physiology, 2nd edition." OpenStax*. https://openstax.org/books/anatomy-and-physiology-2e/pages/20-5-circulatory-pathways?query=azygos&target=%7B%22index%22%3A1%2C%22type%22%3A%22search%22%7D#fs-id2589135.

218 Pirie, Egle. 2023. "Bronchial veins." *Kenhub.* October 30. https://www.kenhub.com/en/library/anatomy/bronchial-veins.

219 Thoracic Key. 2016. "Fig. 7.1 Schema of bronchopulmonary anastomoses and other forms of venous admixture in the normal subject, The pulmonary circulation." *Thoracic Key*, June 12. https://thoracickey.com/the-pulmonary-circulation/.

220 Thoracic Key. 2019. "Pulmonary Circulation." *Thoracic Key*, April 6. https://thoracickey.com/pulmonary-circulation-4/.

221 Conover, Emily. 2023. "Electrons are extremely round, a new measurement confirms." *Science News*, July 6. https://www.sciencenews.org/article/electron-round-new-measurement-matter-physics#:~:text=Electrons%20are%20extremely%20round%2C%20a%20new%20measurement%20confirms (September 22, 2025, date last accessed).

222 Davis, Tim. 2012. "Explainer: what is wave-particle duality." *The Conversation*, July 27. https://theconversation.com/explainer-what-is-wave-particle-duality-7414

223 LibreTexts. "12.9: Orbital Shapes and Energies." https://chem.libretexts.org/Bookshelves/General_Chemistry/Map%3A_Chemistry_(Zumdahl_and_Decoste)/07%3A_Atomic_Structure_and_Periodicity/12.09%3A_Orbital_Shapes_and_Energies

224 Astronomy Education at the University of Nebraska-Lincoln. "Transitions." https://astro.unl.edu/naap/hydrogen/transitions.html (November 18, 2025, date last accessed).

225 Chu, Liza, Sharon Wei, Mandy Lam, and Lara Cemo. "Electron Spin." *Physical and Theoretical Chemistry.* LibreTexts. https://chem.libretexts.org/Bookshelves/Physical_and_Theoretical_Chemistry_Textbook_Maps/Sup

plemental_Modules_(Physical_and_Theoretical_Chemistry)/Quantum_Mechanics/09._The_Hydrogen_Atom/Atomic_Theory/Electrons_in_Atoms/Electron_Spin (September 22, 2025, date last accessed).

226 Kathryn Haas. "1.1.1: Coulomb's Law." *CHEM 342: Bio-inorganic Chemistry*, LibreTexts. https://chem.libretexts.org/Courses/Saint_Marys_College_Notre_Dame_IN/CHEM_342%3A_Bio-inorganic_Chemistry/Readings/Week_1%3A_Analysis_of_Periodic_Trends/1.1%3A_Concepts_and_principles_that_explain_periodic_trends/1.1.1%3A_Coulomb%27s_Law

227 The University of Illinois at Urbana-Champaign. "6. Polyelectronic Atoms and Ions." *Bonding Module.* https://www.astrochymist.org/chemicalbonding/WB/wb-1-06-00.html

228 Averill, Bruce, and Patricia Eldredge. 2011. "8.6: Exceptions to the Octet Rule." in *General Chemistry: Principles, Patterns, and Applications*. LibreTexts. https://chem.libretexts.org/Bookshelves/General_Chemistry/Book%3A_General_Chemistry%3A_Principles_Patterns_and_Applications_(Averill)/08%3A_Ionic_versus_Covalent_Bonding/8.06%3A_Exceptions_to_the_Octet_Rule. https://chem.libretexts.org/Bookshelves/General_Chemistry/Book%3A_General_Chemistry%3A_Principles_Patterns_and_Applications_(Averill) (September 22, 2025, date last accessed).

229 Scerri, Eric. 2013. "The trouble with the Aufbau Principle." *Education in Chemistry, Royal Society of Chemistry*, November 7. https://edu.rsc.org/feature/the-trouble-with-the-aufbau-principle/2000133.article.

230 Breslyn, Wayne. 2014. "Electron Configuration for Chromium (Cr, Cr2+, and Cr3+)." *University of Maryland website*. https://terpconnect.umd.edu/~wbreslyn/chemistry/electron-configurations/configurationChromium-Cr.html (September 22, 2025, date last accessed).

231 Breslyn, Wayne. 2014. "Electron Configuration for Copper (Cu, Cu+, and Cu2+)." *University of Maryland website.* https://terpconnect.umd.edu/~wbreslyn/chemistry/electron-configurations/configurationCopper-Cu.html (September 22, 2025, date last accessed).

232 Encyclopaedia Britannica. 2025. "Ionic bonding in sodium chloride." https://kids.britannica.com/students/assembly/view/92139#:~:text=An%20atom%20of%20sodium%20(Na,based%20on%20this%20ionic%20bond (September 22, 2025, date last accessed).

233 Biga, Lindsay M., Staci Bronson, Sierra Dawson, Amy Harwell, Robin Hopkins, Joel Kaufmann, Mike LeMaster, Philip Matern, Katie Morrison-Graham, Kristen Oja, Devon Quick, and Jon Runyeon. 2019. "Figure 2.11 – Hydrogen Bonds between Water Molecules." *Anatomy & Physiology*. OpenStax. https://open.oregonstate.education/aandp/chapter/2-2-chemical-bonds/.

234 Malik, Muhammad Arif. 2025. "9.3: Fatty acyls." *Science of Food*, edited by Trisha Russell, LibreTexts, June 8. https://chem.libretexts.org/Courses/Whitworth_University/Science_of_Food_(Russel)/09%3A_Fats/9.03%3A_Fatty_acyls https://chem.libretexts.org/Courses/Whitworth_University/Science_of_Food_(Russel)/00%3A_Front_Matter/03%3A_Table_of_Contents.

235 Sathee Initiative. “Chemistry Sigma And Pi Bond.” *Ministry of Education, India and IIT Kanpur.* https://sathee.iitk.ac.in/article/chemistry/chemistry-sigma-and-pi-bond/#:~:text=Strength:%20pi%20Bonds%20are%20weaker%20than%20sigma,to%20lower%20electron%20density%20between%20the%20nuclei (September 22, 2025, date last accessed).

236 Williams Integracare. “What is the Difference Between Unsaturated Fats and Saturated Fats?” https://integracareclinics.com/unsaturated-fats-vs-saturated-fats-whats-the-difference/

237 Cleveland Clinic. “The Skinny on Unsaturated Fats: Why You Need Them and the Best Sources.” https://health.clevelandclinic.org/the-skinny-on-unsaturated-fats-why-you-need-them-the-best-sources

238 Flowers, Paul, Klaus Theopold, and Richard Langley. 2025. “8.4: Molecular Orbital Theory.” *Chemistry, OpenStax*, 1e. https://chem.libretexts.org/Courses/University_of_Kentucky/UK%3A_General_Chemistry/08%3A_Advanced_Theories_of_Covalent_Bonding/8.4%3A_Molecular_Orbital_Theory.

239 Fridovich Irwin. 2013. “Oxygen: how do we stand it?” *Medical Principles and Practice,* 22 (2): 131-7. https://pmc.ncbi.nlm.nih.gov/articles/PMC5685332/.

240 Miller, Mark JS. 2016. “Are Oxidants the same as Free Radicals?” LinkedIn, August 30. https://www.linkedin.com/pulse/oxidants-same-free-radicals-mark-js-miller (September 22, 2025, date last accessed).

241 Abe Chizumi, Miyazawa Taiki, and Miyazawa Teruo. 2022. “Current Use of Fenton Reaction in Drugs and Food.” *Molecules*, 27 (17): 5451. https://pmc.ncbi.nlm.nih.gov/articles/PMC9457891/

242 Li Robert, Jia Zhenquan, and Trush Michael A. 2016. “Defining ROS in Biology and Medicine.” *Reactive Oxygen Species (Apex)*. 1 (1): 9-21. https://pmc.ncbi.nlm.nih.gov/articles/PMC5921829/.

243 Stoakes, Shelley Farrar .2019. “Lipid Peroxidation.” *News Medical*, April 16. https://www.news-medical.net/life-sciences/Lipid-Peroxidation.aspx (September 22, 2025, date last accessed).

244 Engwa, Godwill Azeh. 2018. “Free Radicals and the Role of Plant Phytochemicals as Antioxidants Against Oxidative Stress-Related Diseases.” *Phytochemicals - Source of Antioxidants and Role in Disease Prevention*. InTech. https://www.intechopen.com/chapters/60884.

245 Kıran, Tugba Raika, Otlu, Onder and Karabulut, and Aysun Bay. 2023. "Oxidative stress and antioxidants in health and disease." Journal of Laboratory Medicine, 47 (1): 1-11. https://doi.org/10.1515/labmed-2022-0108. https://www.degruyterbrill.com/document/doi/10.1515/labmed-2022-0108/html.

246 Moazzen, Amir, Nesrin Öztinen, Ezgi Ak-Sakalli, and Müberra Koşar. 2022. "Structure-antiradical activity relationships of 25 natural antioxidant phenolic compounds from different classes." Heliyon, 8 (9). https://www.cell.com/heliyon/fulltext/S2405-8440(22)01755-8.

247 Kasote DM, Katyare SS, Hegde MV, Bae H. 2015. “Significance of antioxidant potential of plants and its relevance to therapeutic applications.” International Journal of Biological Sciences. 11 (8):

982-91.
https://pmc.ncbi.nlm.nih.gov/articles/PMC4495415/#:~:text=Plant%20phenolics%20are%20mainly%20classified,metal%20ion%20chelating%20ability%2061.

248 Vara Dina, Pula Giordano. 2014. “Reactive oxygen species: physiological roles in the regulation of vascular cells (Fig-1-Natural-antioxidants).” *Current Molecular Medicine.* 14 (9): 1103-25. https://www.researchgate.net/profile/Giordano-Pula/publication/262845999/figure/fig1/AS:601657134026756@1520457647103/Fig-1-Natural-antioxidants-This-figure-represents-the-structure-and-chemical.png (Fig-1-Natural-antioxidants). https://www.researchgate.net/publication/262845999_Reactive_Oxygen_Species_Physiological_Roles_in_the_Regulation_of_Vascular_Cells (full article).

249 LibreTexts. “Delocalization of Electrons (in Valence Bond Theory, Chemical Bonding, Supplemental Modules, Physical & Theoretical Chemistry).” *Physical & Theoretical Chemistry*, LibreTexts.
https://chem.libretexts.org/Bookshelves/Physical_and_Theoretical_Chemistry_Textbook_Maps/Supplemental_Modules_(Physical_and_Theoretical_Chemistry)/Chemical_Bonding/Valence_Bond_Theory/Delocalization_of_Electrons.

250 Charlton, Nathan C, Mastyugin Maxim, Török Béla, and Török Marianna. 2023. “Structural Features of Small Molecule Antioxidants and Strategic Modifications to Improve Potential Bioactivity.” *Molecules*. 28 (3): 1057. https://pmc.ncbi.nlm.nih.gov/articles/PMC9920158/.

251 Francenia Santos-Sánchez, Norma, Raúl Salas-Coronado, Claudia Villanueva-Cañongo, and Beatriz Hernández-Carlos. 2019. ‘Antioxidant Compounds and Their Antioxidant Mechanism’. *Antioxidants*. IntechOpen. https://www.intechopen.com/chapters/66259.

252 Levine, Mark., Arie Katz, Sebastian Padayatty, Yaohui Wang, Peter Eck, Oran Kwon, Sumin Chen, and Jee-Hyuk Lee. 2004. “Vitamin C.” *Encyclopedia of Dietary Supplements 1st ed*. CRC Press. https://www.researchgate.net/publication/330483530_Vitamin_C.

253 FAO and WHO. 2001. “Summary of the role of vitamin E in human metabolic processes.” *Human Vitamin and Mineral Requirements*, Report of a joint FAO/WHO expert consultation, Bangkok, Thailand.
https://www.fao.org/4/y2809e/y2809e0f.htm.

254 Njus David and Patrick M Kelley. 1991. “Vitamins C and E donate single hydrogen atoms in vivo.” *Federation of European Biochemical Society Letters*. 284 (2): 147-51. https://pubmed.ncbi.nlm.nih.gov/1647978/#:~:text=Energetic%20and%20kinetic%20considerations%20suggest%20that%20cycling,via%20separate%20electron%20transfer%20and%20protonation%20reactions (a summary of the article).
https://www.sciencedirect.com/science/article/pii/001457939180672P/pdf?md5%3D27f00ee9a3bec72f01bcddfccb77d6aa%26pid%3D1-s2.0-001457939180672P-main.pdf&ved=2ahUKEwiVmvP2gPuPAxVz2zQHHWnLNF4Q1fkOegQIBxAF&opi=89978449&cd&psig=AOvVaw1m5Nhj4Wwgkg9H9MJPy95U&ust=1759133455101000 (the article in full and in pdf form)

255 Kasote Deepak M, Surendra S Katyare, Mahabaleshwar V Hegde, and Hanhong Bae. 2015. “Significance of antioxidant potential of plants and its relevance to therapeutic applications.”

International Journal of Biological Sciences. 11 (8): 982-91. https://pmc.ncbi.nlm.nih.gov/articles/PMC9920158/.

256 Ogun Aminat S and Adebayo Adeyinka. 2025. "Biochemistry, Transferrin." StatPearls Publishing, Treasure Island (FL). https://europepmc.org/article/NBK/nbk532928.

257 National Institute of Standards and Technology (NIST). 2025. "How Do You Measure Cholesterol in Blood Tests?" *NIST*, U.S. Department of Commerce. https://www.nist.gov/how-do-you-measure-it/how-do-you-measure-cholesterol-blood-tests (September 22, 2025, date last accessed).

258 Atlas Medical. "Liquid Cholesterol (CHOD/POD method)." *Atlas Medical, Germany.* https://atlas-medical.com/upload/productFiles/208008/PPI1444A01%20Cholesterol%20LIQUID%20(GHOD-POD)%20Rev%20A.pdf (September 22, 2025, date last accessed).

259 Fortress Diagnostics. "Cholesterol." *Fortress Diagnostics, U.K.* https://www.fortressdiagnostics.com/products/clinical-chemistry/cholesterol (September 22, 2025, date last accessed).

260 Dr. Kanika. "Blood Test for HDL Cholesterol: Purpose, Preparation, Procedure, & Results." *Dr. B. Lal Clinical Laboratory*, Jaipur, India. https://blallab.com/blogs/blood-test-for-hdl-cholesterol (September 22, 2025, date last accessed).

261 Chemical Thinking Laboratory. "Cholesterol Determination (video to show the cholesterol test using reagents and a spectrophotometer)." *University of Arizona Department of Chemistry and Biochemistry* https://www.youtube.com/watch?v=CQbgmKO0QTw (September 22, 2025, date last accessed).

262 Sorachim. "HDL Direct Cholesterol." https://sorachim.com/wp-content/uploads/2021/11/RHDL-10JA-RHDL-10JB.pdf (November 15, 2025, date last accessed).

263 Fitech. "Fitech Mission Cholesterol Pro. (example of a spectrophotometer for cholesterol tests)" *Fitech UK.* https://missioncholesterol.co.uk/index.php. https://fitech.uk/cholesterol-devices/36-mission-cholesterol-monitoring-system-pro.html (September 22, 2025, date last accessed).

264 PTS Diagnostics. "CardioChek PA Analyzer (example of a spectrophotometer for cholesterol tests)." *PTS Diagnostics USA.* https://www.ptsdiagnostics.com/cardiochek-pa-analyzer/ (September 22, 2025, date last accessed).

265 BIOLABO. "HDL-Cholesterol – Direct Method." *BIOLABO S.A.S.* https://www.biolabo.fr/pdfs/noticesE/biochimieE/AT-90406.pdf (September 22, 2025, date last accessed).

266 Fujifilm. "LabAssay™ HDL-Cholesterol." *Fujifilm Wako Pure Chemical Corporation*, Japan. https://labchem-wako.fujifilm.com/us/product/detail/W01W0129-9650.html#:~:text=2)%20The%20second%20reaction%20(color%20reaction%20of,measuring%20the%20absorbance%20of%20the%20blue%20color (September 22, 2025, date last accessed).

267 Shull, Bruce, Hyeon-Sook Zeng, Sunil Anaokar, and Gena Antonopoulos. 2003. “Test strip and method for determining LDL cholesterol concentration from whole blood.” *U.S. Patent and Trademark Office*. https://patents.google.com/patent/US20040126830A1/en (November 16, 2025, date last accessed).

268 Medichem. “LDL - Cholesterol.” https://www.medichem-me.com/Method/english/LDL-auto.pdf (November 16, 2025, date last accessed). (November 16, 2025, date last accessed).

269 BIOLABO. “Triglycerides GPO Method.” *BIOLABO S.A.S*. https://www.biolabo.fr/pdfs/noticesE/biochimieE/AT-LP80519-LP80619.pdf (September 22, 2025, date last accessed).