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OZONE LAYER DEPLETION AND ITS IMPACTS ON THE ENVIRONMENT AND PUBLIC HEALTH: A REVIEW

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ABSTRACT: *The level of solar UV radiation is increasing worldwide due to the depletion of the stratospheric ozone layer. The ozone layer is considered a protective shield from harmful ultraviolet radiation emitted from the sun to humans and the environment. In this narrative review, the paper investigates the cause of Ozone depletion, its impacts on the environment and human health, and initiatives to protect the ozone layer. It gives an overview of the depletion of the ozone layer from natural and anthropogenic processes, which has led to numerous harmful effects on human health and the environment. The exposure to harmful UV radiation, which has led to increased long-term effects including the rise of melanoma, is estimated to rise to 510,000 new cases and 96,000 deaths by 2040, with a decline in crop productivity by about 3% for every 10% increase in UVB radiation. However, the ratification of the Montreal Protocol globally has led to combined efforts to recover the stratospheric ozone layer. The challenges of limited funding to implement activities tailored towards abating ozone layer depletion, and porous borders in many countries still hinder the initiatives to save the ozone layer.*

KEYWORDS: Ozone; Ozone Layer Depletion; Environment; Ultraviolet Radiation.

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INTRODUCTION

The ozone layer is a region of the Earth's stratosphere that is made up of ozone (O_3) (Aggarwal et al., 2013). This layer was first discovered by Henri Buisson and Charles Fabry in 1913 and acts as a barrier against most of the ultraviolet radiation emitted by the sun (Anjali et al., 2013). The greatest concentration of ozone is about 25 kilometers above the Earth's surface (Udoh, 2014). Ozone (O_3) is a pungent gas that is formed when the molecular oxygen (O_2) encounters UV light within the stratosphere (Adeoye & Aina, 2019). Ozone is inherently unstable but has a long life span in the stratosphere and is very short-lived in the troposphere. Upon exposure to UV radiation, it breaks down into an oxygen molecule and a single oxygen atom. UV radiation is categorized according to the wavelengths as ultraviolet A (315–400 nm), ultraviolet B (280–315 nm), and ultraviolet C (<280 nm) (Barnes et al., 2019). The ozone layer prevents the harmful UV radiation from reaching the Earth's surface. Ultraviolet A (UVA) is less harmful. The ozone layer absorbs and filters the majority of the sun's harmful ultraviolet B (UVB) and ultraviolet C (UVC) radiation, which can damage ecosystems and cause skin cancer, cataracts, and other health issues. The whole UVC and 90% of UVB are absorbed by stratospheric ozone, while 90-99% of UVA reaches the Earth's surface (Narayanan et al., 2010), as shown in Figure 1.

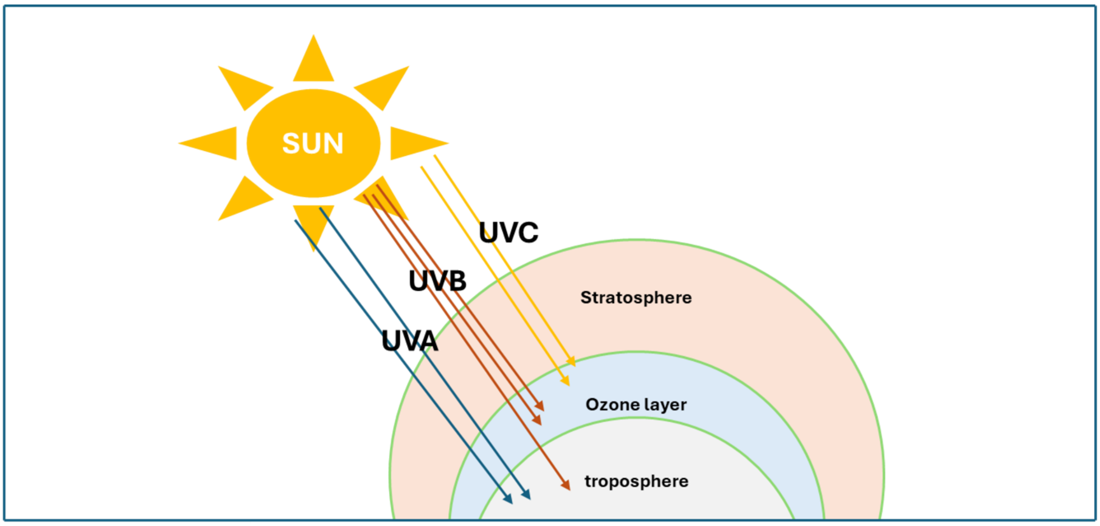

Figure 1: The UV radiation intensity in the atmosphere

Ozone depletion is the thinning of the ozone layer, which happens when fluorine, chlorine, and bromine radicals in the atmosphere come in contact with the ozone, leading to the destruction of ozone molecules (Avani et al., 2023). The depletion of stratospheric ozone leads to increased UVB radiation at the surface of the Earth (Barnes et al., 2019). The compounds that destroy the ozone layer are termed ozone-depleting substances (ODSs) (Udoh, 2014). ODSs generally contain chlorine, bromine, fluorine, hydrogen, and carbon in varying properties (Li et al., 2021). Furthermore, ozone layer depletion is primarily caused by man-made substances such as chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs) (Saxena, 2018). The CFCs are organic and stable, and no natural processes can remove them from the troposphere. However, with time, CFCs are driven by winds into the stratosphere and exposed to strong UV radiation that breaks them down to release atomic chlorine (Udoh, 2014). As observed, each of

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these radicals can destroy over 100,000 ozone molecules in two years (Verisae, 2009). The chlorine atom is what damages the ozone layer in a repetitive process, as summarized in the mechanism:

$Cl + O_3 \rightarrow ClO + O_2$

$O + ClO \rightarrow Cl + O_2$ (Cl then goes to the atmosphere to destroy more ozone)

There is considerable progress in understanding the effects of ozone depletion on human health and the environment. This review article provides an overview of the causes and significant impacts of ozone depletion in recent literature. It also explores the mitigation measures implemented to retard ozone depletion. The review article further discusses the challenges affecting the implementation of measures to protect the ozone layer.

METHODOLOGY

In this review, we modified the data search process used by Komakech *et al*. (2017) to obtain information from original peer-reviewed articles published in scientific journals. We searched through electronic literature databases including Research Gate, Science Direct, Google Scholar, and PubMed for relevant peer-reviewed articles from 2000 to 2024. The following key search terms were used: “ozone layer depletion” OR “ozone layer” AND “causes” OR “public health” OR “environment.” The selection of publications was limited to journal articles written in English. The data obtained were verified independently for their accuracy. Any identified discrepancies were resolved through collaborative discussions among authors. The final data obtained were summarized and compared, and conclusions were made accordingly.

Causes of Ozone Layer Depletion

As a major concern, ozone layer depletion results from anthropogenic and natural factors. The anthropogenic factors originate from human activities and are directly linked to human behavior, industries, technological advancements, agriculture, and fossil fuel combustion (Steffen, 2007). They include chemicals such as chlorofluorocarbons and hydrofluorocarbons used in refrigeration and air conditioning that remain stable in the atmosphere but break down in the stratosphere under ultraviolet radiation, thus releasing chlorine and fluorine atoms that destroy the ozone molecules (Protocol, 2022). Fire suppression systems also affect the ozone layer mainly through halons that are used in fire extinguishers because they release bromine atoms when exposed to UV light (Brenna, 2019). Ozone depletion is also a result of the continuous use of aerosol propellants and foams. These agents use CFCs as propellants, which drift into the stratosphere and damage the ozone layer once they are sprayed (McKenzie, 2007). Agriculture is another cause of ozone depletion because it involves the use of nitrogen-based fertilizers, which contribute to the release of nitrous oxide (N_2O), a potent ozone-depleting gas (Ogwugwa & Bandh, 2023). During the cleaning processes of manufacturing industries, chemicals like carbon tetrachloride (CCl_4) and methyl chloroform (CH_3CCl_3) are used. These break down and release chlorine that damages the ozone layer when it reaches the stratosphere (Kim, 2011). These are known as ozone-depleting substances (ODSs) and are key anthropogenic ozone destroyers as shown in Table 1.

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Table 1: Anthropogenic ozone depletion agents (Source: Bryne, 2001)

Chemical	Application	Contribution to Ozone depletion
Chlorofluorocarbons (CFCs)	Propellants, refrigerants, aerosols	Releases chlorine
Hydrochlorofluorocarbons (HCFCs)	Propellants, refrigerants, aerosols	Releases chlorine
Carbon tetrachloride (CCl4)	Cleaning agents, fire extinguisher, refrigerants	Releases chlorine
Hydrobromofluorocarbons (HBFCs)	Cleaning agents, fire extinguisher, solvents, refrigerants	Releases bromine
Halons	Fire extinguisher	Releases bromine
Methyl bromide	Pesticide	Releases chlorine
Methyl chloroform	Cleaning solvent	Releases chlorine
NO_X	Fertilizers, bacterial denitrification	Releases dinitrogen oxide that gets oxidized and reacts with ozone

However, ozone-depleting substances are being phased out through various measures like the Montreal Protocol (WMO, 2018).

The ODSs that contain chlorine include chlorofluorocarbons, carbon tetrachloride, hydrochlorocarbons, and methyl chloroform (Basu, 2024). The other substances that contain bromine are halons, methyl bromide, and hydrobromofluorocarbons (Udoh, 2014). Other major ODSs include hydrochlorofluorocarbons (HCFCs), chlorine monoxide (ClO), and Volatile Organic Compounds (VOCs) that are responsible for depleting the thickness of the ozone layer (Aggarwal et al., 2013).

The natural causes of ozone depletion are found in the atmosphere (Molina, 2020). Significant amounts of gases and particulates like sulphur dioxide (SO_2) are ejected into the stratosphere during volcanic eruptions (Eric, 2017). These particles form aerosols that provide surfaces for chemical reactions involving chlorine and bromine, accelerating ozone depletion (Brenna, 2019). Solar activity is also a significant threat to the ozone layer. The variations in solar radiation, like solar flares and changes in UV radiation intensity, influence ozone levels. Furthermore, increased UV radiation breaks down ozone molecules, hence weakening the ozone layer (Adeoye & Aina, 2019). A study by Molina (2020) showed that stratospheric

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winds and temperature changes affect the distribution and concentration of ozone molecules. For example, polar vortices in Antarctica and the Arctic isolate ozone-poor air, leading to seasonal ozone depletion. The regions of the stratosphere where ozone layer depletion is severe are known as the 'ozone hole' and are particularly over the polar regions of the Earth (Udoh, 2014). The most severe depletion occurs over Antarctica between September to November. Earth's surface is being exposed to harmful UV radiation due to ozone layer depletion. These radiations are detrimental to the environment and human life. The restoration of the ozone layer is far-reaching; however, immediate intervention is very key to addressing and mitigating the existing causes of ozone depletion to protect life on Earth (Avani, 2023).

Impacts of Ozone Layer Depletion

Ozone depletion has significant environmental, health, and ecological consequences mainly due to the increased penetration of harmful ultraviolet radiation to the Earth's surfaces (McKenzie, 2007).

Impact of Ozone Depletion on Public Health

Human health is seriously threatened by exposure to these radiations, which raises the risk of serious conditions like leukemia, breast cancer, melanoma, vision impairment, and genetic abnormalities (Avani et al., 2023). The most common cause of visual impairment worldwide is cataracts. A study by Anwar et al. (2016) showed an increase of 0.3% to 0.6% in the risk of cataract development would follow a 1% drop in ozone levels. In addition, UV radiation causes damage to the cornea and lens of the eye by producing reactive oxygen, which damages these structures (Lucas, 2015). In 2015, 12.6 million people were blind and 52.6 million people were visually impaired globally due to the development of cataract (Flaxman et al., 2017). A study by Berhard et al. (2020) found that exposure of the skin to UV radiation influences the effectiveness of vaccination and the risk of folate deficiency. Chang (2010) noted that the increased number of skin cancer victims is due to exposure to UV-B radiation, with over 5,000 Americans diagnosed each year. Furthermore, melanoma is the most severe skin cancer due to exposure to UV radiation and accounts for about 60,000 deaths worldwide annually (Barnes et al., 2019). The most exposed part of the human body to UV radiation is the skin, which increases the prevalence of skin cancer (Narayanan et al., 2010; Anwar et al., 2016). A total of 325,000 new melanoma cases and 57,000 deaths globally were due to exposure to UVR in 2020 (Arnold et al., 2022). In South Africa, 1777 new cases of melanoma were reported in 2020, affecting the whole population (Rocky et al., 2024). The World Health Organization (WHO) also reported that 59 deaths out of 156 cases were due to skin cancer in Uganda, in a report published in 2022 (Globocan, 2022). The rise of melanoma is estimated to rise to 510,000 new cases and 96,000 deaths by 2040 (Rocky et al., 2024). The UV exposure can result in leukemia and breast cancer (Wargent et al., 2013).

Prolonged exposure to UV radiation has been observed to suppress and weaken the human immune system, making individuals more vulnerable to infections, hence lowering their life span (McKenzie, 2007). The more the ozone is depleted, the weaker the human immune system becomes, leading to acceleration of the aging process of human skin (Andersen & Sarma, 2002). The depletion of ozone causes DNA structural damage because UVB radiation is directly absorbed by the DNA, whereas UVA indirectly damages DNA due to the formation of reactive oxygen species (Narayanan et al., 2010). The exposure to UV radiation affects the

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lungs, potentially leading to conditions such as bronchitis, emphysema, asthma, and lung obstruction (Wargent *et al*., 2013).

As a consequence of the depletion of the ozone layer, UV radiations penetrate the troposphere and catalyze the production of tropospheric ozone that poses a threat to the environment and human life (Narayanan et al., 2010). The changes in UV radiation have modified the air quality within the environment. Globally, 4.2 million deaths per year have been attributed to poor air quality (Wilson et al., 2019). In addition, UV enhances the reactions of pollutants with nitrogen oxides and volatile organic compounds that are toxic to humans (Wilson et al., 2019).

Impacts of Ozone Depletion on the Environment

Over the years, ozone layer depletion has led to a profound impact on the environment globally (Barnes et al., 2019). A study by Ballare et al. (2011) showed that there is a decline in crop productivity by about 3% for every 10% increase in UVB radiation. Moreover, the UVB radiations affect the plant's height, fresh & dry weight, and ash content, inhibiting the development of the crops (Aggarwal et al., 2013).

Phytoplankton, which are the foundation of aquatic food webs, are damaged by UV radiation, hence disrupting aquatic ecosystems (Williamson, 2019). Further, the UV-B radiations affect the mobility, orientation, photosynthetic processes, and enzymatic reactions of the phytoplankton. In addition, the UVB radiation affects the microbial decomposition of matter, especially leaves and litter. This impacts carbon sequestration in terrestrial ecosystems and carbon dioxide flux in the atmosphere (Ballare et al., 2020).

Materials *inter alia,* plastics, paints, and other manufactured substances, are constantly damaged by UV radiation, accelerating their degradation by altering their lifespan and durability (UNEP, 2016). Ozone depletion changes stratospheric temperatures, impacting weather patterns and hence contributing to climate change, which affects tropical ecosystems. The tropical ecosystem provides community livelihoods and carbon sinks. These are prone to decrease in abundance due to the interacting effects of climate and UV radiation (Berhard et al., 2020). The increased UVB radiation causes changes in species composition in forests and grasslands, thus altering biodiversity in different ecosystems (Adeoye et al., 2019).

Mitigation and Adaptation Measures of Ozone Depletion

There are a number of measures that can be adopted to mitigate ozone layer depletion. The Montreal Protocol, a landmark treaty that was signed in 1987, aimed at phasing out the production and consumption of ozone-depleting substances like CFCs (Oberthür, 2001). The protocol has undergone amendments to include new substances and stricter timelines, hence leading to a significant reduction in ODS emissions (UNEP, 2020). Global efforts and individual actions have been implemented to reduce the release of ODSs as well as to protect the ozone layer (Bernhard, 2019). Fire suppression systems have been improved through the replacement of halons with other alternative fire retardants that do not harm the ozone layer (UNEP, 2020).

The Parties to the Montreal Protocol have, in the recent past, enhanced collaboration between the Kyoto Protocol Secretariat and the Ozone Secretariat (Birmpili, 2018). This is aimed at ensuring that climate change matters are addressed using a holistic approach, with the control of the production and consumption of HFCs being embedded in the Kigali Amendment, as the

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Kyoto Protocol is concerned with control of emissions of HFCs into the atmosphere (Perry et al., 2024). Parties have continued to advocate for collaboration between the secretariats of the two protocols in order to work towards achieving the dual benefits of protecting and contributing to the recovery of the ozone layer, and mitigating the causes of global warming.

Hydrocarbons (HCs) are recommended alternatives to the use of HCFCs and HFCs, which are both ozone-friendly but have high global-warming potential (Purohit et al., 2016). Restrictions on the manufacture of HCFCs worldwide took effect on 14th May, 2008, according to Article 2(9) of the Montreal Protocol that accelerated their phase-out schedule (UNEP, 2020). The developing countries are required to completely phase out HCFCs by 2030 instead of 2040 (Birmpili, 2018).

Several alternatives, including HCFCs (Figure 2), HFCs, HCs, Ammonia, Propane, Iso-butane and water as a blowing agent in the manufacture of foam, are now on the world market and are being used to replace the use of ODSs (Purohit et al., 2016).

Figure 2: An example of alternatives to ODSs in commercial shops in Uganda. **A** - HCFC; **B** - HFC

Continuous monitoring of ozone levels, using satellites like NASA Aura and the European Space Agency's Copernicus Missions, helps to track recovery and measure trace gases important for the ozone layer such as nitrogen dioxide (NO_2), sulfur dioxide (SO_2), and formaldehyde (HCHO) that contribute to research regarding the mapping of sources and transport of pollution hence reducing ozone depletion (Levelt, 2018).

Public awareness and education on the dangers of ozone depletion and promotion of proper disposal of appliances that contain ODSs are critical in the mitigation of ozone layer depletion (Ogwu, 2024). People have been encouraged to use sunscreens, sunglasses, and protective clothes to shield against increased UV radiation, thus reducing the effect of ozone depletion on

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human health (Rabbetts, 2019). Concerning the above, people have been advised to change their behaviors to match the current weather conditions, for example, wearing light clothes during extremely hot hours to avoid discomfort, hence reducing the effects of ozone depletion (White, 2019).

Challenges Faced While Implementing the Montreal Protocol

The Montreal Protocol and its amendments continue to be implemented, but several challenges threaten the future ozone recovery. Actions need to be supported by all partners to affirm control on future levels of ODSs.

- Porous borders allow for the movement of prohibited/restricted ODSs across borders, yet they should not be entering the country, but only be allowed to enter the country in permissible quotas.
- Some importers, manufacturers, and dealers of ODSs falsify or counterfeit the labelling to depict the permitted refrigerants, yet they are ODSs.
- Low capacity of the customs officers and other law enforcement officers, especially in low-developed countries, to detect the ODSs. This can increase the case of dumping of ODSs from more developed countries to low developed countries and can go unnoticed.
- Low capacity of the refrigeration and air conditioning (RAC) technicians. Some of these RAC technicians learn on the job, and they do not know the chemical properties of the refrigerants and the consequences of releasing those refrigerants/ ODSs into the atmosphere.
- Lack of awareness. Some of the consumers and end-users who use equipment containing the ODSs are not aware of the consequences that the ODSs pose to their lives and the environment.
- There is limited funding to implement activities tailored towards abating ozone layer depletion, inter alia, awareness creation, routine monitoring, licensing, training, and developing a single window where all regulators contribute towards clearing of the ODSs before they enter the country. Ozone layer protection plays second fiddle among environmental problems when it comes to prioritization and resource allocation by governments.
- Lack of equipment such as refrigerant identifiers, Dobson spectrophotometers, and ozonesondes that are used in monitoring ozone-related aspects, like refrigerants, ozone concentrations in the stratosphere, among others.

CONCLUSION

Ozone layer depletion, caused by human activities and natural factors, has significant impacts on human health, ecosystems, and the climate. It leads to issues such as increased UV radiation, higher risks of skin cancer, disrupted ecosystems, and reduced agricultural productivity. However, global efforts like the Montreal Protocol and technological advancements have been instrumental in addressing this issue. Continued collective action and sustainable practices are

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essential to protecting the ozone layer and ensuring environmental health for future generations. The Earth is the only one we have that protects life; thus, preserving the ozone layer and reducing greenhouse gas emissions is key. There is a need for sensitization of the public on the impact of sun exposure on health issues.

Declaration of Competing Interest

The authors affirm that they do not possess any conflicting financial interest or personal relationships that might have been perceived to influence the findings presented in this paper.

Limitations

This review has some limitations. We might have missed studies or vital information published on sites other than those we focused on. Nevertheless, this review is very significant in understanding ozone depletion.

Authors' Contributions

A. Tumwebaze is the author of the review. T. Dennis, E. Baluku, M. Isaac, A. Barirega, and O. S. Francis reviewed and edited the work. R. Komakech is the corresponding author.

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