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Revisiting the challenges of ozone depletion in life cycle assessment

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ABSTRACT

Recent works have highlighted the interconnected impacts of stratospheric ozone depletion, ultraviolet (UV) radiation, and climate change on various sectors, including water quality, agriculture, human health, and biodiversity. Increased UV-B exposure has diverse environmental impacts, including potential benefits like enhanced plant resistance and reduced vitamin D deficiency. However, the quantification of these effects remains incomplete. Life Cycle Assessment (LCA) serves to quantify the environmental impacts of product systems. This article revisits challenges related to ozone depletion in LCA by reviewing 15 Life Cycle Impact Assessment (LCIA) methods. It is shown that the currently available LCA ozone depletion practices are outdated. The combined effects of outdated background databases and incomplete impact assessment methods must be further investigated. Collaboration with atmospheric scientists and expansion of substances covered by characterization models are required. The study emphasizes the need to address interlinkages between impact categories and recommends climate scenario-dependent characterization for robust decision-making in an uncertain world.

1. Introduction

The ozone layer in the stratospheric region of the atmosphere plays a pivotal role in protecting living species on Earth. It filters the ultraviolet (UV) radiation in the 220–320 nm wavelength range, which comprises UV-B (280–315 nm) and part of UV-C (200–280 nm) (Baird and Cann, 2012a, b), performing a silent but fundamental task. While the UV-C radiation is completely filtered by the ozone layer and does not reach the Earth's surface, the UV-B partly penetrates the ozone layer due to the limited absorption by ozone in this part of the spectrum (Baird and Cann, 2012a, b). The UV-B radiation increases the risk of, among others, skin and eye damage in humans and animals, and reduces photosynthesis in plants (UNEP, 2023b). The crucial role of stratospheric ozone has been endangered by the gradual increase in anthropogenic emissions of ozone-depleting substances (ODSs), leading to an even higher amount of UV-B penetrating the ozone layer. ODSs can be found in various sources such as automobile and truck air conditioning units, domestic and commercial refrigeration and air conditioning/heat pump equipment, aerosol products, portable fire extinguishers, insulation boards, panels, pipe covers, and pre-polymers (UNEP, 2020a). While chlorofluorocarbons (CFCs) are the most well-known ODSs, there are several other compounds classified as ODS, including halons, carbon tetrachloride, methyl bromide, 1,1,1-trichloroethane, hydrochlorofluorocarbons (HCFCs), hydrobromofluorocarbons (HBFCs), and bromochloromethane (UNEP, 2020a).

The awareness of the threat to the ozone layer was raised when Molina and Rowland (1974) suggested that two CFCs could function as catalysts for ozone destruction in the stratosphere. However, it was not till the mid-1980s, when scientists discovered the ozone hole over Antarctica, that the issue gained large-scale attention (Drake, 1995). Consequently, the Vienna Convention for the Protection of the Ozone Layer was established to promote global cooperation in limiting the anthropogenic contribution to ozone layer depletion (UNEP, 2020b). Building upon the Vienna Convention, the Montreal Protocol on Substances that Deplete the Ozone Layer, commonly known as the Montreal Protocol (MP), entered into force in 1989 (Singh and Bhargawa, 2019). Initially, the MP regulated five CFCs and three halons, which are halogenated hydrocarbons in Annex A, Group II of the MP, mostly used for firefighting applications (UNEP, 2020a). Today, thanks to subsequent

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Abbreviations

AoP	Area of protection
CF	Characterization factor
CFC	Chlorofluorocarbons
CML	Centrum voor milieuwetenschappen Leiden
DALY	Disability-adjusted life year
DU	Dobson unit
EDGAR	Emissions database for global atmospheric research
EESC	Equivalent effective stratospheric chlorine
EF	Environmental footprint
GHG	Greenhouse gas
GLAM	Global guidance for life cycle impact assessment indicators and methods
HBFC	Hydrobromofluorocarbon
HCFC	Hydrochlorofluorocarbon
HFC	Hydrofluorocarbon
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
MP	Montreal Protocol
ODP	Ozone depletion potential
ODS	Ozone-depleting substance
RCP	Representative concentration pathway
SSP	Shared socio-economic pathway
UNEP	United Nations Environment Programme
UV	Ultraviolet
VSLS	Very short-lived substance
WMO	World Meteorological Organization

amendments, the MP governs the production and consumption of nearly 100 ODSs. Reduction schedules have been established for each group of ODS, targeting their production, consumption, or both. These reduction targets are typically incrementally raised over time. It is important to note that developing countries have experienced delayed implementation of these reduction schedules, resulting in divergent reduction trajectories (UNEP, 2020a).

The limitation on ODSs shifted the consumption towards replacement substances such as HCFCs and hydrofluorocarbons (HFCs). The late awareness of the powerfulness of some HFCs as greenhouse gases (GHGs) stimulated the adoption of the 2016 Kigali Amendment to the MP (UNEP, 2016). Since many ODSs are potent GHGs, the current regulation on ODSs has a beneficial side effect: it is expected to alleviate climate change, possibly reducing global warming by 0.2–0.4 °C compared to a scenario without the Kigali Amendment (Flerlage et al., 2021). This is the first link between ozone depletion and climate change, whose physicochemical interactions will be explained in section 2.

Thanks to this global effort, a decline in ODS emissions has been observed since the late 1980s (Fang et al., 2019). The atmospheric abundances of most ODSs also decrease after reaching their peak in the 1990s and 2000s (Fang et al., 2019). Presently, the consumption levels represent less than 1% of the peak consumption (UNEP, 2023a). More importantly, ozone layer recovery has been observed in recent years (Singh and Bhargawa, 2019), averting the negative effects of UV-B exposure (Barnes et al., 2019; WMO, 2022). Many researchers have predicted a complete recovery of the ozone column to 1960 levels, but the timing of this recovery remains uncertain. Return dates are, for example, typically around 2040 for global mean column ozone and 2066 for the Antarctic in October, but with large uncertainty due to, e.g., climate change scenarios (Chipperfield and Bekki, 2024; WMO, 2022).

Recent scientific literature has highlighted that the quantification of the environmental effects and benefits of ozone layer depletion is currently lacking (Barnes et al., 2019). Also, challenges to full recovery subsist, and additional measures are required (Fang et al., 2019; Portmann et al., 2012). For example, in 2018, an increase in CFC-11 emissions since 2012 was discovered, which was inconsistent with the reported production being close to zero (Montzka et al., 2018). Although the uncontrolled production source of at least half of these emissions has been identified, uncertainty regarding unexplained emissions for CFC-11 and other banned substances persists (WMO, 2022). It is important to highlight that the MP does not control existing banks of ODSs, which may still pose leakage risks (Solomon et al., 2020). Additionally, certain critical applications may be exempt from the ban (UNEP, 2020a). Another threat is caused by emissions of unregulated ODSs. For example, very short-lived substances (VSLSs) such as CH_2Cl_2 and $CHCl_3$ are growing in atmospheric abundance despite having a lifetime shorter than six months (Fang et al., 2019). Therefore, continuous monitoring of ozone depletion threats and fostering close collaboration between scientific findings and policy decisions remain necessary (Portmann et al., 2012).

Life Cycle Assessment (LCA) is a methodology for quantifying the potential environmental impacts of a product system, and it has various applications, including "informing decision-makers in industry, government, or non-government organizations for strategic planning, priority setting, product or process design or redesign" (ISO, 2006). Specifically, an LCA study quantifies the environmental effects related to the emissions that occur throughout the entire life cycle of a product or service, from the raw material extraction, production, and use until the final disposal. Regarding the impact category of ozone depletion, once the different elementary flows (emissions of ODSs) are inventoried, the potential impact is calculated by summing up the contributions of the individual elementary flows. To this end, the flows are previously converted into the same unit of measurement by applying a conversion factor for each substance, called characterization factor (CF). The inclusion of the ozone depletion impact category in life cycle impact assessment (LCIA) methods dates to the early 1990s when ozone depletion potentials (ODPs) for halogenated hydrocarbons (WMO, 2022) were used by the Centrum voor Milieuwetenschappen Leiden (CML) to develop the CML impact assessment method (Heijungs and Guinée, 1992). Already then, several challenges and limitations of the ozone depletion impact assessment method were mentioned, such as the complex interactions between carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and ozone depletion, and the lack of ODPs for substances emitted by planes, e.g., nitric oxide (NO) (Heijungs and Guinée, 1992). At the time, scientific understanding of these issues was not advanced enough to calculate robust ODP values for non-halogenated hydrocarbons (Heijungs and Guinée, 1992). Lane and Lant (2012) reviewed the literature on the atmospheric science of ozone depletion and concluded that the inclusion of ODPs for N_2O in LCIA methods was recommendable and that the state of modeling was mature enough to do this. Hauschild et al. (2013) reviewed LCIA methods, and, despite the existing limitations, the ozone depletion impact category at midpoint received the highest quality classification, "recommended and satisfactory", mainly because international agreements exist. The same study evaluated the endpoint characterization model from Struijs et al. (2010) as the best existing at the time. Now, 10 years later, we revisit the challenges related to ozone depletion in LCA through this critical review aiming to answer the following research questions:

I. What is the state-of-the art of ozone layer science relevant for LCA?
II. To what extent does the current approach to ozone layer depletion in LCA align with the state-of-the-art of ozone layer science?

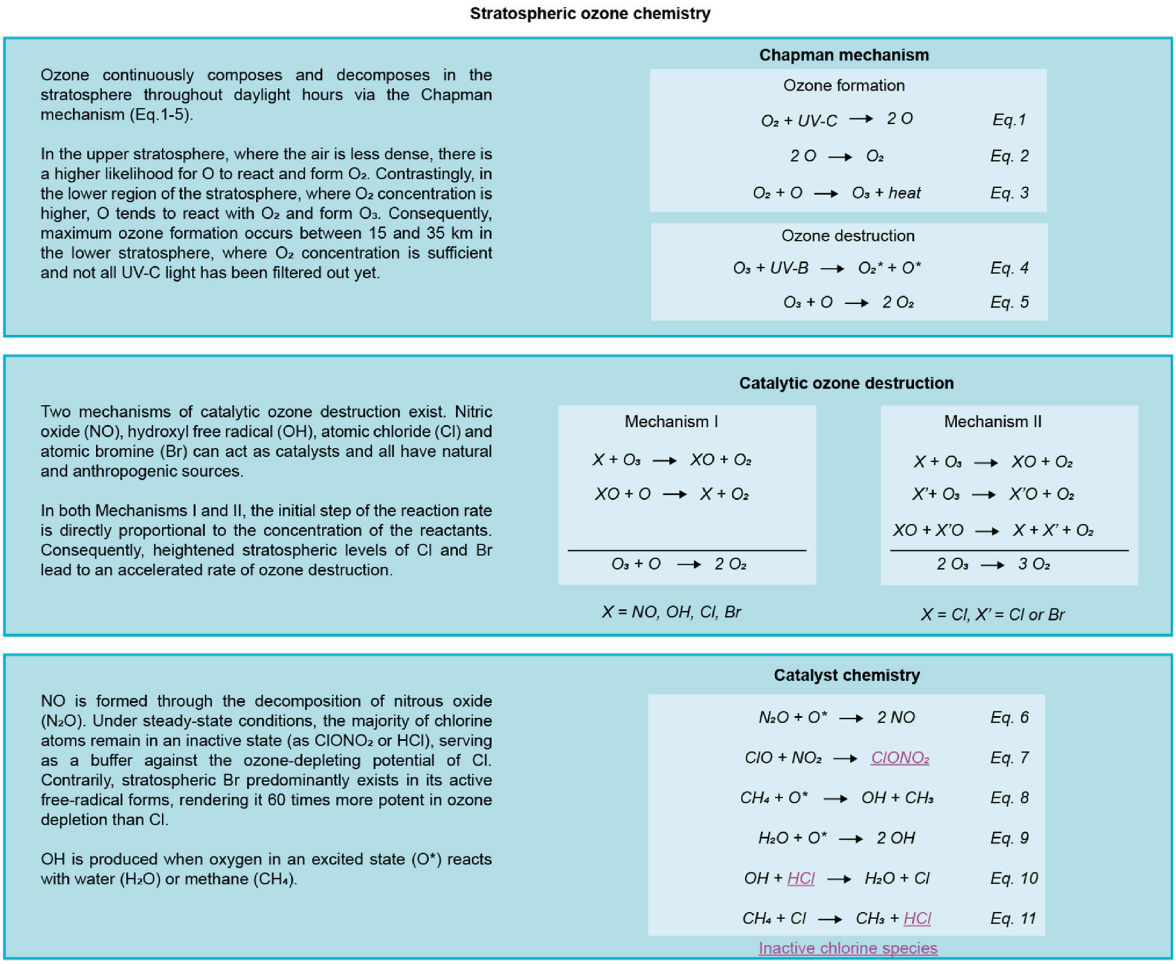
III. Which challenges hinder the use of LCA results to inform decision-making in ozone layer protection?
IV. Which improvements can be suggested to address these challenges?

To answer the first research question, section 2 presents a narrative review of stratospheric ozone science to lay the basis for understanding how well it is represented in LCA. Notably, the most recent authoritative assessment of ozone depletion (WMO, 2022) and its environmental effects (UNEP, 2023b) were reviewed. These reports, generated quadrennially by the collaboration between the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP), serve to apprise stakeholders under the MP of the prevailing status and developments in ozone depletion. Additionally, the state-of-the-art section builds on reports and peer-reviewed publications that focus on stratospheric ozone chemistry or the environmental effects of increased UV-B radiation. This narrative review aimed to give a broad overview, and publications that overly emphasized the intricacies of specific aspects were not considered. To answer the next three research questions, a systematic review was conducted following the methodology described in section 3. Section 4 presents the results of this systematic review. Readers without a background in LCA may benefit from reading a concise introduction to LCA (Sphera, 2020; PRé Sustainability, 2022) prior to reading this section. Finally, section 5 provides the outlook and conclusions.

2. Ozone layer depletion: causes and effects

Before delving into the various mechanisms responsible for ozone layer depletion, it is important to understand the key terms and the normal equilibrium between ozone formation and destruction (Fig. 1). The Chapman mechanism describes the normal equilibrium cycle that causes the ozone layer to exist. The thickness of this layer is measured in Dobson Units (DU), representing the thickness that a pure ozone layer would have under standard conditions (atmospheric pressure and 0 °C). A normal thickness is 290 DU, approximately equal to a 3-mm layer, while the thickness can be considered critically low when it falls below 220 DU (WMO, 2022). This level is only transgressed over Antarctica during Austral Spring (WMO, 2022), leading to the ozone hole.

Diverse definitions of ODS have been put forth. In theory, any substance that leads to increased stratospheric concentrations of ozone destruction catalysts (NO, OH, Cl, or Br) is an ODS. Within the MP, only volatile compounds containing Cl or Br, subject to regulation under the Protocol, are classified as ODSs (UNEP, 2020a). This subset of ODSs will be referred to as "controlled ODSs". Even with controls in place, controlled ODS emissions emanate from various sources (UNEP, 2023c; FOEN, 2021): I) diffuse emissions from foam insulation materials containing ODSs already in buildings and refrigeration systems; II) losses from refrigeration and air conditioning systems and heat pumps; III) emissions from the disposal of equipment containing ODSs; IV) halon emissions from fire control equipment and systems. Emissions of controlled ODSs have historically been the primary culprits behind ozone layer depletion and the formation of the so-called "ozone hole" (WMO, 2022). The annual occurrence of the ozone hole is influenced by



Stratospheric ozone chemistry

Ozone continuously composes and decomposes in the stratosphere throughout daylight hours via the Chapman mechanism (Eq.1-5).

In the upper stratosphere, where the air is less dense, there is a higher likelihood for O to react and form O_2. Contrastingly, in the lower region of the stratosphere, where O_2 concentration is higher, O tends to react with O_2 and form O_3. Consequently, maximum ozone formation occurs between 15 and 35 km in the lower stratosphere, where O_2 concentration is sufficient and not all UV-C light has been filtered out yet.

Chapman mechanism

Ozone formation

$O_2 + UV\text{-}C \rightarrow 2\,O$ Eq.1

$2\,O \rightarrow O_2$ Eq. 2

$O_2 + O \rightarrow O_3 + heat$ Eq. 3

Ozone destruction

$O_3 + UV\text{-}B \rightarrow O_2^* + O^*$ Eq. 4

$O_3 + O \rightarrow 2\,O_2$ Eq. 5

Two mechanisms of catalytic ozone destruction exist. Nitric oxide (NO), hydroxyl free radical (OH), atomic chloride (Cl) and atomic bromine (Br) can act as catalysts and all have natural and anthropogenic sources.

In both Mechanisms I and II, the initial step of the reaction rate is directly proportional to the concentration of the reactants. Consequently, heightened stratospheric levels of Cl and Br lead to an accelerated rate of ozone destruction.

Catalytic ozone destruction

Mechanism I

$X + O_3 \rightarrow XO + O_2$

$XO + O \rightarrow X + O_2$

$O_3 + O \rightarrow 2\,O_2$

X = NO, OH, Cl, Br

Mechanism II

$X + O_3 \rightarrow XO + O_2$

$X' + O_3 \rightarrow X'O + O_2$

$XO + X'O \rightarrow X + X' + O_2$

$2\,O_3 \rightarrow 3\,O_2$

X = Cl, X' = Cl or Br

NO is formed through the decomposition of nitrous oxide (N_2O). Under steady-state conditions, the majority of chlorine atoms remain in an inactive state (as $ClONO_2$ or HCl), serving as a buffer against the ozone-depleting potential of Cl. Contrarily, stratospheric Br predominantly exists in its active free-radical forms, rendering it 60 times more potent in ozone depletion than Cl.

OH is produced when oxygen in an excited state (O*) reacts with water (H_2O) or methane (CH_4).

Catalyst chemistry

$N_2O + O^* \rightarrow 2\,NO$ Eq. 6

$ClO + NO_2 \rightarrow \underline{ClONO_2}$ Eq. 7

$CH_4 + O^* \rightarrow OH + CH_3$ Eq. 8

$H_2O + O^* \rightarrow 2\,OH$ Eq. 9

$OH + \underline{HCl} \rightarrow H_2O + Cl$ Eq. 10

$CH_4 + Cl \rightarrow CH_3 + \underline{HCl}$ Eq. 11

Inactive chlorine species

Fig. 1. Summary of stratospheric ozone chemistry following the explanation in Baird and Cann (2012a, 2012b).

unique Antarctic weather conditions, prompting the conversion of inactive chlorine into its reactive form, causing massive ozone depletion (Baird and Cann, 2012b).

It is worth mentioning that certain controlled substances, such as CH_3Cl and CH_3Br, also possess natural origins, primarily originating from the ocean (Cadoux et al., 2022). Furthermore, specific chlorine and bromine-containing compounds with extended lifetimes, like halothane, are not yet controlled by the MP (WMO, 2022). All long-lived organic ODSs with lifetimes higher than 0.5 years, irrespective of their controlled status or natural origins, will be collectively referred to as "traditional ODSs".

Due to the extended atmospheric lifetimes of most traditional ODSs, their concentrations in the stratosphere have remained relatively stable over the past two decades (Fig. 2) (Vuppaladadiyam et al., 2022). Still, the consistent trends observed in stratospheric ODS measurements indicate that ODS emissions have been declining, as continuous releases would have led to a build-up of ODSs in the stratosphere. Furthermore, for chemicals with relatively short atmospheric lifetime compared to the enforcement of the MP, such as methyl chloroform (5 years), actual depletion from the atmosphere is observed.

Another class of ODSs comprises halogenated VSLSs with atmospheric lifetimes of less than 0.5 years and may stem from anthropogenic or natural sources (WMO, 2022). In contrast to traditional ODSs, this class also contains substances with iodine. The primary source of stratospheric iodine stems from methyl iodide emissions from the ocean. However, compounds such as iodotrifluoromethane (CF_3I) and methyl iodide (CH_3I) are potential future anthropogenic sources, serving as promising candidates for replacing HFCs, which are being phased out by the Kigali Amendment (Zhang et al., 2020). Although the photochemical processes of ozone destruction by iodine are less well understood than those of bromine and chlorine, iodine has a stronger ozone-depleting effect and must be monitored (Chipperfield and Bekki, 2024; Klobas et al., 2021). A large fraction of VSLSs is destroyed in the troposphere, and the actual effect on the stratosphere depends on emission location, troposphere-stratosphere transport patterns, chemical processing, and deposition processes (WMO, 2022). Despite their short lifetimes, they can still contribute to ozone depletion, particularly when emitted in regions with swift transport or directly into the stratosphere, for example, through the exhaust from rockets employing solid propellants (Dallas et al., 2020). Emissions of chlorinated VSLSs used as solvents or chemical feedstocks have been increasing since the late 2000s and may continue to grow (Chipperfield et al., 2020). Currently, VSLSs are not subject to regulation under the MP (Chipperfield et al., 2020).

A third type of ODSs are NOx, H_2, H_2O, OH, HBr, HI and HCl, henceforth called inorganic ODSs. H_2 can be converted to H_2O, which can be converted to OH. OH, NOx, and HCl act as ozone destruction catalysts in Mechanism I. These substances are not usually considered ODSs since they have too short lifetimes to reach the stratosphere. Natural sources of inorganic ODSs are large volcanic eruptions or wildfires (Chipperfield and Bekki, 2024). However, they may also be emitted directly to the stratosphere from rocket or supersonic aircraft exhaust, thus representing an anthropogenic impact on the ozone layer (Brown et al., 2023). Currently, this group of ODSs is not controlled under the MP.

The fourth type of substances has indirect impacts on ozone depletion. GHGs such as CO_2, N_2O, H_2O, and CH_4 also exert an indirect influence by cooling the stratosphere through solar infrared radiation absorption, thus modifying ozone destruction kinetics (Chipperfield and Bekki, 2024; Fang et al., 2019). The reaction rates of Mechanisms I and II rely on the stratospheric temperature, which is lowered by heightened stratospheric GHG concentrations (Baird and Cann, 2012a). Moreover, N_2O produces NOx, while CH_4 and H_2O produce OH. Both NOx and OH act as catalysts for ozone destruction (Fig. 1). Furthermore, both NOx, OH, and methane additionally influence the conversion of reactive chlorine to its inactive state (Baird and Cann, 2012b).

Beyond stratospheric cooling, GHGs also contribute to climate change, which has multifaceted interactions with the ozone layer. Notably, global warming increases the release of natural ODSs from the ocean to the atmosphere (Cadoux et al., 2022; Fang et al., 2019). Furthermore, increased incidences of wildfires can be expected, potentially leading to large emissions of carbonaceous aerosols to the stratosphere (Chipperfield and Bekki, 2024). Climate change also affects atmospheric circulation patterns, which cause changes in ozone, water vapor, and ODS distributions (Garcia, 2021; Tian et al., 2023). Both stratospheric ozone depletion and climate change may also increase tropospheric ozone formation as higher amounts of UV-B reaching the troposphere will strengthen the photochemical ozone production processes in regions with high NOx concentrations (Barnes et al., 2019) and the stratosphere-to-troposphere circulation patterns (Bernhard et al., 2020; Garcia, 2021). Finally, many ODSs are also potent GHGs, altering the stratospheric temperature and, consequently, the ozone kinetics. These interlinkages are a part of the complex coupling between climate change and ozone depletion (Fig. 3), and continuous monitoring and improved modeling are required to understand these links better. It is

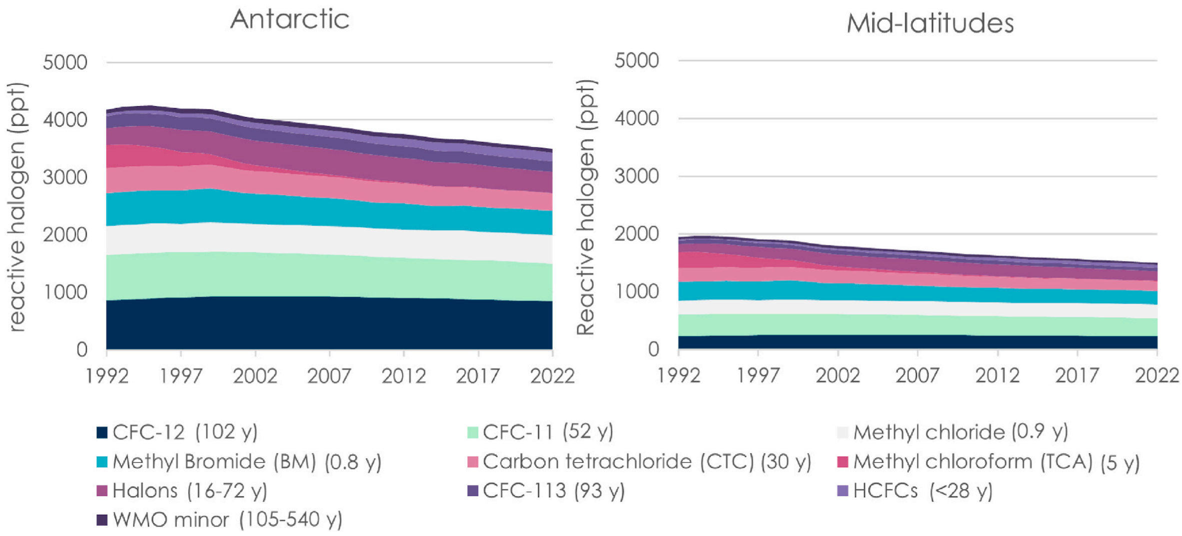


Fig. 2. Stratospheric abundances of long-lived ozone-depleting substances (ODS) in the Antarctic and mid-latitudes in ppt based on NOAA measurements. Atmospheric lifetimes in years (y) are shown in parentheses. CFC = chlorofluorocarbons. Halons represent halon 1211, halon 1301, and halon 2402, all controlled by the Montreal Protocol. WMO minor represents CFC-114, CFC-115, and halon 1201. Adapted from GML (2023).

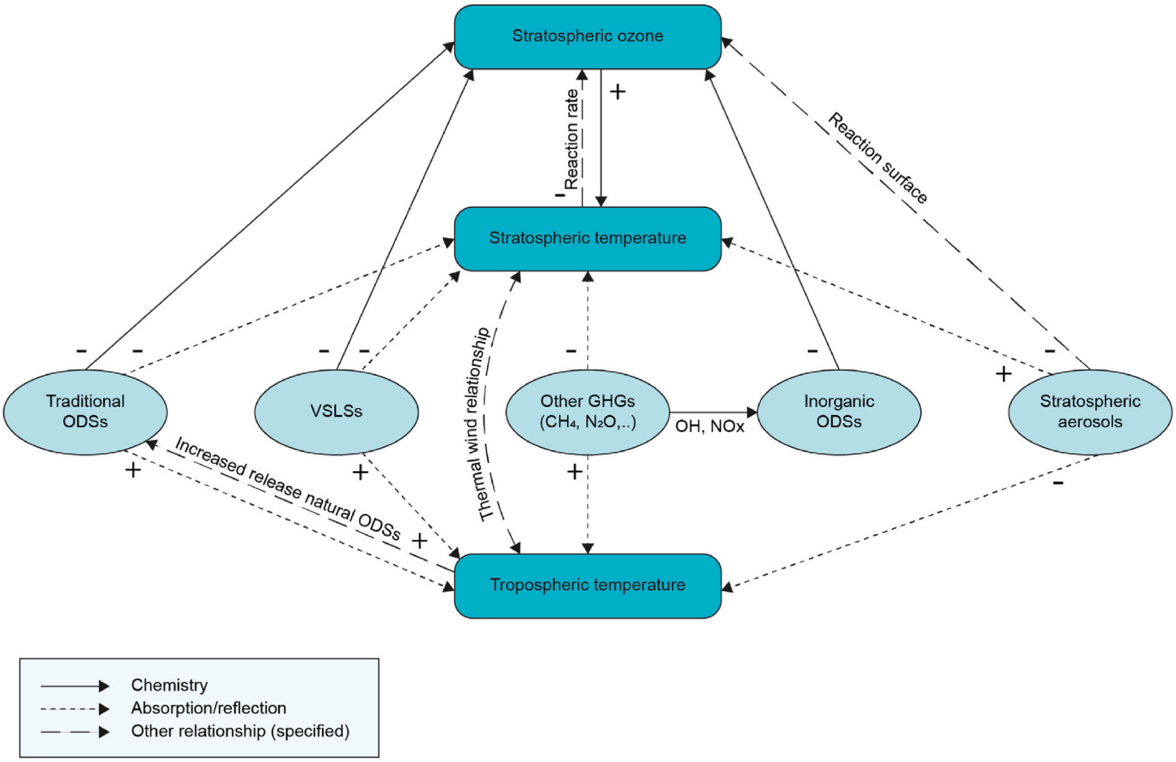


Fig. 3. Different interactions between ozone-depleting substances (ODSs) in light green and atmospheric conditions (stratospheric ozone, temperature) in dark green. Note how ODSs and stratospheric aerosols have opposing effects on stratospheric and tropospheric temperature. Other greenhouse gases (GHGs) refer to any GHG not included in the groups "Traditional ODSs" or "very short-lived substances (VSLSs)". Minus signs refer to decreasing effects, while plus signs refer to increasing effects. Adapted from WMO (2011).

worth noting that despite representing the largest contribution to stratospheric ozone destruction today (Fang et al., 2019), N_2O is not controlled by the MP (WMO, 2022). Yet, in the coming decades, N_2O emissions are expected to rise following the increasing global food demand, as approximately 75% of the anthropogenic emissions originate from fertilizing processes in agriculture (Aryal et al., 2022). Other anthropogenic sources are combustion processes, wastewater treatment, and land-use change (Aryal et al., 2022).

The last type of ODSs is stratospheric aerosols, such as aluminum and soot particles emitted from rocket exhausts, reflective aerosols from volcanic eruptions, aerosols from proposed stratospheric aerosol geoengineering endeavors or soot aerosols from wildfires. These stratospheric aerosols can act as catalysts for ozone destruction (Chipperfield and Bekki, 2024; Dallas et al., 2020; Kravitz and MacMartin, 2020). At the surface of these aerosols, the inactive halogen species can react quickly, increasing the concentration of ozone destruction catalysts (Brown et al., 2023; Ross and Vedda, 2018). Although all types of stratospheric aerosols have been associated with ozone loss, the exact reaction mechanism for each type of aerosol is not yet fully understood, for example, in the case of wildfire particles (Chipperfield and Bekki, 2024). In addition to this direct impact, stratospheric aerosols also heat the stratosphere by absorbing near-infrared radiation (Chipperfield and Bekki, 2024), thereby accelerating ozone destruction kinetics. With the current growth trends in the global space sector, rocket launches could increase significantly in the coming decades, leading to ozone depletion impacts comparable to or even surpassing the effects of all banned ODSs combined (Miraux, 2022).

The relative strength of ODSs in depleting the ozone layer is commonly measured through the ODPs, which are periodically published by the WMO (WMO, 2022). An ODP is defined as the ratio of the change in global stratospheric ozone concentration due to the emission of a given mass of a substance and the respective change due to the same mass emission of CFC-11 and can be written as presented in Equation (12) (Solomon et al., 1992).

$$ODP_i = \frac{\sum_z \sum_\theta \sum_t \Delta O_3(z,\theta,t) for\ i * \cos(\theta)}{\sum_z \sum_\theta \sum_t \Delta O_3(z,\theta,t) for\ CFC-11 * \cos(\theta)} \qquad \text{Eq. 12}$$

where z is the altitude, θ is the latitude, t is the time, and ΔO_3 is the change in ozone at steady state per unit mass emission rate. CFC-11 was chosen as a reference gas, as it was a widely used substance in the 1970s and 1980s (WWMO, 2011). The ODPs refer to a system in a steady state, describing the impact over an infinite time horizon, i.e., the ozone depletion during the entire life of substances is accounted for (Verones et al., 2020). Following Equation (12), the ODP is 1 for CFC-11 and, for the other ODSs, is measured in kg CFC-11 eq/kg.

The ODPs reported in the last WMO assessment (WMO, 2022) were obtained from atmospheric model simulations or by using a semi-empirical relationship, e.g., as reported in Papanastasiou et al. (2018) and represented in Equation (13).

$$ODP_i = \frac{n_{Cl}}{3} * \frac{f_i}{f_{CFC-11}} * \frac{\tau_i}{\tau_{CFC-11}} * \frac{m_{CFC-11}}{m_i} \qquad \text{Eq. 13}$$

where n_{Cl} is the number of Cl atoms in the molecule, 3 is the number of Cl atoms in CFC-11, f is the fractional release factor (dimensionless), τ the global atmospheric lifetime in years, and m is the molecular weight in g/mol. For brominated and iodine molecules, the number of atoms is multiplied by an alpha factor of 60 and ~250, respectively, expressing their relative strength in destroying ozone compared to chlorine. Notably, employing current atmospheric conditions in atmospheric model simulations produces results consistent with those obtained from semi-empirical methods (WMO, 2014).

The effects of heightened UV-B radiation resulting from ozone layer depletion manifest in various dimensions of human health. Notably, skin cancers are caused by overexposure to UV-B radiation, and it is estimated that the effective implementation of the MP will have avoided over 400 million skin cancer incidences by 2100 (UNEP, 2023b). Additionally, prolonged UV-B exposure is linked to cataracts, potentially leading to blindness, particularly in regions with elevated UV-B radiation (UNEP, 2023b). Other potential effects on human health include immunosuppression, photo-aging, and solar keratosis (Bernhard et al., 2020; Hayashi et al., 2006; Struijs et al., 2010). Positive effects also exist, like the reduction in vitamin D deficiency (UNEP, 2023b; Umar and Tasduq, 2022; Zerefos et al., 2023). It is noteworthy that behavioral adaptations, such as sunscreen usage and sun exposure avoidance, can significantly mitigate these health impacts (Bernhard et al., 2020).

Beyond human health, ozone depletion affects various life forms and the biogeochemical carbon cycle. For instance, increased UV-B irradiance adversely affects phytoplankton growth and productivity, influencing the ocean's biological carbon fixation rate (Gao et al., 2018). However, forecasting phytoplankton growth is complex due to their intricate interactions with ocean warming and acidification, which may exhibit synergistic, antagonistic, or neutral effects (Liaqat et al., 2023). Moreover, increased UV-B irradiation also affects plant morphological, molecular, and physiological attributes (Liaqat et al., 2023). Depending on the species and the stressors induced by climate change, these effects can be beneficial or detrimental. In crops, for example, increased UV-B exposure has been associated with an increase in anti-nutritional compounds in some species, while in others, it is associated with an increase in vitamin D (UNEP, 2023b). Therefore, comprehensive studies on the combined effects of increased UV-B exposure and climate change on individual species are essential (UNEP, 2023b). Certain crops experience reduced productivity at higher UV-B levels, yet adaptation mechanisms developed under high UV-B stress can render plants more resilient (Mmbando and Hidema, 2021) and more resistant to biotic stresses (Mmbando, 2023). Differences in UV-B resistance between species can generally lead to ecosystem changes (Hyyryläinen et al., 2018) and biodiversity loss (Bernhard et al., 2020). For example, amphibians are particularly sensitive to the immunosuppressive capacity of UV-B, leading to a higher disease susceptibility and extinction rate (Cramp and Franklin, 2018). Species with slow adaptation capacity, such as trees with long generation times, are susceptible to extinction if the UV radiation alters significantly (UNEP, 2023b). More research is required to understand the wide effects of UV-B on living species, in particular, animals, for which only a few studies have been performed. Therefore, UNEP (2023b) underlines the critical need to develop action spectra for all organisms to assess their biological responses to varying radiation levels. However, for aquatic organisms, the relationship between UV-B and biological responses goes beyond action spectra. In fact, the dose of UV-B radiation received depends on water transparency, the mixed layer depth, and potential ice and snow cover, all of which are directly affected by UV-B radiation themselves (UNEP, 2023b). An additional complicating factor in assessing the effect of UV-B radiation on aquatic organisms is the exposition to a range of other environmental problems, such as ocean warming, eutrophication, and acidification, which may have antagonistic, neutral, or synergistic effects (UNEP, 2023b). Finally, increased UV radiation from both climate change and ozone depletion affects the biogeochemical cycles. For example, it is estimated that the MP has prevented 325–690 billion tonnes of carbon emissions from the generally reduced capacity of plants and soils to store carbon under high UV-B conditions (Young et al., 2021). Furthermore, the photodegradation of organic matter stored in permafrost soils that become exposed to UV radiation due to thawing could lead to the release of large amounts of GHGs (UNEP, 2023b).

Increased UV-B radiation also affects materials, leading to diverse effects such as degradation, discoloration, decreased lifetime, or the production of potentially toxic by-products (UNEP, 2023b). Consequently, at higher UV-B radiation levels, materials regularly exposed outside, such as wood, plastics and composites used in buildings, textiles, and photovoltaic panels, will need either more regular replacements or more protective treatment with UV stabilizers (UNEP, 2023b). Although the use of UV stabilizers has been shown to counteract the effects of UV-B radiation, they may lead to unwanted side effects, such as increased life cycle cost and environmental impacts (UNEP, 2023b). Finally, the enhanced photo-oxidation of plastics increases the production of microplastics and nanoplastics (Andrady et al., 2022), which may bioaccumulate. However, the effects of bioaccumulation of micro and nanoplastics are uncertain (UNEP 2023b). In summary, the consequences of ozone depletion are far-reaching.

3. Methodology

The search aimed to identify contemporary approaches within life cycle impact assessment methods to assess ozone depletion in LCA, focusing on the identification of existing methods and relevant scientific literature. A review protocol consisting of the following steps was defined: strategic search, screening, and data analysis.

3.1. Strategic search

At first, a selection of pertinent LCIA methods was made based on their inclusion in the widely used software for LCA operationalization, namely Activity Browser 2.9.2 (Steubing et al., 2020), Gabi 10.7 (Sphera, 2023), openLCA LCIA methods 2.2.1 (openLCA Nexus, 2023), and SimaPro 9.5 (PRé Sustainability, 2023). For each LCIA method that was identified, the most recent documentation was retrieved. Additionally, a systematic search was conducted in the scientific databases Scopus and Web of Science with the search string (“life cycle assessment" AND (“ozone depletion" OR "ozone layer depletion") AND (characterization OR characterisation OR "impact assessment method")).

3.2. Screening

The LCIA methods were screened by excluding the superseded ones and the ones that excluded ozone depletion as an impact category. The documents identified through the database search were screened based on the following exclusion criteria: conference proceedings, case-studies that merely reported ozone depletion results without further interpretation, and publication year ≤2013. Articles unrelated to LCIA methodology for ozone depletion were not considered suitable for the review.

3.3. Data analysis

The data analysis consisted of a structured synthesis of the results, followed by a descriptive analysis. Although the primary focus of the review is on the impact assessment phase, it is important to acknowledge that the LCA methodological framework comprises four interconnected phases (ISO, 2006): goal and scope definition, life cycle inventory (LCI) analysis, LCIA, and life cycle interpretation. Each step in the LCA process builds upon the preceding ones. The descriptive analysis considers the four phases of the LCA, emphasizing the necessity to consider all phases concurrently to ensure a comprehensive and meaningful impact assessment. For the goal and scope definition, LCI analysis, and life cycle interpretation, existing challenges are based on the reviewed body and complemented with other scientific literature. The challenges in these three phases are disclosed to support the discussion of the findings of the review on LCIA while not being formally part of the systematic review.

The reviewed body was divided into literature and LCIA methods for the structured synthesis. For the literature, the publication year, subject, and a concise description of the relevant content were retrieved and summarized in Table 1. Similarly, for the LCIA methods, a thorough investigation was undertaken for each selected LCIA method to summarize the primary data sources, CFs, and underlying model assumptions.

Table 1
Description of the 15 life cycle impact assessment methods selected for this review. Legend: M = midpoint, E = endpoint, n.a. = not available, ODS = ozone-depleting substance.

Impact assessment method	# of substances	N_2O included	Time horizon	Type	Endpoint effects included	Normalization	Weighting
TRACI 2.1 (Bare, 2011)	90	No	Infinite	M	No	US and Canadian ODS emission 2008	n.a.
EPS2015d (Steen, 2015)	101	No	Infinite	E	Skin cancer, cataract	n.a.	Willingness-to-pay
CML-IA baseline (Oers, L. van, 2016)	23	No	Infinite	M	n.a.	Per capita global ODS emissions 1995	n.a.
CML-IA non-baseline (Oers, L. van, 2016)	15	No	5,10,15,20,25,30,40 years	M	n.a.	Per capita global ODS emissions 1995	n.a.
ReCiPe 2016 -Individualist (Huijbregts et al., 2016)	22	Yes	20 years	M/E	Skin cancer (Hayashi et al., 2006)	n.a.	n.a.
ReCiPe 2016 -Hiërarchisch (Huijbregts et al., 2016)	22	Yes	100 years	M/E	Skin cancer (Hayashi et al., 2006)	n.a.	n.a.
ReCiPe 2016 -Egalitarian (Huijbregts et al., 2016)	22	Yes	Infinite	M/E	Skin cancer, cataract (Hayashi et al., 2006)	n.a.	n.a.
Environmental prices (De Bruyn et al., 2018)	25	No	100 years	M/E	Skin cancer, agricultural crops (Hayashi et al., 2006)	n.a.	Damage-costs
Impact World+ (Bulle et al., 2019)	25 (midpoint) 23 (endpoint)	No	Infinite	M/E	Skin cancer, cataract (Struijs et al., 2010) et al., 2010)	Global damage 2000	n.a.
LC-IMPACT all effects, infinite (Verones et al., 2020)	21	Yes	Infinite	E	Skin cancer, cataract (Hayashi et al., 2006)	n.a.	n.a.
LC-IMPACT all effects, 100 years (Verones et al., 2020)	21	Yes	100 years	E	Skin cancer, cataract (Hayashi et al., 2006)	n.a.	n.a.
LC-IMPACT certain effects, infinite (Verones et al., 2020)	21	Yes	Infinite	E	Skin cancer (Hayashi et al., 2006)	n.a.	n.a.
LC-IMPACT certain effects, 100 years (Verones et al., 2020)	21	Yes	100 years	E	Skin cancer (Hayashi et al., 2006)	n.a.	n.a.
Ecological scarcity 2021 (FOEN, 2021)	42	No	Infinite	M	n.a.	Swiss emissions 2021	Distance-to-target (Swiss emissions 2040)
Environmental Footprint 3.1 (Andreasi et al., 2023; Fazio et al., 2018)	23	No	Infinite	M	n.a.	Per capita global emissions 2010	Hybrid evidence-based and expert-judgement

4. Results and discussion: ozone depletion in LCA

Based on the identification of LCIA methods in existing software and literature search, 28 LCIA methods and 83 abstracts have been screened. From this screening, 15 distinct methods (Table 1) and 5 publications (Table 2) have been identified and further analyzed in Section 4.3.

4.1. Goal and scope definition

In an LCA study, the definition of the goal consists of the general framework: the intended applications, the limitations of the study, the reasons for the study, the target and type of audience, and its commissioner. In line with the goal, the scope is defined, specifying the studied system, the system boundaries, and the environmental problems (impact categories) considered (Hauschild et al., 2018).

Table 2
Overview of publications included in the review.

Source	Subject	Relevant content
Bjørn and Hauschild (2015)	Normalization	Carrying capacity-based normalization factors method
Crenna et al. (2019)	Normalization	Inventories used for normalization factors in Environmental Footprint (EF) 3.1
Hauschild et al. (2013)	Characterization	Classification of best available characterization models at midpoint and endpoint level.
Miao et al. (2021)	Weighting	Example of distance-to-target weighting factors for China based on the Montreal Protocol
Sala et al. (2016)	Normalization	Inventories used for normalization factors for EU-27 in 2010

In this phase, the relevance of ozone depletion as an impact category can be questioned. If ozone depletion is no longer a significant concern, there might be no need to include it in LCA studies, and efforts to improve existing methods may not be justified. Since the ozone layer is recovering, the health impacts from historical damage are expected to decrease in the future. This perspective is supported by LCA experts who ranked ozone depletion as the second-least important impact category for human health in Environmental Footprint (EF) 3.1 (Andreasi et al., 2023; Fazio et al., 2018; Sala and Cerutti, 2018). Furthermore, a global "LCA of the world" based on the year 2000 inventory of anthropogenic emissions and extractions using IMPACT World+ (Bulle et al., 2019) demonstrated a negligible contribution of ozone depletion to total human health damage. However, considering the identified limitations in characterization discussed in section 3.3.1, the reliability of these results must be questioned. Others contend that ozone depletion remains relevant in LCA, given the goal of assessing a wide range of potential impacts (Lane and Lant, 2012).

Additionally, the emergence of new potential threats to the ozone layer, such as large-scale deployment of new technologies, must be considered. For example, ozone depletion remains an important impact category for the space sector. Additionally, model simulations and historic volcanic eruptions demonstrate that large-scale deployment of geoengineering projects, such as injecting sulfate aerosols into the stratosphere, could significantly impact stratospheric ozone chemistry and transport mechanisms (Klobas et al., 2017; Kravitz and MacMartin, 2020; Østerstrøm et al., 2023; WMO, 2022). Similarly, it remains an important impact category for the agricultural sector due to fertilizer-related N_2O emissions. Furthermore, ozone depletion is relevant for the chemical industry, as data gaps between ODS consumption reports and atmospheric measurements point to potential leakage issues from ODS serving as precursors or intermediates (WMO, 2022). Finally, even if the likelihood of critically depleting the ozone layer is currently low, the consequences related to its depletion affect all life forms on Earth. Given this risk, it is appropriate to continue maintaining and improving the ozone depletion impact assessment.

4.2. Life cycle inventory analysis

Another crucial aspect of conducting a meaningful impact assessment is using a relevant LCI. The purpose of this phase is to quantify all the flows to and from the biosphere in the different phases of the life cycle of the analyzed system. Previous studies have revealed that for construction products (Silva et al., 2020) and heavy-duty transport (van den Oever et al., 2023), the predominant contribution to ozone depletion originates from background processes. Background processes in LCA refer to the processes that are part of the supply chain of the studied product system (Mendoza Beltran et al., 2020), e.g., the energy required to produce a refrigerant. Data on background processes is typically derived from LCI databases, such as the ecoinvent database (Wernet et al., 2016). Therefore, the accuracy of LCI databases is pivotal in achieving reliable ozone depletion impact assessments, except in cases where product systems incorporate refrigerants with high ODP in their foreground model. However, conventional LCA databases are lacking in representing the phase-out of ODSs mandated by the MP (Puricelli et al., 2022; Roibás et al., 2018; van den Oever et al., 2023). For example, Roibás et al. (2018) found that generic pesticide datasets in the United States environmentally-extended input-output (USEEIO) database (Yang et al., 2017) contain methyl bromide, whereas the import and production of this substance have been banned in developed countries since 2005. They also found that, when using the ecoinvent v3.1 database (Wernet et al., 2016), the biggest impacts were linked to fugitive emissions of halon 1211 and halon 1301 from fire extinguishers and cooling systems (present in crude oil production and natural gas production installations). Puricelli et al. (2022) made the same observation in their LCA of passenger cars.

The import and production of both halons have been banned in all countries since 2010 (UNEP, 2020a). Although existing installations are still allowed to recycle halon 1211 and halon 1301, it can be expected that the stocks will steadily decrease in the coming years. This limitation implies that utilizing such databases for ozone depletion impact assessment may lead to significant overestimations of the ODP associated with banned substances (Bueno et al., 2016; Hauschild et al., 2018; Senán-Salinas et al., 2022). The implications of these overestimations are particularly concerning for prospective studies, as the usage of banned substances is projected to decrease over time. Hence, it becomes imperative to address this issue by updating background databases, such as the ecoinvent database, to ensure a comprehensive reflection of both global regulations (such as the MP) and regional legislations (e.g., the Ozone Regulation in the European Union) (Senán-Salinas et al., 2022). On the other hand, qualitative estimates on ODS leakages from existing installations and insulating foams are limited and uncertain (WMO, 2022) and must be added to existing LCI databases. Only through such updates can accurate and reliable assessments of ozone depletion impact be assured, facilitating informed decision-making and effective policy implementation. Substituting ODSs will also affect climate change and other impact categories. For example, the first ban on CFCs stimulated the use of HFCs, but the high global warming potential of some of them led to their limitation through the Kigali Amendment. Hydrofluoroolefins (HFOs) are gradually replacing HFCs. However, the production of HFOs requires CCl_4, whose usage to produce HFOs is not controlled by the MP (WMO, 2022), thus potentially leading to high emissions of CCl_4. Moreover, certain HFOs are converted to trifluoroacetic acid in the atmosphere, which is a toxic substance to some organisms (WMO, 2022). UNEP (2023b) concluded that the compound is unlikely to cause adverse effects in terrestrial and aquatic organisms but that continued monitoring is advisable. As alternatives to ODSs and HFCs, nonfluorinated refrigerants (i.e., ammonia, carbon dioxide, propane, and isobutane) are gaining interest (WMO, 2022).

Regarding the foreground model, ensuring the availability of all relevant emissions is crucial. The challenges associated with this phase are case-specific, but some illustrative examples of risks can be provided. For instance, ongoing investigations into new rocket and aviation propellants are noteworthy, but their exhaust emissions are often absent from environmental assessments due to a lack of in-situ exhaust measurements (Brown et al., 2023; Dallas et al., 2020). For agricultural processes, accurate N_2O emission inventory data is a bottleneck (Lane and Lant, 2012; Portmann et al., 2012). To enhance the foreground models of chemicals, it becomes essential to quantify ODS leakages accurately. While the present atmospheric ODS monitoring tools possess insufficient analytical power for such assessments, it is imperative to broaden the observation network's geographic coverage (Fang et al., 2019) and undertake more systematic investigations into monitoring "unanticipated emissions" stemming from chemical intermediates, as emphasized by recent research (Fang et al., 2019).

4.3. Review findings: life cycle impact assessment

4.3.1. Characterization

During the LCIA stage, CFs are applied to an LCI result to obtain the common unit of the impact category indicator. These CFs are categorized into two distinct types: midpoint and endpoint. In the case of endpoint categories, the characterization model encompasses the entirety of the cause-effect chain, starting from emissions and culminating in impacts on so-called endpoints or areas of protection (AoP). The results are articulated in units such as disability-adjusted life years (DALYs) for the AoP human health or analogous metrics. Conversely, midpoint categories represent a state along the cause-effect chain (Hauschild et al., 2018). In the case of ozone depletion, the midpoint CF of an ODS is quantified through the ODP. The impact of ozone depletion is calculated by using Equation (14).

$$Impact_{midpoint} = \sum_i (m_i \bullet ODP_i) \qquad \text{Eq. 14}$$

where: m_i and ODP_i are, respectively, the mass and the ODP of substance *i*. The impact of ozone depletion is, therefore, expressed in kg CFC-11-equivalents.

The endpoint characterization is calculated by following Equations (15)–(17) (from Huijbregts et al. (2016)):

$$F = \Delta EESC_{CFC-11} \ * \ \sum_k \sum_q \sum_j \Delta UVB_{k,q} * EF_{k,q,j} * DF_j \qquad \text{Eq.15}$$

$$ODP_i = \frac{\Delta EESC_i}{\Delta EESC_{CFC-11}} \qquad \text{Eq. 16}$$

$$Impact_{endpoint} = ODP_i * F \qquad \text{Eq. 17}$$

where: F is the midpoint to endpoint factor in DALY/kg CFC-11-eq, $\Delta EESC_{CFC\text{-}11}$ is the change in equivalent effective stratospheric chlorine (EESC) caused by the emission of 1 kg of CFC-11. For substances containing bromine or iodine, the EESC is calculated by using the alpha factor. $\Delta EESC_i$ is the change in EESC caused by the emission of substance j, $\Delta UVB_{k,q}$ is the increase in UV-B radiation (kJ/m^2) of bandwidth *q* in region *k*. $EF_{k,q,j}$ describes the extra incidence of disease *j* in region *k* caused by UVB radiation of bandwidth *q*, and DF_j describes the damage to human health caused by the incidence of disease *j*. For the underlying assumptions in the exposure ($\Delta UVB_{k,q}$), effect ($EF_{k,q,j}$) and damage (DFj) modeling, the reader is referred to Hayashi et al. (2006) and Struijs et al. (2010). Note that in LCA, the ratio in the change in global stratospheric ozone concentration (see Eq. (12)) is approximated with the ratio in the change of EESC.

When reviewing the characterization models of currently relevant LCIA methods (Table 1, Fig. 4), it becomes clear that they differ in the time horizon, the CF data sources, the number of substances included in

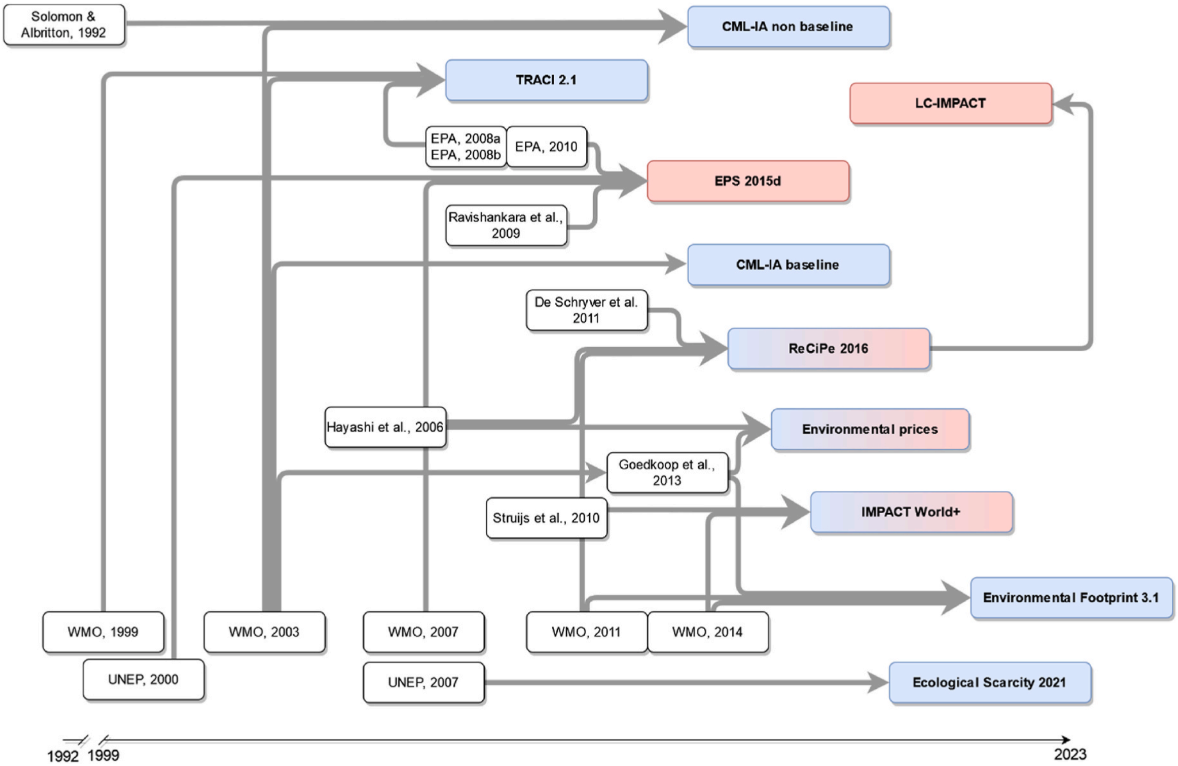


Fig. 4. Overview of the life cycle impact assessment methods selected in this review (Table 1). White ovals represent data sources for ozone depletion potentials and model assumptions. Blue ovals refer to midpoint methods, while red ovals represent endpoint methods. (De Schryver, 2011; EPA, 2010, 2008a, 2008b; Hayashi et al., 2006; Goedkoop et al., 2013; Ravishankara et al., 2009; Solomon and Albritton, 1992; Struijs et al., 2010; UNEP, 2007, 2000; WMO, 2014, 2011, 2007, 2003, 1999).

the characterization model, their consideration of midpoint or endpoint categories, and the encompassed endpoint effects.

While most LCIA methods follow the infinite time horizon approach, others also provide the impacts occurring during a finite time horizon, e.g., 100 years. For the CML-IA non-baseline method (Oers, L. van, 2016), time-dependent ODPs from Solomon and Albritton (1992) were used to estimate the impact after 5, 10, 15, 20, 25, 30, and 40 years. ReCiPe 2016; Huijbregts et al., (2016) used the relationship from De Schryver (2011) to convert the steady-state ODPs to time-dependent ODPs as described by equations (18) and (19):

$$ODP_{t,x} = ODP_{inf,x} * \frac{F_{t,x}}{F_{t,CFC-11}} \qquad \text{Eq. 18}$$

$$F_t = 1 - e^{(-t-3)*k} \qquad \text{Eq. 19}$$

where F_t is the fraction of the total damage caused by an ODS during the first t years, and k is the removal rate of ODS in y^{-1}.

The reviewed characterization methods suffer from several limitations. Firstly, none of the reviewed LCIAs has yet implemented the newest ODPs by WMO (2022) and some methods are based on old WMO assessments that require updates (Fig. 4).

In addition, most of the existing LCIA methods do not include all substances controlled by the MP. The last version of the UNEP Handbook for the Montreal Protocol (UNEP, 2020a) enlisted 93 CFs, sometimes expressed in terms of range, in the case of isomers. Despite relying on relatively old data sources, TRACI 2.1 (Bare, 2011) is the midpoint LCIA method, including the highest number of CFs (90). Ecological Scarcity 2021; FOEN, 2021) follows, with 42 substances included. CML-IA baseline (Oers, L. van, 2016), EF 3.1 (Andreasi et al., 2023; Fazio et al., 2018), Impact World+ (Bulle et al., 2019; ReCiPe, 2016; Huijbregts et al., 2016) include a range of 22–25 substances. Lastly, the CML-IA non-baseline method (Oers, L. van, 2015) accounts for 15 CFs. It is recommended that the coverage of ODSs in current LCIA methods is increased, as ODPs are already available in the last version of UNEP Handbooks or WMO Assessments.

Another limitation is that substances not controlled by the MP are only sparsely included in LCIA methods. This review identified 32 substances not controlled by the MP but, instead, reported in WMO (2022). These substances can exert an impact, regardless of their presence in current international agreements. Only 5 of them were sparsely included in the LCIA methods. One example of such a substance is N_2O. As anthropogenic N_2O emissions, and not halocarbons, are the greatest source of human-induced stratospheric ozone depletion today (WMO, 2022), their impact is important (Lane and Lant, 2012). From the reviewed LCIA methods, only ReCiPe 2016; Huijbregts et al. (2016) and LC-IMPACT (Verones et al., 2020) include preliminary CFs for N_2O emissions.

The consideration of stratospheric aerosols is currently lacking in characterization models, as shown in Fig. 6. However, they are known to affect stratospheric temperature, transport, and chemical reactions in the atmosphere (e.g., ozone destruction and formation) (WMO, 2022). Consequently, it is expected that large increases in stratospheric aerosols, for example, due to the large-scale deployment of rocket launches, stratospheric aerosol injection, and supersonic aircraft, would affect the ozone layer. Currently, the number of studies and model simulations on the effects of aerosols on ODSs and the ozone layer is limited (WMO, 2022), and existing studies show both positive and negative results (Tracy et al., 2022). These divergent outcomes may be caused by the timing of the injections, the location, and the vast heterogeneity of aerosol particles, which is currently poorly represented in climate-chemistry models (WMO, 2022). Consequently, deriving CFs for aerosols is likely not yet feasible. More laboratory studies and climate-chemistry model simulations are required to understand the coupling between fluid mechanics and chemistry at aerosol particles (Tuck, 2021; WMO, 2022).

Another limitation is that ODPs are calculated using current atmospheric conditions, while the ODP of ODSs depends on these. In fact, atmospheric conditions and CH_4, CO_2, and halocarbon concentrations are considered the biggest sources of uncertainty regarding future stratospheric ozone levels (WMO, 2022). Considering future atmospheric conditions is important for accurate ODP assessments, particularly for N_2O, the biggest source of ozone depletion in the coming decades (Portmann et al., 2012; Ravishankara et al., 2009; Revell et al., 2015; Singh and Bhargawa, 2019). Under current atmospheric conditions, the ODP of N_2O (0.017 kg CFC-11 eq/kg) is in a similar range to many HCFCs, but a return to pre-industrial chlorine concentrations, *ceteris paribus* would increase it by 50% (Ravishankara et al., 2009). This effect can be explained by the reaction of NO_2 with ClO (Fig. 1), fixing both the NO_2 and ClO in the inactive reservoir. In addition, CO_2 and CH_4 both have an overall positive effect on the N_2O ODP, and model simulations indicate that the ODP for a scenario considering high effects on climate change (representative concentration pathway (RCP) 8.5) would be 200% higher than for a low climate change scenario (RCP 2.6) (Revell et al., 2015). However, these simulations did not consider the climate change-induced strengthening of the Brewer-Dobson circulation. This global circulation pattern consists of the upwelling of tropospheric air in the tropics, its transport to higher latitudes, and downward transport at the poles, and its acceleration would reduce the stratospheric N_2O lifetime (Revell et al., 2015). The ODP of iodine-containing substances has also been found to be sensitive to atmospheric conditions: the alpha factor of iodine could be 45% higher under RCP 8.5 in 2100 compared to 1980, while it would barely change in RCP 2.6 (Klobas et al., 2021). In light of these effects, developing a set of climate change-dependent ODPs using climate-chemistry models is recommended. Collaboration with atmospheric scientists will be required for the development of these CFs. As prospective LCI databases become more common in LCA practice, scenarios for the background and the characterization model must be consistent with each other and with existing climate change scenarios. Therefore, it is recommended that prospective CFs should be developed based on the existing shared socio-economic pathway (SSP) storylines and RCPs.

The midpoint characterization models do not consider regional differentiation, meaning that for the calculation of the midpoint impact in Eq. (14), globally integrated values for ODP_i and m_i are used. The rationale behind this is that the transport time from the emission point to the stratosphere is long (3–5 years) (WMO, 2022). Due to horizontal tropospheric transport processes, an ODS might enter the stratosphere at a completely different region than where it was emitted (Solomon et al., 1992). Additionally, due to the long stratospheric lifetimes of ODSs and the stratospheric transport processes, the impact of one ODS molecule emitted is not restricted to one specific region (Solomon et al., 1992). However, if N_2O, rocket exhaust emissions, and VSLSs would be included in midpoint characterization models, regional aspects must be considered. Although N_2O contributes to ozone depletion at mid-latitudes and the tropics, its contribution to arctic ozone destruction, dominated by the release of inactive halogen release in specific weather conditions, is negligible (Ravishankara et al., 2009). For any substances emitted from rocket launches (water vapor, N_2O, HCl, etc.) directly to the stratosphere, direct impacts in the wake of the rocket occur (Dallas et al., 2020), which should not be globalized. Finally, for VSLSs, local conditions can determine whether they reach the stratosphere within their lifetime and, thus, whether or not they can destroy stratospheric ozone (Zhang et al., 2020).

Progress in the development of endpoint characterization models has been slow in the past decades. ReCiPe 2016; Huijbregts et al. (2016) and LC-IMPACT (Verones et al., 2020) used the damage functions developed for the Japanese LCIA LIME (Hayashi et al., 2006). On the other hand, IMPACT World+ (Bulle et al., 2019) adopts the damage model proposed by Struijs et al. (2010), which improves the human health damage functions of Hayashi et al. (2006) by incorporating factors like future changes in population density, life expectancy, and skin color distribution. EPS2015d (Steen, 2015) uses excess cancer incidence and mortality rate estimates and cataract incidence reported by EPA (2010). Note that, in contrast to the midpoint impact, the endpoint impact is spatially differentiated, as the UV-B increase due to ozone loss is region-specific, as well as the human health damage, which depends on skin color and age distribution (Hayashi et al., 2006; Struijs et al., 2010). Still, it is evident that since 2010, there have been no significant advancements in ozone depletion endpoint characterization.

The existing endpoint characterization models suffer from several limitations. Foremost, important updates have been published in the ODP_i of various substances, the UV-B radiation projections ($\Delta UVB_{i,q}$ in Eq. (15)), the dose-response relationships for the different health effects ($EF_{k,q,j}$ and DF_j in Eq (15)) (EPA, 2020). It is recommended that the existing endpoint methods include these data in their models. Furthermore, existing methods only include skin cancer and cataract effects (Table 2), while all other human health effects are excluded. Moreover, the AoPs ecosystem quality and resources are disregarded.

The existing limitations for assessing ozone depletion at the midpoint and endpoint level are summarized in Fig. 5. Given these numerous limitations, it becomes evident that the current midpoint characterization models must be further developed, and endpoint characterization models are not mature enough for a recommendation (Hauschild et al., 2013) since they capture only a fraction of the damage induced by ozone layer depletion. In order for the LCA community to do so, effect factors and damage factors for the excluded health effects, including positive effects, must be further investigated. Similarly, the dose-response relationship between UV-B and net primary production from Young et al. (2021) could be used to define CFs for ecosystem quality. This AoP could be further refined using species-specific dose-response relationships for terrestrial and aquatic species. Finally, relationships between increased UV-B radiation and increased material breakdown (leading to increased material replacement and consumption) must be established to include the effects of ozone depletion on the AoP resources. Although current knowledge of plastic degradation might be insufficient to do so (Andrady et al., 2022), UV-induced wood degradation has been extensively studied (UNEP, 2023b). Including all the discussed effects presents a daunting challenge, requiring substantial amounts of additional data and sophisticated modeling techniques to account for the synergistic and antagonistic effects with other impact categories, such as climate change and acidification. Due to that, different scientific communities, including the environmental effects community, must collaborate towards a harmonized terminology and allow for a correct transfer of knowledge to the LCIA methods.

4.3.2. Normalization and weighting

Normalization and weighting are optional steps in LCA that can be applied to increase the interpretability of the results. Normalization expresses the characterized results relative to a reference state, for example, national or global emission inventories, while weighting offers a mechanism for addressing trade-offs among distinct impact categories (Hauschild et al., 2018).

Most LCIA methods offer normalization factors derived from outdated global inventories dated before 2010 (Table 2). EF 3.1 (Andreasi et al., 2023; Fazio et al., 2018) provides the most recent normalization factors based on a global inventory for 2010. However, it should be noted that the completeness of this inventory is estimated to be below 30% (Crenna et al., 2019). Other normalization methods were found in the literature (Table 2). Sala et al. (2016) have provided CFs based on the ODS emissions of the European Union in 2010. They also mention that the inventory robustness is a limitation, particularly bromine source gases (e.g., halon 1211, methyl bromide), which are less reported. Bjørn and Hauschild (2015) have proposed a different approach and derived normalization factors based on the planetary boundary concept (Steffen et al., 2015).

The current normalization factors lack the inclusion of N_2O emissions and other substances that have not been incorporated into existing impact assessment methods. Consequently, currently, the scientifical

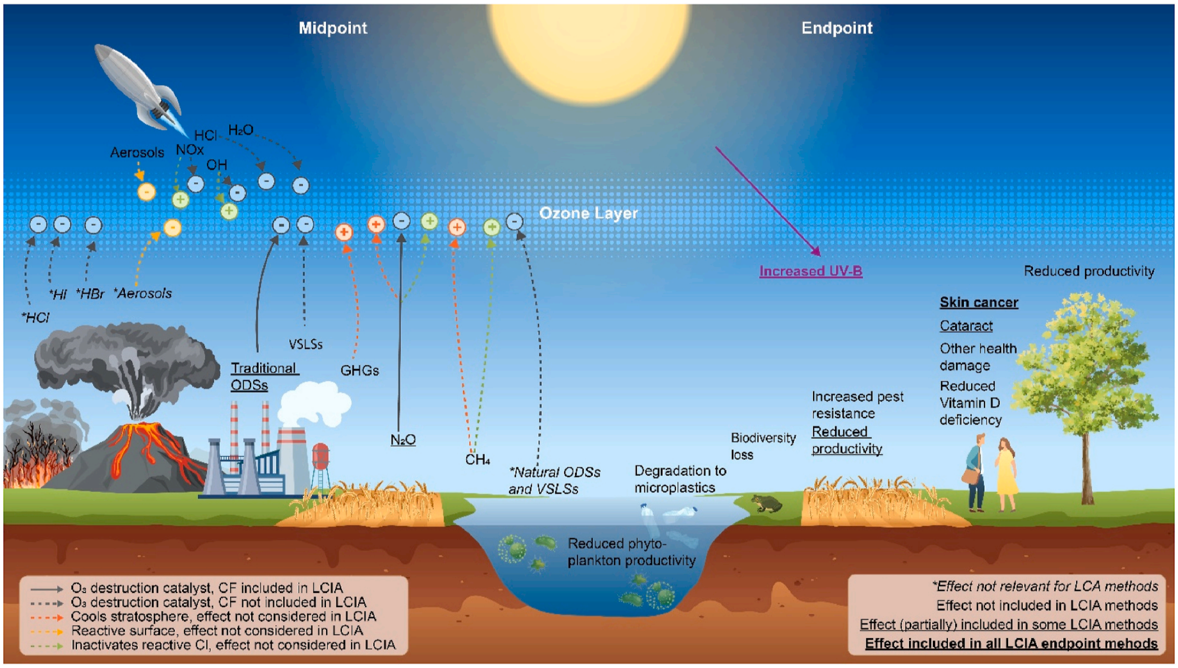
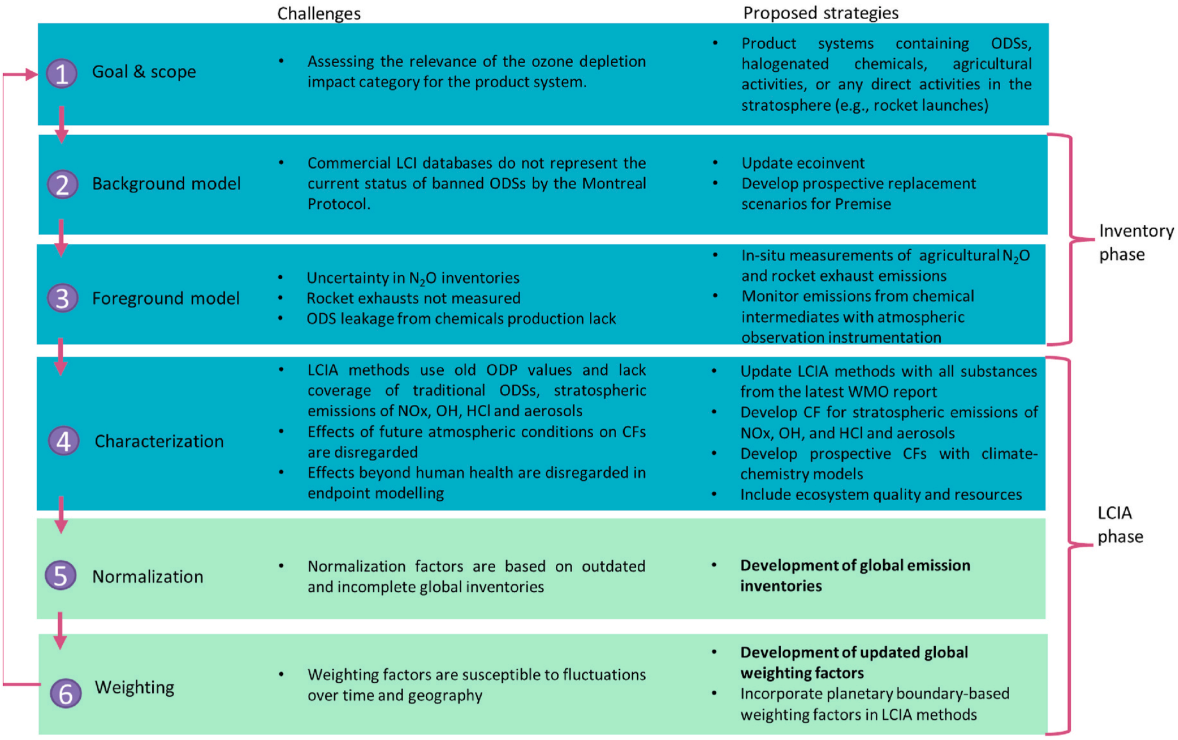


Fig. 5. Summary of the limitations and challenges related to midpoint and endpoint characterization. Plus signs refer to positive effects on the ozone layer, and minus signs to negative effects. GHG = greenhouse gas, LCA = life cycle assessment, LCIA = life cycle impact assessment, ODS = ozone-depleting substance, VSLS = very short-lived substance. Illustration by: Francesco Gavardi.



	Challenges	Proposed strategies	
① Goal & scope	• Assessing the relevance of the ozone depletion impact category for the product system.	• Product systems containing ODSs, halogenated chemicals, agricultural activities, or any direct activities in the stratosphere (e.g., rocket launches)	
② Background model	• Commercial LCI databases do not represent the current status of banned ODSs by the Montreal Protocol.	• Update ecoinvent • Develop prospective replacement scenarios for Premise	Inventory phase
③ Foreground model	• Uncertainty in N_2O inventories • Rocket exhausts not measured • ODS leakage from chemicals production lack	• In-situ measurements of agricultural N_2O and rocket exhaust emissions • Monitor emissions from chemical intermediates with atmospheric observation instrumentation	
④ Characterization	• LCIA methods use old ODP values and lack coverage of traditional ODSs, stratospheric emissions of NOx, OH, HCl and aerosols • Effects of future atmospheric conditions on CFs are disregarded • Effects beyond human health are disregarded in endpoint modelling	• Update LCIA methods with all substances from the latest WMO report • Develop CF for stratospheric emissions of NOx, OH, and HCl and aerosols • Develop prospective CFs with climate-chemistry models • Include ecosystem quality and resources	LCIA phase
⑤ Normalization	• Normalization factors are based on outdated and incomplete global inventories	• **Development of global emission inventories**	
⑥ Weighting	• Weighting factors are susceptible to fluctuations over time and geography	• **Development of updated global weighting factors** • Incorporate planetary boundary-based weighting factors in LCIA methods	

Fig. 6. Summary of challenges related to ozone depletion assessment in LCA. Light green steps are optional. Future work in bold is ongoing. CF = characterization factor, LCI = life cycle inventory, LCIA = life cycle impact assessment, ODS = ozone-depleting substance, WMO = world meteorological organization.

accuracy of normalized results on ozone depletion should be increased, as it would allow the comparison of the contributions of different sectors (e.g., agriculture vs. space travel) to ozone layer depletion. In this regard, the Global Guidance for Life Cycle Impact Assessment Indicators and Methods (GLAM) initiative (Life Cycle Initiative, 2024) will publish an updated normalization reference using recently published data. Unlike prior studies using emission data differentiated by individual countries (Laurent et al., 2011; Sleeswijk et al., 2008), the GLAM inventory uses global emission data, which are more consistent. ODS emissions data for 2022 were sourced from the WMO 2022 Scientific Assessment of Ozone Depletion, whereas supplementary N_2O emissions data were obtained from the Emissions Database for Global Atmospheric

Research (EDGAR) v.7 (EC and JRC, 2021) and Minx et al. (2021).

Three different weighting methods are present in the reviewed LCIA methods. Ecological Scarcity 2021; FOEN, 2021) provides distance-to-target weighting factors, which express the normalized results relative to the Swiss policy targets for 2040. Similarly, Miao et al. (2021) developed weighting factors for China in 2030 based on the MP policies. The drawback of these methods is their limited geographic representativeness. EF 3.0 (Fazio et al., 2018) developed combined general public and expert panel-based weighting factors still used in EF 3.1 (Andreasi et al., 2023; Fazio et al., 2018). Ozone depletion ranked middling for all human health-related impacts according to the general public, while the LCA expert panel deemed it the second-least significant impact category. However, the drawback of the weighting factors developed by these panels is that they represent the panel's *perception* rather than the absolute hierarchy of ozone depletion's significance. Finally, the methods Environmental Prices and EPS 2015d; De Bruyn et al. (2018); Steen (2015) each adopt monetary weighting factors, albeit founded on divergent valuation methodologies. EPS2015d (Steen, 2015) employs a willingness-to-pay framework, while Environmental Prices (De Bruyn et al., 2018) integrate damage-cost assessments. The limitation common to all the reviewed weighting methodologies lies in their susceptibility to fluctuations over time and geography, owing to the dynamic nature of policies, perceptions, and prices. Therefore, the authors advocate for developing weighing approaches with a global scope. Such global weighting schemes are currently under development in the GLAM initiative, using conjoint analysis and multi-criteria decision analysis, as well as a global survey of more than 3000 respondents from countries spanning various income levels. Another possible development is the global extension of the approach from Miao et al. (2021) based on the MP. Finally, recent developments (Bjørn et al., 2015; Sala et al., 2016; Vargas-Gonzalez et al., 2019) that aim to develop weighting factors based on planetary boundaries (Steffen et al., 2015) could be particularly relevant.

Although their scientific robustness is often questioned, normalization and weighting are considered valuable for decision-making (Pizzol et al., 2017), and they may help answer the question: is ozone depletion still a relevant impact category today? This could be done by performing an "LCA of the world", similar to the one conducted by Bulle et al. (2019), but with updated LCI databases, characterization, normalization and weighting factors.

4.4. Life cycle interpretation

In the last phase of an LCA study, the results obtained are presented and analyzed considering the goal and scope. The interpretation phase comprises a completeness check, a consistency check, a sensitivity analysis, identifying key issues, and communicating conclusions, limitations, and recommendations (Laurent et al., 2020). The identified challenges in this review show that the inventory and LCIA phases severely lack completeness. Therefore, in the interpretation phase of ozone depletion impact results, LCA practitioners must consider these limitations. Additionally, both LCA practitioners and policy-makers must be aware of the scope of LCA, which concerns human-produced products and services. However, natural phenomena, such as large volcanic eruptions and wildfires, can also contribute significantly to stratospheric ozone depletion and delay the recovery by several years (Chipperfield and Bekki, 2024; Eric Klobas et al., 2017; Østerstrøm et al., 2023). These are not covered by LCA but must instead be studied by other research fields for a comprehensive understanding of the threads of the ozone layer.

The strategies proposed in this review to address the challenges of ozone depletion in LCA are summarized in Fig. 6. This figure can serve both as a roadmap for improving LCA methods as well as a checklist for identifying study limitations in the interpretation phase of LCA.

5. Outlook and conclusions

This review has shown that the currently available LCA ozone depletion practices are not up to date with the state-of-the-art of stratospheric ozone science. The combined effects of outdated background databases and incomplete impact assessment methods must be further investigated to understand their full scope. Therefore, some strategies that could be developed to address the identified shortcomings are proposed.

Foremost, in the short term, a thorough review of commercial LCI databases is necessary to validate the accurate representation of the ODS phase-out mandated by global environmental legislation. Additionally, the inventories of key contributing sectors must be revised, paying special attention to the leakage emissions of ODSs from chemical precursors and intermediates. In instances of inaccuracies, efforts should focus on identifying and rectifying outdated datasets. However, a one-time database update would not be sufficient, as the phase-out of ODSs and their substitutes is still in progress. Therefore, regular updates are required. Another approach is the development of a prospective background scenario to account for ODS substitution, considering the approach taken in Premise (Sacchi et al., 2022), a tool that creates prospective versions of a given LCI database. It systematically applies modifications to LCI inventories from key energy-consuming sectors to account for future developments based on scenarios provided by integrated assessment models or the user. The suggested ODS phase-out scenario would have temporal and geographical differentiation, considering varied country-specific phase-out timelines and the emission lag associated with existing ODS stocks. The envisaged background scenario holds the potential to substantially influence the climate change and ozone depletion impacts associated with many product systems. Moreover, it would allow to assess the broader environmental effects of the large-scale ODS substitution initiated by the MP beyond the climate change and ozone depletion impacts. Early identification of environmental burden shifting (e.g., to more toxic compounds) is key in the prevention of unwanted side effects of the MP.

Additionally, an updated LCIA method needs to be developed that includes the CFs of the latest WMO assessment (WMO, 2022) for all ODSs. In the long term, different sets of CFs, considering different future atmospheric conditions, could be developed. These sets should also encompass regionalized CFs for anthropogenic N_2O and stratospheric emissions for NOx, HCl, and OH, necessitating collaboration with atmospheric scientists to address the complexities associated with varying future atmospheric conditions. A harmonious relationship between background and characterization scenarios and alignment with existing climate change scenarios like shared SSPs and RCPs is pivotal. Furthermore, exploration into the inclusion of CFs for stratospheric aerosols in LCIA methods warrants dedicated research efforts.

Recent advancements in experimental data and methodologies have also led to the development of alternative metrics for evaluating ODP (WMO, 2022). For instance, a new metric was recently proposed (Pyle et al., 2022) called Stratospheric ODP (SODP), but it only refers to ozone depletion in the stratosphere. This concept is more suitable for application to VSLSs. In the case of CF_3I, for example, the SODP is about zero because almost all the ozone depletion caused by CF_3I occurs in the lower troposphere. Since the ozone in the troposphere has increased over the last century due to human activities, the action of CF_3I could paradoxically be beneficial to the environment; in fact, tropospheric ozone formation harms human health, as the presence of a dedicated impact category in the LCIA methods indicates. Therefore, the original ODP concept, which concerned the total ozone column, could inflate the concerns about the impact of VSLSs on human health. In the future, this concept should be considered in the midpoint calculation methods. Further improvements would be to consider the point of emission to develop regionalized ODPs for VSLSs.

More generally, this work showcases the importance of analyzing interlinkage challenges between impact categories. Climate change, in particular, exhibits both synergistic and antagonistic relations with ozone depletion and potentially with other impact categories. Therefore, it is recommended that specific challenges of the other impact categories be reviewed rigorously, both individually and collectively. In light of the uncertain trajectory of climate change, the development of climate scenario-dependent characterization and normalization factors is advocated. These advancements empower LCA practitioners to evaluate environmental performance across a spectrum of future conditions, thus facilitating robust decision-making within our inherently uncertain world.

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CRediT authorship contribution statement

Anne E.M. van den Oever: Writing – original draft, Visualization, Methodology, Formal analysis, Data curation, Conceptualization. **Stefano Puricelli:** Writing – original draft, Visualization, Methodology, Formal analysis, Data curation, Conceptualization. **Daniele Costa:** Writing – review & editing, Supervision, Conceptualization. **Nils Thonemann:** Writing – review & editing. **Maeva Lavigne Philippot:** Writing – review & editing, Visualization. **Maarten Messagie:** Supervision, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

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