CHAPTER

1

CO_2 emission sources, greenhouse gases, and the global warming effect

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Abbreviations

CCS	carbon capture and storage
CCSU	carbon capture, storage and utilization
CFC	chlorofluorocarbon
EDD	ecological debt day
EOD	Earth overshoot day
FCC	fluid catalytic cracking
GHG	greenhouse gas
Gt	gigatons
HFC	hydrofluourocarbon
Mt	metric tons
ppm	parts per million
ppmv	parts per million volume
SG	smart grids
UN	United Nations
UNFCC	United Nations Framework Convention on Climate Change

1.1 Introduction

One common challenge confronting many developing countries in recent times is environmental degradation as a result of the indiscriminate emission of CO_2 into the atmosphere [1]. Industrial activities have led to an increasing level of carbon emissions in the atmosphere

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because of the growing level of industrialization and urbanization in many developing countries. This has also led to a significant increase in the global atmospheric concentration of anthropogenic greenhouse gases, such as CO_2, leading to global warming and climate change. Climate change results in a decline in global agricultural output due to low rainfall, fluctuation in seasons, and temperature rise [2]. Many parts of the world are experiencing drought and becoming no longer suitable for commercial farming due to climate change. Incessant temperature and precipitation changes are also likely to lead to an increase in soil and water degradation. However, adaptive behavior has the potential to alleviate these impacts, as land use and management have been reported as having a greater impact on soil conditions than the indirect impact of climate change [3]. Even if all emissions from human activities suddenly stop, climatic conditions would continue to change [4]. The current level of anthropogenic pollution and the indiscriminate emission of greenhouse gases into the atmosphere could aggravate global warming, ocean acidification, desertification, and changing weather conditions. However, food security, rising sea levels and severe storms affecting coastal areas, health problems, migration, and the increasing economic damage are just some of the immediate implications of climate change.

As the knowledge base in the area of mitigating CO_2 emission is expanding, there is a need to update it with recent advances and future prospects in this field that could lead to a clean environment [5]. More efforts are also needed to develop strategies to address the root cause of anthropogenic climate change, as well as proffering solutions to some of the most serious effects of climate change and environmental degradation. According to Ahmed et al. [6, 7], environmental degradation is a disturbance in the balance of the natural ecosystem by which the existence of different life form is hindered, thereby affecting the survival of other lives in the ecosystem. On the other hand, the international disaster reduction strategy arm of the United Nations defines environmental degradation as reduction in the ability of the environment to meet environmental goals, as well as social and ecological needs [8].

In this study, environmental degradation is defined as the depletion of environmental resources such as air, water, and soil; the elimination of ecosystems; extinction of wildlife; and pollution, perceived to be harmful to the ecosystem. Environmental degradation is one of the 10 threats affecting the world today as documented by the United Nations high-level panel on threats, challenges, and climate change [9]. Environmental degradation exists in different forms [10]. For example, when natural territories in the ecosystem are destroyed and resources depleted, the environment deteriorates. Attempts have been made so far to combat this global problem through the protection of the environment and the management of resources. There are many examples of environmental degradation globally. A current example is the burning of Amazon which constitutes 60% of all tropical forests. Amazon is regarded as the lungs of the Earth, and its destruction poses a great threat to the environment globally [11]. Furthermore, deforestation is another example of environmental degradation and its effect leaves devastating effects on the world around us. The constant felling of trees is eliminating our oxygen supply, as well as CO_2 absorption by plants. With the continuation of deforestation, the world will have less oxygen, which could be a problem that is detrimental to human health. Another problem that results from deforestation is the excessive consumption and waste of paper products that come from the trees. The waste normally produced during deforestation is not usually recycled, therefore, an immense amount of waste is created. Excessive felling of trees could lead to soil degradation and constant deforestation makes the soil less nutritious, making it difficult to use again [12]. The main purpose of this chapter is to address environmental problems attributed to the increasing levels of CO_2 in the atmosphere. So far, the combustion of fossil fuel is well known as the major emitter of CO_2 to the atmosphere [13]. It is worthy to note that although other fossil fuel-linked sources of CO_2 emission (e.g., burning of oils and naturals gas) also contribute to the increasing concentration of greenhouse gases in the atmosphere, none has contributed more CO_2 to the atmosphere than coal combustion. As far as could be ascertained, the combustion of coal, especially for power generation, is the major contributor of CO_2 to the atmosphere [14–16]. The high concentration of CO_2 in the atmosphere is predicted to continuously increase if the problem of CO_2 emission is not addressed. For instance, in 2019 it was reported that the average concentration of CO_2 in the atmosphere (414.7 ppm) was 45% higher than that obtained between 1980 and 1990 [17]. It has also been reported in open literature that the concentration of CO_2 has increased by over 2 ppm/year in the last decade [18]. In addition, global CO_2 emissions due to human activities have increased by over 400% since 1950 [19]. As a result, the concentration of atmospheric CO_2 has increased to 410 ppm, against 280 ppm reported since 1750 (around the start of the first industrial revolution) [20]. According to the 2015 Paris agreement, the rise in temperature of the Earth's interior should be kept below 2°C in comparison to the preindustrial levels, and the increase in Earth's temperature should be limited to below 1.5°C. According to a study by Van-Soest et al. [21], attaining the target set in the Paris agreement requires the capture and storage of at least 1 gigaton (Gt) of CO_2 annually until 2030.

In addition, it has also been documented in open literature that fossil fuel-fired power plants contribute about 33%–40% of the total CO_2 emission globally, with coal-fired power plants being the main contributor [22, 23]. For instance, a typical 500 MW power plant is capable of emitting about 2–3 million tons of CO_2 per year. Furthermore, as the call for the minimization of global CO_2 emissions intensifies, the need to reduce anthropogenic CO_2 emissions from power plants is becoming increasingly important. Carbon capture and storage (CCS) technology has been proposed as a potential practice that allows the continued use of fossil fuels in power plants and at the same time minimizes CO_2 emissions to the atmosphere [24, 25]. The primary purpose of capturing and storing CO_2 is to curtail CO_2 emissions.

Anthropogenic CO_2 emission occurs from direct human activities on forestry and other land use, such as deforestation, land clearing for agriculture, and soil degradation [26, 27]. Other sources of anthropogenic CO_2 identified in this study are human respiration, automobiles, power plant, and airplane emissions. However, it is noteworthy that the exhalation of CO_2 during human respiration does not make any significant contribution toward the depletion of the ozone layer (a layer in the Earth's stratosphere that prevents most of the sun's ultraviolet radiation from reaching the Earth), global warming, and climate change [28]. CO_2 emitted into the atmosphere does not lead to climate change directly. First, it depletes the ozone layer, exposes the Earth's surface to direct ultraviolet radiations from the sun which leads to an increase in the temperature of the Earth (global warming), then an incessant shift in global or regional climatic patterns of the Earth (climate change). A schematic illustration of the trend for climate change evolution is presented in Fig. 1.1.

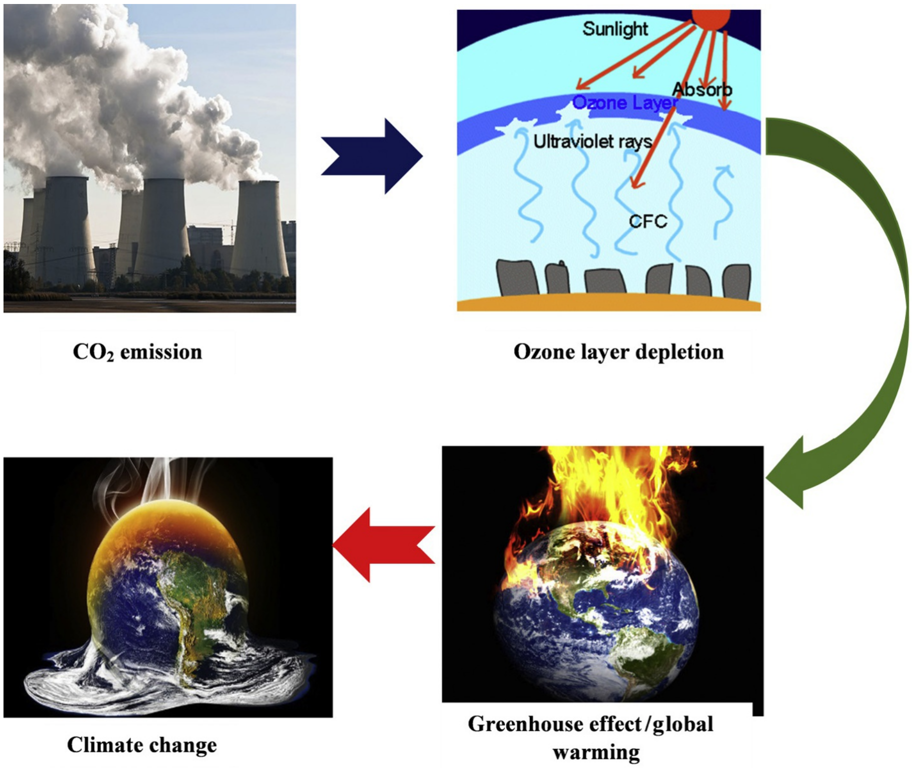

FIG. 1.1 Evolution of global warming and climate change from the combustion of fossil fuels. *Modified from How Carbon Capture Works, HowStuffWorks, 2008. 09 July. Available from: https://science.howstuffworks.com/environmental/green-science/carbon-capture.htm (Accessed 24 December 2019).*

Global attention has expressly shifted toward addressing the issue of climate change resulting from CO_2 emissions. Most studies reported in this field from the beginning of the 21st century to date focused mainly on CO_2 emission [29–32], its impacts [33–36], and remediation [37–41]. To this point, it is evident that scientists have made substantial contributions toward providing solutions to the problem of climate change by developing and testing new materials that can effectively capture CO_2 [42–47]. On a wider scope, researchers have recommended two major ways to minimize the emission of CO_2 as depicted in Fig. 1.2.

The first option shown in Fig. 1.2 will require the deployment of alternative renewable energies, or improving the energy efficiency of existing systems. However, the second solution may require the application of carbon capture and sequestration technologies to close the carbon cycle. This chapter seeks to explore the second option which suggests CO_2 capture as a more reliable alternative to minimizing CO_2 emissions to the atmosphere, thereby saving the Earth from extreme weather conditions. Carbon capture and storage (CCS) technology is widely embraced as one of the leading and easiest ways of mitigating carbon emissions to the atmosphere [48].

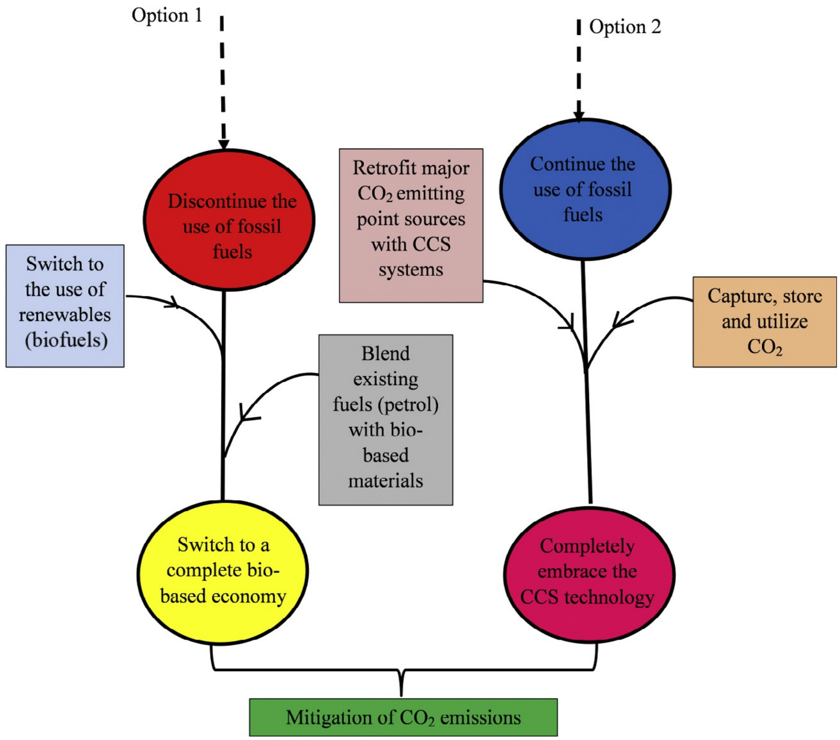

FIG. 1.2 A general roadmap toward minimizing global CO_2 emissions. *Modified from K.O. Yoro, Numerical Simulation of CO_2 Adsorption Behaviour of Polyaspartamide Adsorbent for Post-Combustion CO_2 Capture (MSc thesis), University of the Witwatersrand Johannesburg, South Africa, 2017.*

1.2 Major greenhouse gases and their forms of emission

1.2.1 CH_4 emission

The atmospheric concentration of methane has increased due to agriculture (rice and livestock farming), coal mining, including human activities; oil and gas production and distribution; biomass combustion; and municipal landfills [49, 50]. This means that unless immediate action is taken in the aforementioned sectors, methane emission is expected to increase even beyond 2030. The energy sector, which includes coal mining, natural gas systems, oil systems as well as fixed and mobile combustion systems, is the largest source of methane emissions into the atmosphere. In 2009, approximately 303 tons of methane was emitted from these sources [51].

Emissions from agricultural activities (mainly cattle breeding) and waste management (mainly landfills) are other sources of emissions, which contribute about 216 tons of methane to the atmosphere [52]. Methane is a greenhouse gas with a global warming power estimated to be 28–36 times more than CO_2 over the last 100 years, thereby ranking it as the second most anthropogenic greenhouse gas emitted into the atmosphere [53]. Therefore, it is important to study methane emissions to assess the impact of the biogas industry on climate change. Methane is also released in large quantities during biogas combustion [54]. However, a significant contribution to this emission comes from the waste generated during the conservation and management of biomass. On the other hand, other forms of biomass management strategies could also be considered in the future to reduce the biogenic emissions associated with methane.

In a study conducted by Poeschl et al. [55], methane emission was extensively discussed; in all cases examined by the authors, methane emission rates were below $5\,g\,kg^{-1}$. In addition to cattle manure, a significant reduction in methane emission is associated with the proper processing and management of digestive products. Biomass is characterized by a high emission of methane gas after decomposition in the field without a prior treatment. In agriculture, the full implementation of a nondecomposing feeding strategy for animals can reduce the global methane emissions by 20% before 2030, while a full implementation of periodic aeration of permanently flooded rice shells can reduce methane emission by more than 30% [56]. Emissions from coal mining as well as the oil and gas sector could be reduced by more than 65% if gas leaks are prevented during transportation, distribution, recovery, and the use of gas at the production stage.

1.2.2 N_2O emission

Besides carbon dioxide (CO_2) and methane (CH_4), nitrous oxide (N_2O) is another problematic greenhouse gas with a high potential of causing greenhouse effect. The emission of N_2O from biogas production processes contributes significantly to the global warming budget [57, 58]. The relative impact of N_2O on the environment largely depends on the choice of climate measures. Nonetheless, it is undeniable that the impact of N_2O can exceed the effects of CO_2 and CH_4 if the metric considered is a global temperature with a time change potential of more than 100 years [59].

Nitrous oxide can be emitted from wastewater containing organic-based nitrogen materials, such as materials from human or animal waste [60, 61]. Factors affecting the amount of nitric oxide produced by wastewater comprise temperature, acidity, biochemical oxygen demand, and nitrogen concentration. Natural sources of N_2O include soils, tundra, and oceans. Agriculture has important human resources (nitric oxide fertilizers, soil tillage), manure, biomass combustion, and industrial processes such as fertilizer production [62]. Fertilizers from nitrogen enrichment of soils are the primary human contributor to nitrous oxide emissions [63]. N_2O emission has grown by more than 35% from 2005 to date [64]. The wide uncertainty on estimates of global warming, as well as its mitigation potential largely depends on the evaluation of the emission rate of N_2O in storage and in use as a digestate fertilizer.

1.2.3 CO_2 emission

Carbon dioxide (CO_2) gets emitted when fossil fuels (e.g., coal, natural gas, and oils), solid waste, trees, and other biological materials are burnt [65]. Furthermore, CO_2 can be emitted as a result of certain chemical reactions (e.g., the production of cement). Human activities can also change the carbon cycle, thereby adding more CO_2 to the atmosphere and affecting the capacity of natural sinks, such as forests. The burning of fossil fuels for energy and transport is the main human activity that leads to the emission of CO_2, although certain changes in land use (e.g., deforestation) can also lead to the emission of CO_2 into the atmosphere [66]. Carbon dioxide is naturally removed from the atmosphere (or sequestered) when plants absorb it as part of the carbon life cycle. Alternatively, the emission of CO_2 from stationary point sources (e.g., power and cement production plants) can be minimized through CO_2 capture, storage, and utilization. Co-gasification of coal with biomass materials during combustion in coal-fired power plants is another proven option for mitigating CO_2 emission [67].

1.2.4 SO_2 emission

SO_2 is released during the combustion of carbonaceous fuels (coal, petroleum, and diesel) or other materials containing sulfur. The largest source of SO_2 emissions to the atmosphere is the combustion of fossil fuels from power plants and other industrial structures [68]. Smaller sources of SO_2 emissions include metal processing, foundry facilities, including natural sources such as volcanoes, locomotives (e.g., ships and other heavy vehicles), and fuel-burning equipment with high sulfur content. High concentrations of SO_2 are usually recorded near large industrial facilities and are associated with multiple effects on health and the environment [69]. According to a report by the US Environmental Protection Agency, short-term contact with SO_2 in the air can lead to a number of adverse health effects [70]. Several clinical, epidemiological, and toxicological studies confirmed the fundamental relationship between short-term exposure of SO_2 in the atmosphere and respiratory morbidity, whose observed health effects are respiratory tract infection and inflammation with many other respiratory problems [71]. Again, SO_2 combines with other air toxins to form sulfate particles, which are constituents of particulate matter ($PM_{2.5}$). Inhalation and exposure to $PM_{2.5}$ [72] have different effects on cardiovascular and respiratory health problems.

In addition to the aforementioned health problems, many ecological problems are also associated with high concentrations of SO_2 in the atmosphere. For instance, SO_2 in combination with nitrogen oxides (NOx) in the air contributes to acid deposition and reduced visibility (regional turbidity indicator). Furthermore, high concentration of SO_2 can also destroy vegetation, (e.g., increased leaf damage, stunted plant growth, low crop yield, and decline in a variety of plant species in the ecosystem). A high concentration of SO_2 and other sulfur oxides in the atmosphere also leads to acid rain which can harm sensitive parts of the ecosystem. Finally, SO_2 can accelerate the corrosion of materials used in buildings, statues, and monuments (e.g., metals, concrete, limestone) [73]. Several techniques have been suggested for reducing the concentration of SO_2 in the atmosphere [74, 75]. A stepwise diagrammatic procedure to minimize SO_2 emission from power plants is presented in Fig. 1.3.

1.3 Greenhouse gases and the greenhouse effect

Greenhouse gases (GHG) are gaseous compounds that can emit ultraviolet radiation within a certain thermal infrared range [76]. Greenhouse gases retain high temperatures in the lower atmosphere, thus allowing less heat to escape back to space. This subsequently

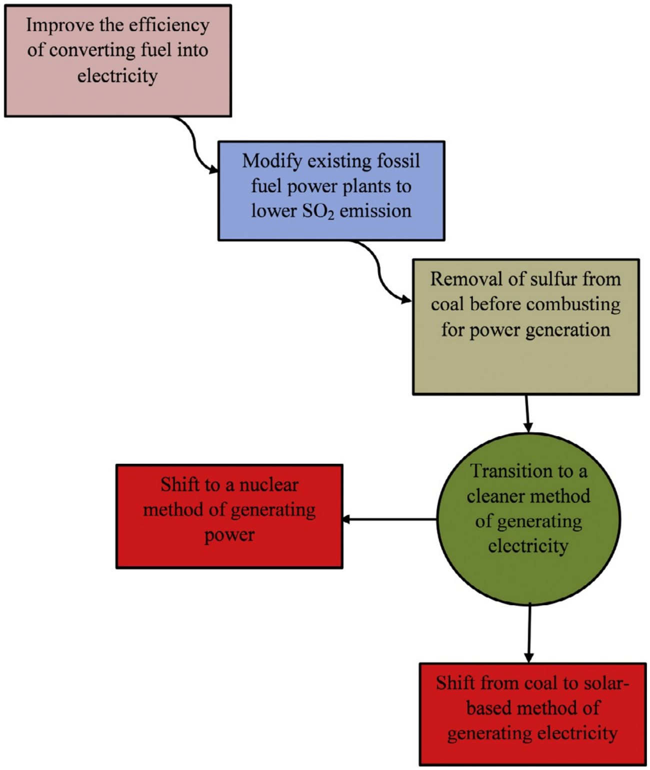

FIG. 1.3 Stepwise procedure to minimize SO_2 emission from power plants.

results in the greenhouse effect and global warming. The greenhouse effect is a natural process that warms the Earth's surface to a temperature above which it would be without the atmosphere. The intensity of the greenhouse effect depends largely on the temperature of the atmosphere, and on the presence of greenhouse gases in the atmosphere. Greenhouse gases are vital for supporting a habitable temperature for the Earth because if there were totally no greenhouse gases present in the atmosphere, the average surface temperature of the Earth would be about −18°C [77]. Common greenhouse gases present in the atmosphere include water vapor, chlorofluorocarbons (CFCs), hydrofluorocarbons (HFCs), carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and ozone (O_3). However, researchers have pointed out that the four main greenhouse gases attracting serious global attention today are CO_2, SO_2, CH_4, and N_2O [78]. Although water vapor is arguably the most abundant greenhouse gas naturally present in the atmosphere, CO_2 is the most emitted greenhouse gas. Hence, different techniques have been reported to capture CO_2 [79–81]. A generalized classification of activities leading to the emission of greenhouse gases into the atmosphere is depicted in Fig. 1.4, while the main greenhouse gases and their major sources are presented in Table 1.1.

Information provided in Table 1.1 reveals that because of the high dependence on burning fossil fuels for power generation and other industrial activities, CO_2 is now the most emitted

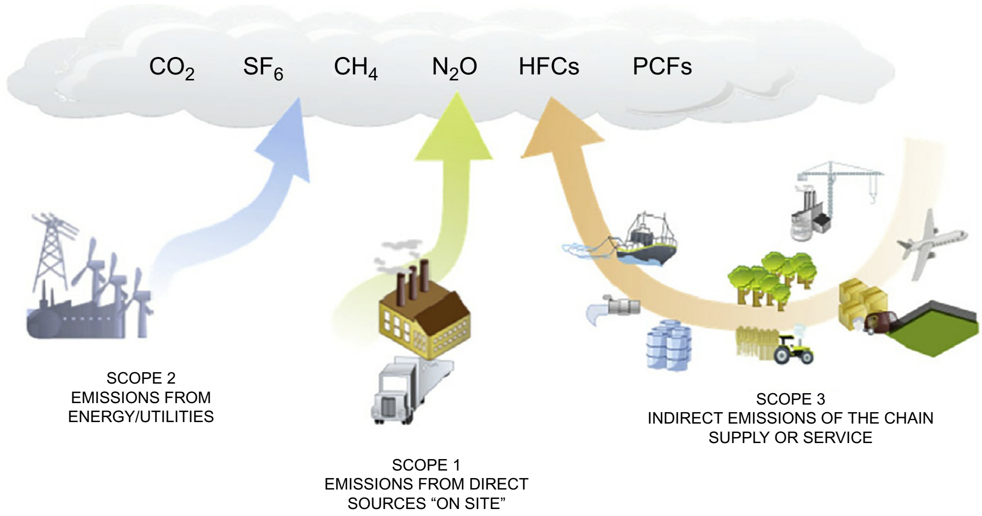

FIG. 1.4 Classified sources of greenhouse gas emission. *Adapted from B.R. Singh, Global Warming: Impacts and Future Perspective, BoD – Books on Demand, 2012.*

TABLE 1.1 Greenhouse gases and their major sources.

Greenhouse gases	Sources	% Emission in 2019
Carbon dioxide (CO_2)	Fossil fuel combustion, deforestation	76
Methane (CH_4)	Biomass combustion, agricultural wastes	13
Nitrous oxide (N_2O)	Fertilizer use	3
Sulfur dioxide (SO_2)	Combustion of coal, oil, and diesel	7
Fluorinated gases (CFCs, HCFs)	Refrigeration	1

Modified from T.J. Blasing, Recent Greenhouse Gas Concentrations, Environmental System Science Data Infrastructure for a Virtual Ecosystem, Carbon Dioxide Information Analysis Center (CDIAC), Oak Ridge National Laboratory (ORNL), Oak Ridge, TN, United States, 2016.

greenhouse gas while fluorinated gases (CFCs and HCFs) are the least emitted greenhouse gases because the use of refrigerants has been phased out in many refrigeration systems in recent times [82].

1.4 CO_2 as a major contributor to global warming and climate change

From the beginning of the second industrial revolution that was characterized by mass production and electricity generation, energy production was largely contingent on the combustion of fossil fuels. Power generation, cement production, and the use of fossil fuels in many homes have resulted in the emission of significant amounts of CO_2 to the atmosphere over the past decades. Researchers have identified that between 1970 and 2002, global emission of CO_2 increased by over 70% [83]. Since then, there have been great concerns over the ever-increasing atmospheric concentration of CO_2 as well as its hard effect on the environment [84]. Capturing CO_2 from large point sources is necessary to minimize the high concentration of CO_2 emitted into the atmosphere. According to a study reported by Schubert and Jahren [85], there are greater natural sources of CO_2 emissions (e.g., decomposition, ocean release, and respiration) than there are sources of CO_2 emission due to human activities such as the burning of oil, coal, and gas; deforestation; industrial manufacturing; and the use of aerosols. However, the natural sources of CO_2 are closely balanced by naturally occurring phenomena such as photosynthesis and weathering of rocks. This balance has made the atmospheric concentration of CO_2 to be as low as 260–280 ppmv for 10,000 years before the start of the industrial era [86]. To date, most anthropogenic (human) sources of CO_2 emission are still from everyday human activities that we do not even think about.

During the industrial era, the demand for electricity was on the increase and power generation increased by almost 50% at the beginning of 2000 [87]. The global fossil fuel estimate of CO_2 emission also increased to about 25,000 metric tons in 2002. Fossil fuels will still remain the primary source of energy which will be on the increase by over 90% [88]. This shows that global energy demand has been on the increase, and it is expected to escalate by over 67% by 2030 [89]. In view of this, it is necessary to identify the major sources of CO_2 emission and how to prevent it. Table 1.2 presents various CO_2 emission sources and how to minimize emissions from such sources.

Information provided in Table 1.2 reveals that the anthropogenic emission of CO_2 has been the major source of CO_2 emission to the atmosphere with fossil fuel combustion engines and coal-fired power plants as the major contributor. Most of the major anthropogenic emissions are from stationary point sources, hence this study suggests carbon capture, storage, and

TABLE 1.2 Major sources of CO_2 emission and their preventive methods.

Sources	CO_2 emission (billion Mt)	Proposed preventive option	References
Anthropogenic/human sources			
Fossil fuel combustion engines	392	CCSU	[90]
Cement production plants	113	CCSU	[91]
Power generation (coal-fired power plants)	279	CCSU, integration to methanol plant	[90]
Transportation	191	Blending fuels with biomass	[92]
Industrial manufacturing	178	CCSU	[93]
Land use changes	13	–	[94]
Nonanthropogenic/natural sources			
Plant, animal, and human respiration	7	–	[95]
Ocean-atmosphere exchange	7	–	[96]
Soil respiration and decomposition	1.54	–	[97]
Volcanic eruptions	0.15	–	[98]

utilization (CCSU) as the most suitable preventive option for CO_2 emission. CCSU simply entails the capture of waste carbon dioxide (CO_2) from large stationary point sources (e.g., coal or gas-fired power plants) and its deposition in a safe storage location where it will not gain access back to the atmosphere [99]. The release of CO_2 and other greenhouse gases from burning fossil fuels come into play in the following major areas:

- **Power industry**: Electricity generation in fossil fuel-fired power plants mostly comes from the burning of fossil fuels (e.g., coal and natural gas) for energy. If other cleaner alternatives for power generation such as nuclear and solar sources are not explored, the power industry will continue to emit large amounts of CO_2 to the atmosphere.
- **Transport industry**: The combustion of fossil fuels (e.g., coal, diesel, petrol) to run automobiles (e.g., cars, trucks, trains) and jets also contribute to the high levels of CO_2 in the atmosphere leading to global warming and climate change. Emissions from automobiles are nonstationary with high volumes of CO_2. So far, the blending of automobile fuels with bio-based materials [100] or switching to complete use of biofuels or electricity to power automobiles [101] has been the most promising option for mitigating CO_2 emissions from this sector.
- **Buildings**: The emissions of greenhouse gases (e.g., CO_2, CH_4, SO_2) from businesses, homes, and industries arise mainly from waste disposal, the combustion of fossil fuels for energy utilization, and the use of certain materials that contain greenhouse gases, which are the major sources of emissions from this sector. To date, no definite technology has been reported for mitigating CO_2 emission from homes and other businesses.

Power generation from the combustion of fossil fuels is the major contributor to CO_2 emission across major sectors of the economy in many developing countries. Furthermore, the agricultural sector has been proven to be the least contributor since 2018 [102]. A general representation of global CO_2 emission by sector is expressed in percentages and presented in Fig. 1.5.

If the random emission of important anthropogenic greenhouse gases like CO_2 is not reduced, the Earth will face the following devastating consequences [103–106]:

(i) The atmospheric temperature in coastal areas will increase by 2°C by 2050 and 4°C by 2100.
(ii) The interior temperature of the Earth will also increase by 4°C by 2050 and 7°C by 2100.

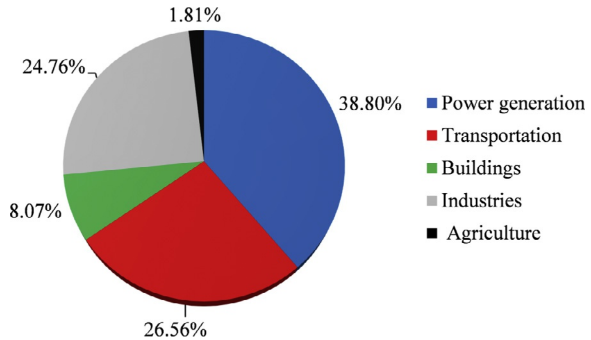

FIG. 1.5 Updated global CO_2 emission by sector in 2019.

(iii) World food security will be adversely affected.
(iv) Invasive plants will increase and negatively influence the water resources on Earth.
(v) Health problems will be aggravated worldwide due to droughts and floods, and there will be an outbreak of diseases related to extreme weather conditions.
(vi) Forests and various commercial plantations on Earth will be vulnerable to forest fires.

Although global warming has not been even across the Earth, the rising global average temperature shows that more regions are warming than cooling [107]. According to a recent global climate report, the combined temperature of land and ocean increased at an average rate of 0.07°C per decade since 1880 [106]. This means that the average rate of temperature increase from 1981 to date is more than double (0.17°C). Models predict that global surface temperatures will be 0.5°C warmer than the 1986–2005 average by 2020, regardless of the carbon emission pathway the world follows [108]. Furthermore, the high thermal capacity of water shows that the temperature of the ocean does not react instantly to the increase in heat trapped by greenhouse gases. Previous studies have shown that for the past 50 years, the global temperature rose at an average rate of about 0.13°C per decade, almost twice as fast as the increase of 0.07°C per decade observed over the past 50 years [109]. Researchers have predicted that the global average temperature will increase by about 0.2°C per decade over the next two decades [110]. It is envisaged in this study that by 2030, the warming imbalance caused by greenhouse gases will gradually overcome the thermal inertia of the oceans, and the projected temperature paths will start to diverge with unchecked carbon emissions, thereby leading to several additional degrees of warming by the end of the century.

1.5 Current CO_2 emission trends

Global CO_2 emissions have been growing on the average in recent times, with CO_2 emissions 1.9% higher in 2019 than in 2018 [111]. According to Janssens-Maenhout et al. [112], the growth in total global greenhouse gas (GHG) emissions (excluding land-use change) in 2018 was at a rate of 2%, equivalent to 51.8 Gt of CO_2 with an annual growth rate of about 1.3%. Global greenhouse gas emissions in 2018 amounted to 55.6 Gt CO_2 including those for land-use change. This increase occurred as the global economic growth in 2018 increased to an average annual rate of 3.5% since 2012 [113]. Current emissions of greenhouse gases that exclude those of land-use change today is approximately 57% higher than in 1990 and 43% in 2000.

In 2018, the 2% (1.0 Gt CO_2 equivalent) increase in global greenhouse gas emissions was primarily due to an increase in global fossil fuel combustion and those from noncombustion industrial processes, including cement production [114]. Global emissions of methane (CH_4) and nitrous oxide (N_2O) increased by 1.8% and 0.8%, respectively [115]. Global emissions of fluorinated gases continued (so-called F gases) increased by about 6% in 2019, contributing to the total growth of 2.0% greenhouse gas emissions. The 2.0% growth in greenhouse gas emissions is higher than the average annual increase of 1.2% since 2012 but less than the 2.5% increase in the first decade of this century (2010). Fossil fuel-related CO_2 emissions are the biggest source of greenhouse gas emissions, with a contribution of about 72%, followed by CH_4 (19%), N_2O (6%), and F gas (3%) [116]. The increase in greenhouse gas emissions in recent years and the highest rate of 2.0% in 2018 is quite similar to the increase in CO_2 emissions in 2018, which contributes nearly 75% of the total greenhouse gas emissions (excluding those related to land-use change) [117].

Generally, 2019 was one of the five hottest years (2015–19) since recordings of global temperature rise started in 1880 [118]. Of the 10 warmest years since 1880, about nine have occurred after 2005. In 2019, temperatures in many parts of the world were warmer than average. Record warm temperatures have been measured across Europe, the Middle East, New Zealand, and parts of Asia. A heatwave of unprecedented intensity and duration hit Europe from April 18 to 22, 2019. France, Germany, and Switzerland had their hottest year in 2019 since 1880 while the Netherlands had its second-hottest year (2014 being the record) [119]. The deviation from the average global temperature level was 0.97°C above the average between 1880–1900, which is slightly lower than that of 2015–17 [120].

The incessant increase in CO_2 emission from 2018 has made the Earth to record the earliest Earth overshoot day in 2019 since 1970. Earth Overshoot Day (EOD), which is also referred to as Ecological Debt Day (EDD), is a calculated calendar date in which humanity's annual resource depletion surpasses the Earth's ability to produce resources [121]. EOD can be expressed as a quotient of the Earth's biocapacity (the amount of natural resources produced by the Earth within 365 days) and the Earth's ecological outline (annual human consumption of the Earth's natural resources), multiplied by 365 which is the number of days in a common Gregorian calendar year. From an economic standpoint, EOD can be defined as a day when humanity comes into environmental shortages, while in the field of ecology EOD is an example of the level at which human population transcends its environmental capabilities [122]. The EOD for 2019 was recorded on July 29, which is the earliest to date. Mathematically, Earth Overshoot Day (EOD) is expressed as

$$\mathrm{EOD} = \frac{\text{World biocapacity}}{\text{World ecological footprint}} \times 365 \tag{1.1}$$

In addition, studies have shown that since the beginning of the second industrial revolution, global CO_2 emissions have continuously increased [123]. In view of this, an updated global CO_2 emission trend for 2019 is presented in this chapter as compiled from previous reports [124–128]:

- The current global CO_2 emission from the combustion of fossil fuel alone is about 58.7 billion tons in 2019.
- 2018 was the sixth consecutive year of large global increases in GHG emissions. In April and May 2018, atmospheric CO_2 concentrations averaged more than 410 ppm at the NOAA Mauna Loa Observatory, thereby surpassing another climate milestone.
- CO_2 emissions are responsible for an estimated 60% of humanity's demand on nature. As a result, Earth Overshoot Day is advancing each year, and humanity is now using nature 1.75 times as fast as the planet's ecosystems can regenerate.
- So far, CO_2 emissions have increased by 0.34% over the previous year, representing an increase of about 122 million tons over 2018, when CO_2 emission was about 35.6 billion tons.
- In 2015, CO_2 concentrations exceeded the symbolic reference by 400 parts per million (ppm) in the northern hemisphere.

- After a relatively decelerating trend since 2012 and 3 years without change, global energy-related CO_2 emissions increased by 1.4% in 2017 and 1.7% in 2018, reaching a record level of 33.1 Gt of CO_2.
- Global carbon emissions from the combustion of coal (the worst pollutant of all fossil fuel) unexpectedly declined by about 0.9% in 2019, However, this drop was offset by strong growth in the use of oil and natural gas worldwide. CO_2 emissions per capita worldwide is equivalent to 4.99 tons per person (based on a world population of 7.7 billion in 2019).
- The UNEP assessment data shows a large gap between emission levels and those corresponding to 2°C and 1.5°C paths, respectively, making it increasingly difficult to reach the 2030 emission targets.

1.6 Mitigation of CO_2 emission in the industries

1.6.1 Power generation

In many countries today, electricity is generated by burning fossil fuels because it is cheap and the source of coal as a raw material is readily available [129]. Coal contains more carbon than petroleum or natural gas, which translates into higher volumes of CO_2 emissions per unit of electricity produced [130]. Since the power sector is widely regarded as the largest source of CO_2 emissions, it is imperative to explore ways to minimize CO_2 emissions from this important sector. The immediate option to mitigate carbon emission from coal-fired power plants could be achieved by

- Operating the most efficient power plants to reduce the fuel supply per unit of energy.
- Investing in technologies that can increase the efficiency of coal plants from 35% to 50%.
- The use of the combined cycle in coal-fired power plants by coal gasification.
- The conversion of gas turbines in open cycle mode to combined cycle mode to increase the efficiency of the installation. However, the real reduction in emissions can only be achieved by radically changing the combination of electricity production.

From the application of energy mainly powered by fossil fuels today, there is a need to move to a combination of nuclear and renewable energy. More wind and solar power plants, as well as nuclear power plants, are the only reasonable and cheapest solutions for power generation with reduced emissions [131].

As the search for knowledge and better alternatives to minimize CO_2 emission is increasing in this fourth industrial revolution era, researchers have proposed a new way to address this challenge. For example, Bari et al. [132] proposed the application of smart grid applications during power generation. A smart grid (SG) is a concept or framework for a modernized, scalable, and next-generation power supply system [133]. It is also portrayed as an integration of components, subsystems, and ancillary services controlled by highly intelligent control and management systems throughout the power system. In addition, a smart grid system is a combination of enabling technologies (hardware, software, or practices) that make the energy infrastructure more secure, reliable, efficient, and sustainable. Also called the smart or future network, the term SG is that of a "digital update." SG intelligence is applicable at the decision-making level of all relay-run computer programs, innovative electronic designs, mail automation systems, and control centers. SG technologies can contribute to reducing CO_2 emissions, improving efficiency and storage by facilitating the integration of renewable energy sources, and enabling the use of hybrid electric vehicles [134].

1.6.2 Cement industry

The methodical approach used for mitigating CO_2 emission in the cement industry is similar to the approach used in the iron and steel industries [135]. The scenario for mitigating CO_2 emission in the cement industry is based on

- capital turnover with a continuous shift from wet production processes to dry production
- increased use of alternative additives to replace cement clinker
- fuel change from coal and petroleum coke to biomass or co-gasified coal + biomass

In addition, modern methods of dry production (i.e., rotary kilns) should replace the extruded production capacity with preheaters and precalciners. Similarly, the production of white cement via clinker production could be replaced with a new one in white cement factories. Clinker production is the largest part of the cement industry's direct release of CO_2. About 60% of carbon dioxide emitted from this sector is from calcination and another 40% from combustion [136, 137], thereby reducing the clinker content of the final cement produced in the process. Coal and petroleum coke continue to dominate gasoline in most cement industries. The supply of other fuels for cement production is expected to increase from 18% in 2010 to 40% by 2050, with 40% consisting of pure biomass. Carbon dioxide emission from the cement industry is calculated as the total carbon dioxide released from the process and from the fuel [138].

1.6.3 Petrochemical plants

Oil refineries produce different fuels and chemical feedstock by the distillation of crude oil, followed by reforming and cracking. CO_2 is produced in the streams of the petrochemical process mainly by reactions with oxygenates (mainly oxygen as in the oxidation of ethylene and water as in the reaction of water-gas change) [139]. The fluid catalytic cracking (FCC) unit is responsible for about 20%–50% of the CO_2 produced in a petrochemical plant [140]. Other petrochemical units such as the ethylene oxide and ammonia processes also produce high-purity CO_2 as a by-product. Most of the CO_2 in the petrochemical industry is emitted from the combustion of fuel oil and combustible gas [141]. CO_2 capture from the streams and flares of the petrochemical process has been recognized as one of the many strategies necessary to mitigate greenhouse gas emissions from petrochemical plants [142]. CO_2 can be captured in petrochemical plants without allowing it to emit into the atmosphere by retrofitting capture systems in the petrochemical plants. Absorption, adsorption, and membrane separation technologies are the most popular techniques that can be used to mitigate CO_2 emission in the petrochemical industry.

1.6.4 Iron and steel industry

The iron and steel industry is one of the largest industrial emitters of CO_2 accounting for about 7% global anthropogenic CO_2 emissions [143]. As a result, researchers are shifting attention toward reducing CO_2 emission from this important sector. Global steel production is also expected to increase by 30% by 2050. Therefore, there is an urgent need to explore techniques that can effectively reduce CO_2 emissions from the iron and steel industry. The most relevant greenhouse gas emitted in the steel industry globally is CO_2. On an average, about 1.83 tons of CO_2 were emitted for each ton of steel produced between 2017 and 2018 [144]. The iron and steel industry generates about 7%–9% direct CO_2 emission from the burning of fossil fuels [145]. Existing technologies, such as dry coke cooling, pressure recovery turbines, continuous casting, and furnace gas recovery facilities, can be used to improve plant efficiency and minimize CO_2 emissions.

The estimated potential to reduce CO_2 emissions in the iron and steel industry is around 27 Mt/year, and this can be achieved through:

- Energy optimization—By upgrading to newer technologies that use energy more efficiently.
- Fuel change—Using an alternative cleaner and less expensive fuel instead of coal.
- Recycling of scrap metal instead of forging new steel.
- Training and creating awareness among iron and steel workers on the different ways to optimize the use of machines, equipment, processes, and other steps to efficiently operate steel production with reduced CO_2 emission.

So far, different literature reports have revealed that some techniques for reducing CO_2 emission can be profitable, and generate other benefits (such as better environmental compliance, health benefits, etc.), although some could be expensive to implement on a large scale [146]. In addition, a transition to a more efficient industrial process or the application of carbon capture and storage technique to mitigate process emissions during operations in iron and steel industries could considerably reduce CO_2 emissions.

1.7 International treaties and limitations on the reduction of CO_2 emission

Climate change is a well-known global problem that is now affecting every country on every continent around the globe. It is detrimental to the national economy and also affects life and communities. Climate patterns are changing, sea levels are rising, weather events are becoming more intense, and greenhouse gas emissions have reached all-time highs because of human activities that are environmentally unfriendly [147].

The devastating consequence of climate change is likely to continue ravaging the Earth if activities leading to the emission of greenhouse gas to the environment are not addressed. Without any action toward mitigating global CO_2 emission, the average surface temperature of the world is likely to exceed 3°C in this century [148]. To proffer solution to the problem of global warming and climate change, different countries all over the world came together to sign treaties that pledge their allegiance toward minimizing the emission of CO_2 to the atmosphere. The signed treaties ranged from the 1979 Geneva Convention on long-distance cross-border air pollution [149], the Montreal Protocol of 1987 [150], 1997 Kyoto protocol [151], the 2012 Doha amendment [152], and the 2015 Paris agreement which became effective in November of 2016 [153, 154].

The Kyoto Protocol is an international accord spearheading the 1992 United Nations Framework Convention on Climate Change (UNFCCC), which obliges participating countries to reduce their greenhouse gas emissions through scientific agreements which are based on the broad facts that

- Global warming is real, and will gradually ravage the world if left unchecked.
- The anthropogenic emission of CO_2 into the environment is the leading cause of climate change.

The Protocol was adopted in Kyoto, Japan on December 11, 1997, and implemented on February 16, 2005. The Kyoto Protocol currently has about 192 signatory countries. The Treaty is based on the principle of joint but separate responsibility. The Kyoto protocol recognizes that different nations have diverse competencies to combat climate change, depending on their level of economic advancement. Hence, it places an obligation to limit carbon emissions by developed countries that have historically contributed to the present high level of greenhouse gas concentration in the atmosphere.

The paramount accounting era of the Kyoto Protocol began in 2008 and ended in 2012. The 36 nations that wholly took part in the first accounting era completed the conventions. Nevertheless, nine nations took advantage of its flexibility to fund emissions drops in additional countries since their carbon emissions were marginally exceeding their marks [155]. A significant reduction of greenhouse gases was recorded between 1990 and 1995 by countries in the former Eastern coalition after the collapse of the Soviet Union [156]. It is worth noting that although about 36 developing nations were able to drop down their emissions from fossil fuel combustion, worldwide carbon emissions still went up by 32% between 1990 and 2010 [157].

In 2012, another obligatory window, referred to as the Doha amendment to the Kyoto Protocol, was enacted, with 37 nation-states having mandatory objectives. Australia, Belarus, Iceland, Kazakhstan, Liechtenstein, Norway, Switzerland, Ukraine, and the European Union (comprising its 28 member states) declared intention to quit from the Kyoto Protocol or they may not implement the amendment in the second round commitment [158]. Japan, New Zealand, and Russia took part in the first cycle of the Kyoto Protocol but did not reach new targets during the second commitment period [159]. Canada (which withdrew from the Kyoto Protocol in 2012) and the United States (which have not ratified it) are among other developed countries that do not have goals in the second commitment period. By December 2019, about 135 countries had acknowledged being part of the Doha amendment, but its full enforcement requires acceptance from at least 144 countries [160]. So far, out of the 37 countries with binding commitments to the Doha amendment, 7 have ratified it. Furthermore, negotiations took place at the annual UNFCCC conference on decisions to be implemented at the culmination of the second obligatory period in 2020 [161]. This led to the enactment of the 2015 Paris Agreement, which is a discrete instrument under the UNFCCC instead of amending the Kyoto Protocol. As of April 2018, 175 countries had ratified the Paris Agreement, and 10 developing countries submitted preliminary editions of their climate change adaptation plans.

Prior to the 1997 Kyoto Protocol, two other international environmental agreements had been signed to indirectly address climate change [162]. Firstly, the 1987 Montreal Protocol on materials that affect the ozone layer which by law requires the parties to withdraw the use of chlorofluorocarbons in 1996 [163]. Secondly, the 1979 Geneva Convention on long-range transboundary air pollution and its protocols regulate the emission of harmful gases, some of which are precursors of greenhouse gases. The main limitation, however, is that these agreements do not solve a complex series of interdependent climate problems.

1.8 Future prospects of heat and mass integration during CO_2 separation

Although the combustion of fossil fuels for power generation and other industrial activities have been publicized to be a major contributor of CO_2 to the atmosphere, it is currently the cheapest form of energy generation [164]. As a result, there is a need to develop new techniques to continue the combustion of fossil fuels in the power industry and yet keep a near-zero emission of CO_2. In view of this, we suggest the retrofitting of CO_2 capture systems in existing fossil fuel-fired power plants. Many industries are refocusing on economically and environmentally benign designs to revamp their design and operational requirements to attain the objective of satisfying both environmental regulations and minimum energy consumptions in chemical processes [165]. Consequently, Several techniques (such as absorption, adsorption, membrane, and cryogenic separation) have been developed and tested for CO_2 capture in the past [136]. However, recent studies identified that these techniques are highly energy and material intensive in nature with high process cost, thereby rendering it an expensive technology to implement in most power plants [166]. Researchers have also suggested the use of phase change solvents, as well as additives and inhibitors (e.g., piperazine) to minimize energy consumption during CO_2 capture [167].

Although the aforementioned suggestions have recorded successes in minimizing energy usage during CO_2 capture to an extent, the major limitation identified with the approach is that it subsequently results in increasing process cost. Again, the aforementioned techniques have only shown effectiveness to an extent in selected CO_2 capture techniques such as gas-liquid separation systems (e.g., absorption), and have not been fully extended to gas-solid separation systems such as adsorption, membrane, and cryogenic separation [168]. There is a need to develop new techniques that can tackle the high energy and material requirement in both absorptive and adsorptive CO_2 separation systems at an optimal process cost. As a result, we suggest the application of heat and mass exchanger network synthesis during CO_2 capture to achieve significant energy and material saving, and yet minimize CO_2 emission to the atmosphere. The proposed technique does not incur high process costs and it can be used to not only minimize energy consumption, but also curtail material requirements during CO_2 capture. So far, this approach is scantily reported in the literature. As far as could be ascertained, no study has adequately discussed the synthesis of a network (considering both heat and mass exchange) for CO_2 capture with the aim of optimizing the system toward attaining minimum consumption of energy and material during CO_2 capture, at an optimal operating cost.

Despite the very promising potentials of heat and mass integration in energy and material recovery studies, only a few reports have considered the application of process synthesis techniques through heat and mass exchange networks to abate excessive energy and material consumption in some industrial applications [169, 170]. This research field is an important area for future development in the use of process synthesis methodologies to handle energy recovery tasks in environmental remediation studies, such as CCS. The application of the heat and mass integration techniques suggested in this chapter may be considered as a joint network of heat and mass exchangers connected to a regeneration network capable of taking energy savings and the material consumed into account. This research area has not been adequately explored in the past for CO_2 capture, thereby making it an interesting area to delve into. Furthermore, it is also envisaged in this chapter that a combination of synthesis techniques in a single procedure for heat and mass integration could be a more reliable approach for integrating heat and mass in CO_2 capture systems. This means that a fully optimized hybrid network approach can be attempted during the integration of heat and mass in future CO_2 capture research. A life-cycle assessment for heat and mass exchangers may also be explored in future R&D to gain an insight into their conservational influences on CCS research.

1.9 Conclusions and future outlook

CO_2 emission, global warming and its resultant effect (climate change) are serious environmental problems that need urgent scientific attention, thereby calling for a reduction in CO_2 emissions in all sectors of human activity, including power generation. Furthermore, the literature reviewed in this study shows that researchers have put in tremendous efforts to reduce the emission of anthropogenic CO_2 into the atmosphere. Similarly, this chapter confirms that different techniques such as adsorption, absorption, and membrane separation have been proposed and tested in the literature for CO_2 capture. The available CO_2 capture techniques are highly energy and material intensive in nature, which makes CO_2 capture an expensive technology to implement in many countries. However, this chapter suggests that the application of process integration techniques through heat and mass exchanger network synthesis can be extended to reduce high energy and material requirement in the aforementioned CO_2 capture techniques. Also, this chapter revealed that CO_2 emission does not directly result in climate change. Instead, it first depletes the ozone layer, leading to global warming (the greenhouse effect), then climate change. In addition, the research efforts documented in this chapter reveal that human activities such as power generation, cement production, and transportation are the major contributors to greenhouse gas emission and global warming. This chapter establishes that the combustion of fossil fuels (e.g., coal) for power generation may still continue with the incorporation of CO_2 capture mechanism to the existing power plants. At the same time, introduction of CO_2 capture strategies to the existing power plants is possible at minimized cost through the application of CO_2 capture with integration of heat and mass exchanger networks in the capture process. Finally, this chapter reveals that some of the international treaties signed by participating countries pledging allegiance to reducing the emission of greenhouse gases are still faced with some limitations ranging from withdrawal by some developed countries, inadequate memberships for full implementation, and incomplete implementation of the signed agreement by some participating countries. Hence, the need to search for other alternatives to protect the environment and prevent future environmental disasters from increasing CO_2 emission resulting from human activities.

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