Beyond the Light : An Ocean of Chemosynthesis

1. Introduction

Traditionally, life is sustained by solar energy provided by sunlight. In environments where sunlight exposure is limited however, it is not possible to rely solely on solar energy. Fortunately, an alternative is provided by chemosynthesis, a process where chemical energy is used to sustain life in the environment rather than solar energy. By understanding the concepts of chemosynthesis and the optimal environments at which it works best, it is possible to acquire knowledge of how life can be sustained in extreme and harsh conditions, such as deep under the oceans of the Earth or in other celestial bodies.

Chemosynthesis may also be the answer to how the early life forms survived in the era before photosynthesis evolved to be used by organisms. This provides insight on how life may have originated on early Earth under the most extreme conditions. By understanding how life may have originated on early Earth, it is also possible to predict the existence of other life forms in other celestial bodies where environments optimal for chemosynthesis to sustain complex life forms are present such as the deep sea hydrothermal vents or under the ice of moons like Europa and Enceladus. Studying how chemosynthetic bacteria play a role in the geochemical processes may also provide insight on how the Earth may change due to environmental factors in the future. Therefore, this paper aims to visualise the optimal environmental conditions for efficient chemosynthesis in the ocean.

2. Research Question

I. How does the ocean's depth and ice cover on a sunless celestial body influence temperature gradients, chemical distribution, and the potential for life at different depths? (Environment)

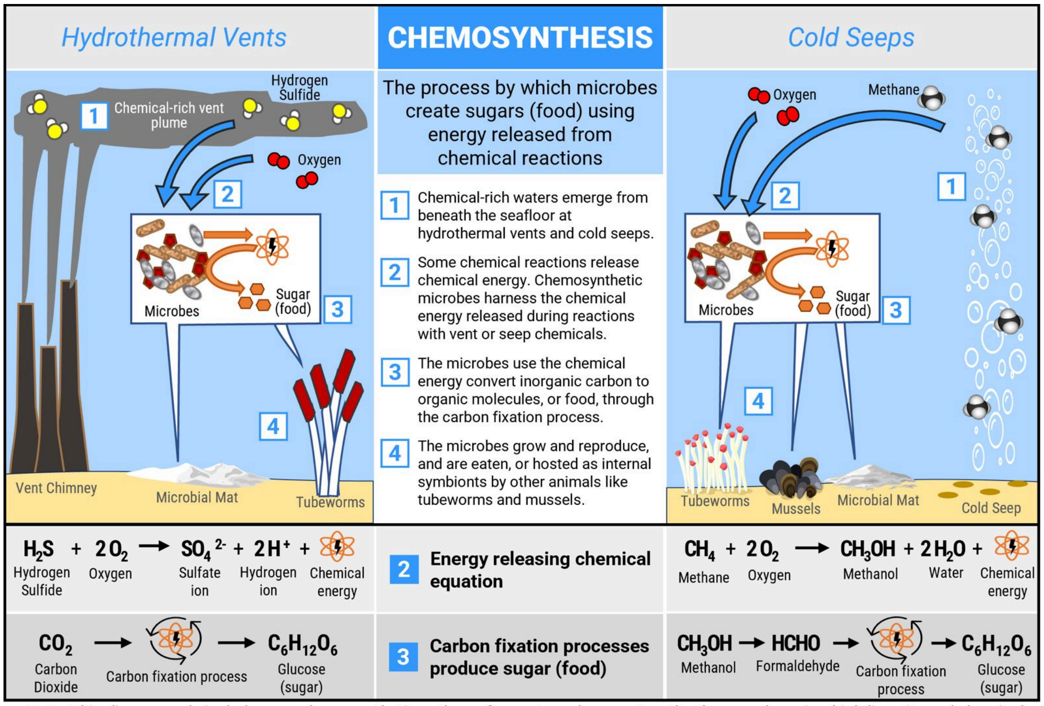
II. How do life in the ocean evolve in the absence of sunlight, and what adaptations allow them to exploit chemosynthetic processes for survival and reproduction? (Life)

III. What are the conditions required for optimal chemosynthesis used to sustain life to occur? (Environment)

3. Literature Review

3.1. Chemosynthesis

Chemosynthesis is the process by which food is made by bacteria or other living things using chemicals as the energy source, typically in the absence of sunlight (NOAA Ocean Exploration, n.d.). Chemosynthetic bacteria form the base of food webs at hydrothermal vents and cold seeps, where chemical energy is used to form sugars through chemosynthesis. There exist multiple chemosynthetic bacteria which use different chemical pathways to produce different products, including sugars. These different chemosynthetic bacteria however, all use the chemicals seeping from the ocean floor through the hydrothermal vents and cold seeps which exude hydrogen sulfide (H_2S) and methane (CH_4) respectively to produce the different products. These chemosynthetic bacteria which convert inorganic carbon to organic molecules are also consumed by other organisms, serving as the lowest of the food chain in a chemosynthetic environment. Despite being able to produce sugars without photosynthesis, the majority of chemosynthesis processes depend indirectly on sunlight. This is due to the aerobic nature of most chemosynthesis processes, which means that most life forms would cease to exist in the full absence of sunlight despite having chemosynthesis. It is still true however, that a small portion of chemosynthesis relying organisms may persevere and sustain in the full absence of sunlight, due to some chemosynthesis processes being anaerobic (C Smith, 2012).



Note: This diagram only includes one chemosynthetic pathway for vents and seeps. Due the the complex microbial diversity and chemicals found in these environments, there are several biochemical pathways that support the chemosynthetic communities found at each.

Figure 1. Processes of Chemosynthesis

Most life forms would cease to exist in the full absence of sunlight as most chemosynthetic bacteria require oxygen, thus having a connection to photosynthesis which requires sunlight. Other than sunlight, they also use oxygen supplied from water and other processes. An increased amount of nitrate, sulfite, and carbon dioxide would result in an increased oxygen output. A lesser amount of chemosynthetic bacteria however, obtain electrons from geothermal sources, allowing them to be completely independent of sunlight (C Smith, 2012).

3.2. Moons Which Offer Optimal Conditions For Chemosynthesis

3.2.1 Europa

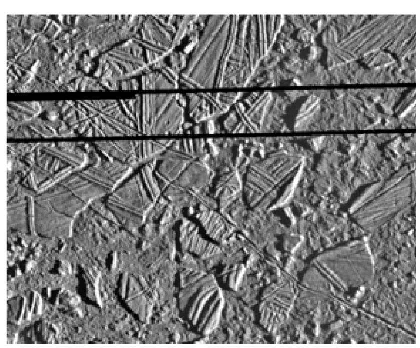


Figure 2. Europa’s Ice Crafts

Slightly smaller than Earth's moon, Europa is considered as Jupiter's smallest and second closest to jupiter. An energy source has kept Europa geologically active to the present day. Figure 1 shows a series of “ice rafts” on Europa’s surface reported by NASA scientists in 1997. The picture is reported as evidence of an ocean below the surface of Europa. The ocean interpretation rests on the belief that the existence of so much lateral motion across the surface requires the presence of some sort of layer to lubricate the flow at depth. These scientists assume that this lubrication requires a liquid, and hence favor the existence of an ocean. The "lubrication" that allows all of this motion and geologic activity is actually solid rock that is simply hotter and thus less viscous than the rock above it (Walter S. Kiefer). Additionally, Europa's icy shell gets stretched and released by the tug of Jupiter's gravity as Europa orbits the giant planet. This squeezing in and out is called tidal flexing, and it creates heat inside Europa. In fact, the tidal flexing is likely creating enough heat inside Europa to maintain the liquid ocean beneath the surface. Tidal flexing is a heating system that can cycle water and nutrients among the moon's rocky interior, ice shell, and ocean. This could create a watery environment rich with chemistry conducive to life (NASA).

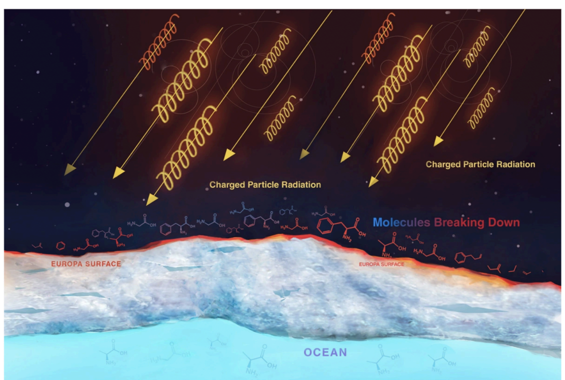


Figure 2. Europa’s Surface blasted by Jupiter’s Radiation

Unable to reach the sunlight, any life existing in Europa would exist under the thick layers of ice. Figure 2 depicts how Jupiter’s radiation wouldn't allow survival on Europa’s surface. Ocean beneath the 1-2 km ice might just be at least 10 kilometers thick, but does not tightly constrain the depth at which this ocean begins (Walter S. Kiefer). Jupiter’s radiation splits apart water molecules, causing hydrogen atoms to float away, and oxygen atoms react with other chemicals in the ocean for chemical energy for microbial life.

3.2.2 Enceladus

In 2005, NASA's Cassini spacecraft discovered that icy water particles and gas gush from the moon's surface at approximately 400 m/s. These water jets come from relatively warm fractures in the crust, which scientists informally call the "tiger stripes." Several gases, including water vapor, carbon dioxide, methane, perhaps a little ammonia and either carbon monoxide or nitrogen gas make up the gaseous envelope of the plume, along with salts and silica. This, among other evidence, points to hydrothermal vents deep beneath Enceladus' icy shell, not unlike the hydrothermal vents that dot Earth's ocean floor (NASA).

Just like Earth's oceans, Enceladus's ocean contains salt, most of which is sodium chloride, commonly known as table salt. The ocean also contains various carbon-based compounds, and it has a process called tidal heating that generates energy within the moon. Additionally, phosphate –a life supporting compound– is found in ice grains of the ocean. Analyzers could pick up a number of potential signatures from cellular material, including amino acids and fatty acids which support potential life under the sea (Fabian Klenner, 2024).

3.3 Life and Ecosystems Deep in the Sea

The deep sea is the part of the sea where light begin to fade, often around 200m deep under the surface of the ocean. It makes up approximately 90% of the Earth's marine environment and is the largest biome on the planet (Deep Sea Conservation Coalition, n.d.). Despite it being one of the environments on Earth with the harshest conditions characterized by its low temperatures, extreme darkness and harsh pressures, it houses various uniquely evolved life forms. Its biodiversity compares to even the world's richest tropical rainforests (Deep Sea Conservation Coalition, n.d.).

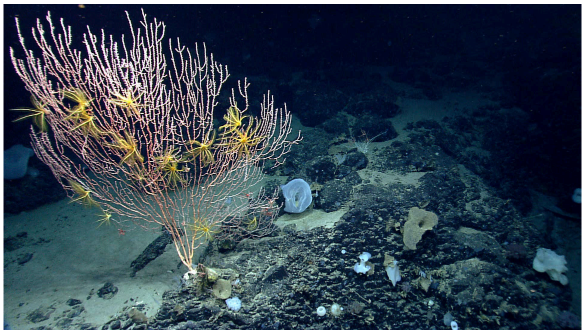


Figure 3. Deep Sea Biome

The seamounts are home to cold-water coral reefs and forests, sponge beds and hydrothermal vents, as well as the many millions of species dependent on these. The ecosystems associated with hydrothermal vents are unique on the planet (OneOcean, n.d.). These hydrothermal vents, along with the cold seeps, are some of the several sources of geothermal and chemical energy which provides the necessary reactants for chemosynthesis which essentially allows the diverse life forms to sustain deep under the ocean where light is absent. The chemosynthetic bacteria which uses chemosynthesis to create sugars perform the role of primary producers in the absence of sunlight. The herbivores and carnivores consume either the chemosynthetic bacteria or each other. Finally, the deep sea worms and other decomposers break down the organic material which reaches the seafloor, recycling the nutrients within the deep sea ecosystem. Most of the deep sea creatures however, grow and develop to be mature very slowly. This is due to the near freezing temperatures of 0℃ - 4℃, low food availability, as well as slow metabolism due to high pressure. These slow development and reproduction of the deep sea creatures renders them vulnerable to human interference and extinction.

4. Data and Analysis

4.1 Comparing 2 Moons and Earth

Table 1. Data Comparison Between the Earth, Europa, and Encaladus

Celestial Body	Ocean Depth (km)	Ice Thickness (km)	pH	Pressure (psi)	Temperature of the oceans (℃)
Earth	3.6-11	2.2-4.8 (polar area) (2.2 on average)	8.05	15750	0-4
Europa	60-150	15-25 (20 on average)	7.95-9.05	18854,9-37709.7	-4-0
Enceladus	10-31 (differs between the regions of Enceladus, with 10 km depth being more common)	3-40 (differs between the regions of Enceladus) (25 on average)	10.8	725,189 - 1450.38	-1

As shown from Table 1, the ocean depth ranked from the celestial body with the shallowest depth to the deepest would be Earth, Enceladus, Europa. This ranking is the same as the temperature ranking from the warmest ocean to the coldest ocean where the ranking is as such: Earth > Enceladus > Europa. This is different from the theoretical ranking which follows the Earth's pattern where deeper ocean levels would have warmer temperatures due to higher pressures. This is due to various variables which show the complexities of these celestial bodies. The variables include the pressure, gravity, ice thickness, as well as other geological factors. Europa's gravity is 0.134 of Earth's gravity, which when added with its thick ice (thicker ice than Enceladus) which reduces the gravitational force exerted on the oceans and itself provides less pressure. The thick ice also provides better heat isolation than that of Enceladus's, explaining why Europa's ocean temperature is lower than Enceladus's. Although Enceladus's gravity is even lesser than that of Europa's being 0.0115 of that of Earth's gravity, its deep water pressure is greater than Earth's due to its more active hydrothermal system on its ocean floor. This active hydrothermal system increases the temperature of the ocean, therefore increasing its water pressure. Enceladus is also known for its active geysers or water jets which suggests that it has active geothermal processes which might generate more localised heat and pressure on its oceans.

Table 2. Chemicals Required For Optimal Chemosynthesis

Category	Chemical	Role in Chemosynthesis
Electron Donors	Hydrogen Sulfide ($H2S$)	Oxidized for Energy
	Sulfur (S)	Oxidized to Sulfate
	Ammonium (NH_4^+)	Oxidized to Nitrate
	Methane (CH_4)	Oxidized by methanotrophs
	Hydrogen (H_2)	Oxidized by hydrogen-oxidizing bacteria
	Ferrous Iron (Fe^{2+})	Oxidized to ferric iron
	Carbon Monoxide (CO)	Oxidized by carboxydotrophic
Electron Acceptors	Oxygen (O_2)	Aerobic electron acceptor
	Nitrate (NO_3^-)	Aerobic electron acceptor
	Sulfate (SO_4^{2-})	Anaerobic electron acceptor
	Carbon Dioxide (CO_2)	Anaerobic electron acceptor
	Ferric Iron (Fe^{3+})	Anaerobic electron acceptor
Carbon Sources	Carbon Dioxide (CO_2)	Used to build organic molecules
	Methane (CH_4)	Use by methanotrophs
Other chemicals	Hydroxylamine(NH,OH)	Intermediate in nitrification
	Nitrous Oxide (N_2O)	Intermediate in denitrification
	Dimethyl Sulfide (DMS)	Sulfur compound in marine ecosystems

Table 2 above depict the important chemicals and their role in chemosynthesis. Its roles include electron donors, where compounds lose electrons and release energy. This energy is critical for converting carbon dioxide or methane into organic molecules, which organisms can use for growth and reproduction. Electrons acceptors on the other hand, are crucial for completion of redox reactions. They act as the final destination for electrons, to maintain metabolism. Using the energy acquired from electron donors, Organisms use simple compounds such as carbon dioxide and methane to synthesise complex organic matter, which is the basis for life. Finally, the process of chemosynthesis results in waste products such as sulfur that serves as nutrients for surrounding bacterias which maintain the food chain.

Table 3. Comparison Between the Chemicals in the Earth's, Europa's, and Encaladus's Ocean

Celestial Body	Chemicals Contained in the Oceans
Earth	Hydrogen sulfide, Methane, Hydrogen, Ammonium, Nitrite, Iron, Sulfur compounds, Oxygen, Manganese, Phosphate, Carbon compounds, Sodium, Potassium, Magnesium, Chloride
Europa	Hydrogen sulfide, Methane, Hydrogen, Ammonium, Nitrite, Iron, Sulfur compounds, Oxygen, Manganese, Phosphate, Carbon compounds, Hydrogen peroxide, Sodium, Potassium, Magnesium, Chloride
Enceladus	Hydrogen, Carbon compounds, Methane, Hydrogen Sulfide, Ammonium, Sulfur compounds, Silica, Chloride, Organic compounds

Table 3 compares crucial chemicals for chemosynthesis and habitability contained in Earth, Europa, and Enceladus. While hydrogen peroxide is present in Europa, it is absent in Earth. Additionally, Enceladus lacks hydrogen sulfide, nitrite, iron, oxygen, phosphate, manganese, sodium, potassium and magnesium. Due to its obvious lack of chemicals Enceladus has compared to Earth, Encaladus is known to sustain less life than Europa.

4.2 Optimum Chemicals from Chemosynthesis for Possible Life

Aside from existing deep sea worms, bacteria, and other decomposers, larger organisms such as jellyfish, squids, bioluminescent predators, and parasites. Inorder for these organisms to survive in such conditions, several factors have to be considered. These factors include how they evolve and chemical concentrations needed for them to survive. These chemicals are more concentrated on the seafloor, due to its high pressure, causing molecules to fall. Additionally, the hydrothermal vents are the key energy source which is provided on the seafloor. Due to this, chemical concentrations range from sea floor to high levels near the surface/ice.

Table 4. Comparison of Chemical Concentrations in Earth's, Europa's, Encaladus's Ocean

Chemical	Earth	Europa	Enceladus
Sodium Chloride (NaCl)	~30 g/L (dominant salt)	10–50 g/L	10–20 g/L
Magnesium Sulfate ($MgSO_4$)	~2.7 g/L	0.1–20 g/L	~2 g/L
Hydrogen (H_2)	Varies; produced in hydrothermal vents	~0.01 to 0.1 moles/m²/year	Not well characterized
Oxygen (O_2)	~250 µM/L (well-oxygenated zones)	0.1 to 1 µM/L	Not well characterized
Hydrogen Sulfide (H_2S)	Varies; can reach 1–10 mM/L in vents	< 1 mM/L	Not well characterized
Methane (CH_4)	~nanomolar to micromolar levels	1 to 100 nM/L	Not well characterized
Ammonia (NH_3)	Varies; often in low concentrations	0.1 to 10 µM/L	Not well characterized
Sulfate (SO_4^{2-})	~28 mM/L	1 to 50 mM/L	Not well characterized
Organic Molecules	0.1 to 1 µM/L	< 1 µM/L	Not well characterized
Hydrogen Peroxide (H_2O_2)	Not typically present	Likely < 1 µM/L	Not well characterized

Observing conditions from chemical concentrations of Earth, Europa, and Enceladus can provide us insights about how habitable a planet is, and optimum chemicals for life with no sunlight. Comparing NaCl concentrations has shown that estimation of Earth fits into Europa's range when Encaladus does not. Seawater is known to be salty, due to its NaCl composition. It plays a crucial role in buoyancy for habitants by increasing density. Moreover, magnesium sulfate estimates of Earth and Enceladus have similar values, and both fit within the range of Europa's Magnesium Sulfate concentration. Further values of chemical concentrations in Enceladus are not well characterised. Further inspections of chemicals present in Earth and Europa mostly are correlated well enough with one and another. This supports that Earth's ocean habitats are possible for conditions similar to Europa.

Analyzing Europa and Earth conditions, oxygen and hydrogen sulfide levels are lower in Europa, while other molecules that fit within its range are sufficient enough to maintain habitats similar to Earth's ocean. The more concentrated the important chemicals are, the more nutrients are available to support a habitable life for chemosynthesis.

For an optimal planet, there must be a sufficient concentration of organic molecules in an ocean, which affects pH level. Optimal pH levels will be analyzed further.

4.3. Optimum Conditions to Sustain Life

4.3.1. Planet's position

For a planet to be able to use chemosynthesis as its main energy source and not photosynthesis, solar energy needs to be significantly weak and surface temperature is low. For this phenomena to occur, it is crucial to position the planet on the outer solar system. However, it is still important for the planet to be placed near Jupiter or Saturn in order to ensure active geological activity which provides geothermal and chemical energy required for lifeforms to survive. To ensure geological activity, positioning the planet near Jupiter or Saturn is required to let tidal heating occur. Tidal heating is a geological phenomenon which occurs when the gravitational pull of a larger celestial body creates deformation on a smaller celestial body, leading to internal heating, encouraging the occurrence of an active geological activity. Therefore, to ensure that the planet has enough geological activity to sustain life, it is important to position it near Jupiter and Saturn, placing it approximately 10 AU (Astronomical Unit) away from the Sun.

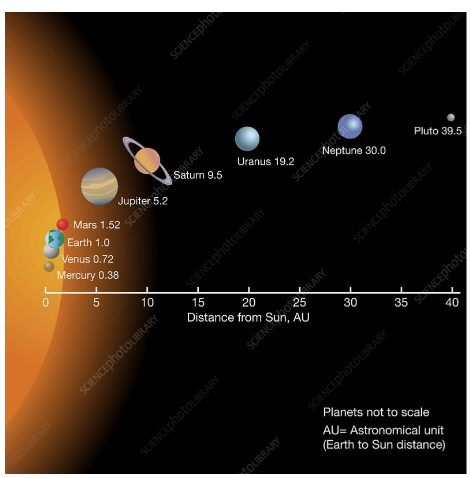


Figure 4. Planet's Distances From The Sun in AUs (Astronomical Units)

4.3.2. Ice thickness

To create a habitable ocean environment, it is also significant to include a thick ice surface. The optimal ice thickness considering the ice thickness of Europa and Encaladus while also considering Earth's conditions would be an ice thickness of 20km to 40km. Through the thick ice, heat would be isolated inside the ocean, allowing liquid water to remain as it is. Isolated heat inside the planet's ocean also supports the survivability of chemosynthetic life forms. Having a thick ice covering the surface of the ocean also provides the planet with a thermal gradient. It would have a cold surface as well as low temperature water on shallow depths and warmer water on deeper depths, especially so if the ocean floors are provided with heat sources such as the hydrothermal system. This thermal gradient would allow the planet to be inhabit diverse life forms in diverse habitats and ecosystems. Moreover, the thick ice would protect the oceans from debris, radiation, as well as other interference which would endanger the life forms inhabiting the planet's oceans, therefore allowing the life forms to survive and develop well.

4.3.3. Ocean Depth

A deep ocean of 20 km to 50 km would be best for a planet relying on chemosynthesis to sustain its inhabitants. The deep ocean depth would provide great pressure levels of approximately 18,000psi to 22,500psi in the depths of 50km which in turn increases the solubility of the contained gases, allowing greater concentrations of dissolved nutrients in greater depths. Due to the anoxic properties of the ocean, a great concentration of dissolved nutrients is crucial for the survival of the organisms inhabiting the planet's oceans. With a harsh environment of great pressures, scarce light and great concentration of dissolved nutrients, the inhabitants of the planet would adapt to the environment by developing metabolic pathways and other physiological features which would greatly increase their survivability.

4.3.4. Temperature

The range of temperatures in the planet's ocean would also be very crucial in a planet where life is sustained through chemosynthesis. As aforementioned, a thermal gradient would encourage the existence of a more diverse ecosystem. Therefore, a surface temperature above the ice of -100℃ to -180℃, similar to that of Europa's and Encaladus's surface temperature, and an ocean temperature of 0℃ to 20℃ would be optimal to create a stable thermal gradient. A warmer temperature also accelerates the metabolic processes of the organisms without denaturing the proteins. Chemosynthesis is also the most prominent in 2℃ to 400℃. However, as most organisms thrive at the temperature of 20℃ to 60 ℃, the temperatures near the hydrothermal vents should not exceed 90℃ to keep it habitable while also allowing the chemosynthesis process to be efficient.

4.3.5. pH Levels

Chemosynthetic organisms uses inorganic substances for energy. Chemical reactions using inorganic substances are most effective depending on the pH levels. In acidic environments, higher concentrations of H^+ ions exist, increasing the reactivity. However, such a low pH level would hinder the complex life forms as acidic conditions would damage the cells of the organisms. In a neutral to slightly alkaline environment of 7-9 pH levels, these chemical reactions involving inorganic substances are still processing at an optimal rate without damaging the organisms. Besides that, most enzymes are also denatured in acidic conditions, further urging the requirements of a slightly alkaline environment. Compounds processed by chemosynthetic organisms are also more available in slightly alkaline pH levels of 7-9. An example of this is carbon dioxide existing as bicarbonate at pH 7-9. Moreover, most chemosynthetic bacteria which are the primary producers in a planet which sustains the life of its inhabitants through chemosynthesis also prefer neutral to slightly alkaline conditions. Therefore, the optimal pH level for chemosynthesis to sustain complex life forms would be pH levels 7-9.

5. Conclusion

I. The ocean's depth and the thickness of the ice cover on a sunless celestial body would influence its temperature gradients, chemical distribution, and the potential for life at different depths in an intricate manner. The ocean's depth and ice cover plays a significant role in shaping the temperature gradients and chemical distribution in a sunless celestial body. As the ocean deepens, the pressure which is also affected by the gravity and also indirectly affected by the ice thickness, also increases. The increased pressure due to the deep depths of the ocean would create a more prominent temperature gradient where the temperature is colder near the ice cover and warmer as it gets closer to the ocean floor where geological and hydrothermal activity are present. The ice cover also isolates the oceans from extreme surface temperatures, providing the oceans with a stable environment where liquid water is sustained. The thermal gradient maintained influences the distribution of chemicals in the ocean which are critical for chemosynthesis. Life at different depths also adapt to the various conditions in different depths of the ocean, adapting to the varying chemical composition and pressure of the ocean. Near the ocean floor and hydrothermal vents where optimal temperature and concentrated chemical nutrients are present, chemosynthetis reliant life forms are to survive and thrive.

II. Chemosynthesis is known for smaller organisms for a sustainable life. What about larger organisms? With modified chemical concentrations suitable for larger organisms, such as increased in oxygen, hydrogen sulfide, and organic molecules, as well as modified environments, larger animals would be able to evolve in such conditions. For example, squids would have evolved to have an increased flexibility, bioluminescence adaptations, and a more rapid reproductive cycles. Other larger deep sea organisms such as jellyfish, would adapt and evolve similarly.

III. To sustain complex life forms through the use of chemosynthesis in the absence of sunlight, it is crucial to create and maintain an environment where optimal and efficient chemosynthesis can occur. The conditions in creating such an environment include an environment with optimal temperature, pH levels, pressure, as well as chemical compositions of the ocean. To facilitate the environment with such conditions, several variables are to be included into the consideration, these variables are:

    1. Planet's position: Positioning the planet in a distance of approximately 10AU is best to encourage the planet to rely on chemosynthesis rather than photosynthesis to sustain life. It is also located near Jupiter and Saturn, allowing tidal heating to provide optimal temperature for chemosynthesis.
    2. Ice thickness: An ice cover of of 20km to 40km thickness is best to isolate heat inside the ocean, allowing liquid water to remain in its liquid state, as well as creating a thermal gradient where the waters near the ice is cold, and the waters near the ocean floor is warmer.

3. Ocean depth: An ocean 20km to 50km deep is also best to provide great pressure levels of approximately 18,000psi to 22,500psi near the ocean floor, increasing the solubility of chemicals in the water, allowing greater concentrations of chemicals on the ocean floor which is crucial for the organisms' survival.
4. Temperature: To create a more prominent thermal gradient which allows a diverse environment, the surface temperature of the planet is best to be -100℃ to -180℃, with a temperature of 0℃ to 20℃ in the ocean. This range of temperature would allow metabolic processes of the organisms to be accelerated without denaturing the protein molecules. Chemosynthesis is also optimal in this range as it thrives in the temperature range of 2℃ to 400℃. Temperatures near the hydrothermal vents should also remain under 90℃ as it would harm the organisms if the temperature is too high.
5. pH levels: A neutral to slightly alkaline pH level of 7-9 would prevent the denaturation of protein molecules while allowing chemical reactions to occur efficiently. A neutral to slightly alkaline environment also provides more availability to the chemicals required for chemosynthesis. Chemosynthetic bacteria also thrive more in such environments.
6. Important chemicals for chemosynthesis: It can be concluded that to maintain a life for large microorganisms, still maintaining Europa conditions, and creating a habitable environment according to Earth, an increased concentration of oxygen and hydrogen sulfide. In need for a higher concentration of oxygen, a larger amount of sulfate, nitrate and carbon dioxide is required. Organic molecules are also sufficient.

6. References

1. *Cassini at Enceladus*. (n.d.). NASA. https://science.nasa.gov/mission/cassini/science/enceladus/
2. Choi, C. Q. (2015, March 31). *Icy-moon discoveries: What they mean for alien life search*. Space.com. https://www.space.com/28978-enceladus-europa-ganymede-alien-life.html#:~:text=The%20pressure%20at%20the%20base,could%20lead%20life%20to%20emerge

3. Dean, J. (2024, February 29). *Ice shell thickness reveals water temp on ocean worlds*. Cornell Chronicle. https://news.cornell.edu/stories/2024/02/ice-shell-thickness-reveals-water-temp-ocean-worlds#:~:text=NASA's%20Cassini%20probe%20generated%20data,to%20minus%201.272%20degrees%20Celsius
4. *Deep ocean*. (2019, December 17). One Ocean. https://www.oceanprotect.org/resources/issue-briefs/deep-ocean/#:~:text=Deep%20ocean%20habitats%20%E2%80%93%20the%20abyssal,sea%20species%20grow%20very%20slowly
5. Deep Sea Conservation Coalition. (2024). *Deep-Sea Life and Habitats*. https://deep-sea-conservation.org/explore/deep-sea-life-and-habitats/
6. Dodds, W. K., & Whiles, M. R. (2010). *Predation and Food Webs*. ScienceDirect. https://www.sciencedirect.com/topics/agricultural-and-biological-sciences/trophic-level
7. *Enceladus*. (2023). NASA Science. https://science.nasa.gov/mission/cassini/science/enceladus/
8. *How deep is the ocean?* (24, June 16). NOAA's National Ocean Service. https://oceanservice.noaa.gov/facts/oceandepth.html#:~:text=The%20average%20depth%20of%20the,U.S.%20territorial%20island%20of%20Guam
9. Johnson-Roehr, S. N. (2024, June 11). *Saturn's ocean moon Enceladus is able to support life*. JSTOR Daily. https://daily.jstor.org/saturns-ocean-moon-enceladus-is-able-to-support-life/
10. Kiefer, W. S. (n.d.). *Europa and Titan: Oceans in the Outer Solar System?* Lunar and Planetary Institute. https://www.lpi.usra.edu/science/kiefer/Education/SSRG2-Europa/europa.pdf
11. Marshall, S. (n.d.). *Exploring Jupiter's Ocean World*. NASA. https://europa.nasa.gov/in-depth/#:~:text=Slightly%20smaller%20than%20Earth's%20Moon,60%20to%20150%20kilometers
12. Marshall, S. (n.d.). *Why Europa*. NASA. https://europa.nasa.gov/why-europa/ingredients-for-life/#:~:text=But%20the%20type%20of%20life,where%20there%20is%20no%20sunlight.&text=Europa's%20surface%20is%20blasted%20by%20radiation%20from%20Jupiter.,-That's%20a%20bad
13. Melosh, H. J., Ekholm, A. G., Showman, A. P., & Lorenz, R. D. (n.d.). *IS EUROPA'S SUBSURFACE WATER OCEAN WARM?* University of Arizona. https://www.lpi.usra.edu/meetings/lpsc2002/pdf/1824.pdf

14. Naganuma, T. (1998, June 12). *Dive Europa: a search-for-life initiative*. PubMed. https://pubmed.ncbi.nlm.nih.gov/11541880/#:~:text=Europa's%20possible%20ocean%20is%20estimated,of%20a%20theoretical%20Earth's%20ocean
15. NOAA OCEAN EXPLORATION. (n.d.). *Chemosynthesis*. Home: NOAA Ocean Exploration. https://oceanexplorer.noaa.gov/edu/materials/chemosynthesis-fact-sheet.pdf
16. Reynolds, R. T. (1983, July 28). *On the Habitability of Europa*. Northwestern University. https://lunar.earth.northwestern.edu/courses/450/europahab.pdf
17. Shibley, N. C., & Goodman, J. (2024, March 1). *Europa's coupled ice–ocean system: Temporal evolution of a pure ice shell*. ELSEVIER. https://www.sciencedirect.com/science/article/pii/S0019103523004517
18. Smith, C. (2012). *Chemosynthesis in the deep-sea: life without the sun*. Biogeosciences Discussions. https://bg.copernicus.org/preprints/9/17037/2012/bgd-9-17037-2012.pdf
19. *Solar system planetary distances from Sun, illustration*. (n.d.). Science Photo Library. https://www.google.com/url?sa=i&url=https%3A%2F%2Fwww.sciencephoto.com%2Fmedia%2F1155598%2Fview%2Fsolar-system-planetary-distances-from-sun-illustration&psig=AOvVaw2ld_1ifTe8vp4n6SeD6yP8&ust=1728292337665000&source=images&cd=vfe&opi=89978449&ved=0CBQQjRxqFwoTCNjx1uy0-YgDFQAAAAAdAAAAABAJ
20. UCL. (2023, November 15). *How much pressure builds up at the deepest point in the ocean?* Culture Online. https://www.ucl.ac.uk/culture-online/case-studies/2021/apr/how-much-pressure-builds-deepest-point-ocean#:~:text=Sometimes%20pressure%20is%20also%20measured,%2C%20it%20is%2015%2C750%20psi