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Face Masks Pollution in the Environment: A Review of Mitigation Strategies

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A B S T R A C T

Background: Face masks are part of personal protective equipment with the majority being disposable and primarily made of plastic materials. The widespread disposal of these masks in the environment has resulted in the accumulation of thousands of tons of contaminated waste, posing significant environmental, social, and waste management challenges. The COVID-19 pandemic has increased the production, consumption, and subsequent disposal of face masks, thereby exacerbating these issues. This study aims to assess the environmental impacts associated with face mask use and to explore strategies for their mitigation.
Methods: Relevant data were gathered from scientific databases including ScienceDirect, Web of Science, and Google Scholar to explore sustainable solutions for mitigating face mask-related pollution. The study examined face mask structure, types, performance, filtration efficiency, plastic pollution, ecological changes, and waste management methods to address environmental issues.
Results: The findings highlight the structural components and types of facemasks commonly used, particularly in medical settings, and their subsequent environmental implications. Disposable face masks have been found to contain harmful compounds, including heavy metals, and contribute to global warming. Waste management methods such as landfilling, incineration, recycling, and reuse are commonly employed, though each has limitations. The adaption of biodegradable mask alternatives is proposed to reduce the release of microplastic consumption and greenhouse gases into the environment.
Conclusion: This review contributes to a comprehensive understanding of the environmental burden of face mask waste and presents potential mitigation strategies. By evaluating various aspects of face mask pollution and disposal, the study supports the development of context-specific waste management practices to prevent environmental contamination.

1. Introduction

Face masks cover the mouth and nose to prevent the risks associated with liquid droplets and airborne particles (Chellamani et al., 2013). Different types of face masks, including surgical masks, N95 respirators, and FFP masks, consist of non-woven Spunbond and Meltblown layers (Chellamani et al., 2013; Torres-Agullo et al., 2021). Plastic is a polymeric material widely used in the production of face masks due to its suitable properties (de Sousa, 2020). The most commonly used plastics for mask production are polypropylene (PP) and polyethylene (PE) (Silva et al., 2020). In the past couple of years, disposable masks have become a source of microplastic (MP) pollution. When improperly

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discarded, they contribute to environmental, economic, and social issues. Additionally, they can enter the food chain through aquatic environments, leading to various health concerns (Shen et al., 2021). During the COVID-19 pandemic, the World Health Organization (WHO) recommended mask usage to prevent airborne virus transmission, resulting in an unprecedented surge in mask demand (Wang et al., 2021). With the onset of the pandemic, global face mask consumption increased to 129 billion per month (Mohanty et al., 2024). The growing use of face masks has posed significant challenges for plastic waste management (Haque et al., 2021). Authorities are exploring strategies for the proper disposal of mask waste within a circular economy framework, emphasizing reduction, reuse, and recycling (Canopoli et al., 2020; Khoo et al., 2021; Mokuolu & Timothy, 2021). This study aims to examine the environmental pollution caused by face masks and explore methods to mitigate pollution and reduce mask consumption.

2. Materials and Methods

This review article was conducted through a comprehensive literature analysis on face mask pollution, its environmental impacts, and mitigation strategies. Peer-reviewed articles published between January 2010 and December 2024 were identified through searches in ScienceDirect, PubMed, and Scopus using keywords such as 'face mask,' 'microplastic,' 'environmental pollution,' and 'waste management.' This timeframe was chosen to capture studies relevant to the environmental impacts of disposable face masks, particularly the surge in mask usage during the COVID-19 pandemic (2020-2022), while also including earlier foundational studies on microplastics and waste management. Articles were selected based on their relevance to face mask composition, environmental impacts, and mitigation strategies. The search was iterative, allowing for the inclusion of seminal works and recent publications to ensure a comprehensive review. Various disposal and recycling techniques, such as waste-to-energy conversion, sterilization for reuse, and biodegradable face masks, were critically examined. Articles were selected based on the following inclusion criteria: (1) peer-reviewed studies published in English, (2) focus on environmental impacts of disposable face masks, microplastic pollution, or waste management strategies, (3) studies addressing mask composition, ecological effects, or mitigation approaches, and (4) availability of full-text articles. Exclusion criteria included: (1) non-peer-reviewed sources (e.g., editorials, opinion pieces), (2) studies not directly related to face mask pollution, and (3) articles lacking empirical data or methodological rigor. A total of 45 articles were included after screening 152 initial search results. The inclusion and exclusion criteria were developed by the lead author and reviewed by all co-authors to ensure alignment with the study objectives. Each selected article was independently assessed by at least two authors for relevance and methodological quality, with discrepancies resolved through discussion. Additionally, policy frameworks from organizations like the WHO and UNEP were analyzed to evaluate existing waste management strategies. The findings highlight the urgent need for sustainable face mask solutions, emphasizing biodegradable alternatives, improved recycling methods, and stricter waste disposal regulations. The study concludes with recommendations for policymakers, researchers, and manufacturers to develop eco-friendly face masks and enhance waste management policies.

3. Results and Discussion

3.1 The structure of face masks and their types

A standard disposable surgical mask typically consists of three layers: an outer Spunbond layer (non-woven and water-resistant), a middle Meltblown layer (which functions as a filter, removing over 99% of bacteria), and an inner Spunbond layer (non-woven with soft fibers). Additionally, it includes ear loops (made of polyisoprene rubber) and other additives (Shen et al., 2021). An N95 mask generally consists of four layers: an outer Spunbond layer (polypropylene), a second layer (cellulose, polyester), a third Meltblown layer (polypropylene), and an inner Spunbond layer (polypropylene) (Selvaranjan et al., 2021). Among these layers, Meltblown fabric is a non-woven material with finer fibers compared to Spunbond, serving as the primary filtration layer (Wang et al., 2021). The Spunbond layer, on the other hand, is a non-woven fabric composed of interwoven plastic fibers with antibacterial and hypoallergenic properties (Allison et al., 2020; Chellamani et al., 2013). Non-woven fabrics are characterized by properties such as permeability, tensile and impact resistance, low cost, and sterility (de Sousa, 2020). Plastic is a crucial component of personal protective equipment (PPE). PPE kits, including disposable masks, are composed of more than 50% plastic, such as polypropylene (PP) and polyethylene (PE). The fiber diameter of mask layers is approximately 30 micrometers for the outer and inner layers and around 5 micrometers for the middle layer (Vanapalli et al., 2021). Plastic is a polymeric material primarily composed of long carbon chains. Its key attributes include low cost, durability, flexibility, strength, user-friendly design, and low density (de Sousa, 2020). Common disposable masks are manufactured using polymeric materials such as polyethylene, polyurethane (PU), polyacrylonitrile, polystyrene, polyester, and especially polypropylene (de Albuquerque et al., 2021; Fadare & Okoffo, 2020). Polypropylene is the most widely used material for mask production due to its hydrophobic microfibers, skin compatibility, and hypoallergenic nature. The polypropylene content in surgical masks is approximately 4.5 grams, whereas in N95 masks, it is around 9 grams (Abbasi et al., 2020; Chellamani et al., 2013). Different types of face masks include surgical masks, respirators (N95, FFP), cloth masks, and activated carbon masks, among others. The aforementioned types are among the most commonly used.

Disposable surgical and N95 masks are primarily designed for healthcare workers (HCWs) to protect against occupational hazards (Silva et al., 2021; Torres-Agullo et al., 2021). Among the general population, disposable masks are preferred over reusable ones. Surgical masks are the most widely used and should be discarded after 3-4 hours of use. In contrast, only 9% of citizens use N95 masks due to their higher cost compared to certain other mask types (Selvaranjan et al., 2021; Silva et al., 2021). The weight of an N95 respirator mask is approximately 18.14 grams, while a surgical mask weighs around 3.5 grams (Selvaranjan et al., 2021). Surgical face masks are manufactured in different sizes, including adult (17.5 × 9.5 cm), children′s (14.5 × 9.5 cm), and infant (12 × 7 cm) sizes (Chellamani et al., 2013). N95 masks filter at least 95% of airborne particles with an average diameter of 0.3 micrometers, whereas surgical masks effectively filter particles larger than 1 micrometer, such as bacteria (Allison et al., 2020). Most surgical face mask manufacturers produce these masks using SMS (Spunbond-Meltblown-Spunbond) technology (Chellamani et al., 2013). Surgical (medical) masks are specifically designed to filter airborne particles, including bacteria and viruses. They comply with the European Union standard EN 14683 and are classified based on performance into Type I, IR, II, and IIR, with Type IIR offering 98% filtration efficiency. Respiratory surgical masks act as a barrier against droplets and airborne particles and are classified according to the European standard EN 149 into FFP1, FFP2, and FFP3 based on their filtration efficiency (Alcaraz et al., 2022; Allison et al., 2020).

3.2 Environmental Pollution Caused by Face Masks

Disposable face masks have become a new social norm and identified as emerging sources of microplastic pollution in ecosystems. The accidental disposal of masks may contribute to the release of microplastic contaminants into the environment. Since these polymer-based masks degrade into smaller particles (less than 5 mm in size), they can be classified as microplastics (Fadare & Okoffo, 2020; Shen et al., 2021). Disposable face masks contain various additives that enhance their properties, such as antiviral and antibacterial barriers, fragrances, and dye molecules, including monomers and oligomers of polyamide-66, polyethylene glycol, and color carriers such as anatopoulos, anastopoulos, and Pashalidis. Additionally, they contain metals such as copper, cadmium, lead, and antimony. Consequently, disposable face masks are expected to gradually release potentially hazardous chemicals into the environment (Silva et al., 2021). Furthermore, various types of face masks contain organophosphate esters, which are used as plasticizers and flame retardants (Torres-Agullo et al., 2021). During the COVID-19 pandemic, the exponential rise in the use of face masks created numerous challenges related to waste disposal and management, as well as serious environmental concerns due to increased waste generation and inadequate management systems (Haque et al., 2021; Wang et al., 2021). For example, China increased its face mask production by 450% in just one month from 20 million to 110 million masks by February 2020. Additionally, the demand for N95 masks surged from approximately 200,000 to 1.6 million (Silva et al., 2020). A study predicted that if each individual in the United Kingdom used a disposable face mask daily for one year, this would generate approximately 66,000 tons of plastic waste (Allison et al., 2020). If not properly managed, face masks can easily enter the environment and contribute to pollution. Due to their lightweight nature, they can be transported by wind and surface currents, quickly dispersing into natural ecosystems. Furthermore, they are often mistakenly disposed of in sewage systems or landfills, where they can release microfibers that become exposed to high concentrations of pollutants and microorganisms. For instance, the combined effects of microplastics and copper have been shown to increase genetic toxicity, neurotoxicity, and physiological effects on neotropical fish muscles. Additionally, microplastics can contribute to the spread of antibiotic-resistance genes and facilitate plasmid transfer, posing threats to both aquatic and terrestrial organisms (Silva et al., 2021). According to a WWF report, even if only 1% of disposable masks were improperly discarded during the pandemic, over 10 million surgical masks would have been released into the environment each month. Given that the weight of each surgical mask is approximately 3-4 grams, this would result in an estimated 30-40 tons of plastic waste being introduced into natural ecosystems (Silva et al., 2021; Silva et al., 2020; Wang et al., 2023). The long-term environmental impacts of microplastics from face masks extend beyond immediate pollution, affecting marine ecosystems and food chains. Microplastics (< 5 mm) from degraded masks accumulate in marine environments, with studies reporting mask debris on coastlines from Hong Kong to Nigeria (Abbasi et al., 2020). These microplastics are ingested by zooplankton and phytoplankton, transferring toxic additives (e.g., bisphenol A, cadmium) through the food chain to fish, birds, and humans (Hasan et al., 2023). For example, microplastics in common carp have been linked to immune suppression and biochemical stress (Silva et al., 2021). In humans, microplastics have been detected in the colon and placenta, raising concerns about chronic health effects (Wang et al., 2023). The ʽplastisphereʼ microbial communities on microplastic surfaces–further exacerbate pathogen transmission, including antibiotic-resistant genes, threatening marine biodiversity and human health (Abbasi et al., 2020). During the COVID-19 pandemic, the increased use of face masks led to a significant rise in mask production, resulting in higher energy consumption. Additionally, the manufacturing of disposable face masks contributes to CO_2 emissions, which exacerbate global warming. The production processes for polypropylene, small aluminum strips, sewing, and weaving involved in the manufacturing of N95 and surgical masks generate a substantial amount of CO_2 emissions. The reported greenhouse gas (GHG) emissions for an N95 mask, excluding transportation, amount to 0.5 kg CO_2-eq per mask, while surgical masks contribute 0.6 kg CO_2-eq per mask, with a major portion of these emissions originating from transportation (Klemeš et al., 2020; Selvaranjan et al., 2021). Surgical masks, primarily composed of polypropylene (approximately 3.5 grams per mask), contribute to microplastic pollution due to their single-use nature and widespread use (Selvaranjan et al., 2021). N95 masks, with a higher polypropylene content (approximately 9 grams) and additional layers, have a greater environmental footprint, generating 0.5 kg CO_2-eq per mask compared to 0.6 kg CO_2-eq for surgical masks, largely due to production and transportation emissions (Klemeš et al., 2020). Cloth masks typically made of cotton or polyester blends, offer reusability, reducing waste generation by up to 93% compared to disposable masks (Allison et al., 2020). However, their environmental impact depends on washing frequency and energy-intensive laundry processes, which can contribute to water and energy consumption (Alcaraz et al., 2022). While cloth masks produce fewer microplastics, their filtration efficiency is generally lower, necessitating careful design to balance environmental and protective benefits. A study by Kumar et al. found that if 10 tons of PPE waste, including face masks, were transported 10 kilometers to a disposal site, the total global warming potential (GWP) impact would be 2.76 kg CO_2-eq (Selvaranjan et al., 2021). Masks have the potential to release microplastic fibers under all conditions, making them one of the major yet often overlooked sources of environmental microplastics (Shen et al., 2021). When disposable masks are exposed to open environments, they are likely to degrade through physical and chemical processes (UV radiation, wind, and water currents) as well as biochemical processes (enzymatic activity), releasing a vast number of small particles, including microplastics (less than 5 mm) and nanoplastics (less than 1 μm) (Silva et al., 2021). As masks break down into smaller fragments, their surface area increases, enhancing their ability to release microplastic fibers. Over time, the gradual degradation of masks results in their transformation into environmental microplastics. The release of microplastics from masks into water, detergent solutions, and alcohol solutions has been measured at 4,400, 5,400, and 3,600 particles, respectively, with microplastic release in water increasing as vibration speed rises. Results indicate that detergents and alcohol enhance the release capacity of microplastics in water. Furthermore, the reuse of masks or prolonged use over multiple cycles further increases microplastic emissions (Shen et al., 2021). When a mask is worn over the mouth and nose, it creates an environment conducive to microplastic inhalation. The use of low-quality masks poses a higher risk of microplastic inhalation compared to high-quality masks (Torres-Agullo et al., 2021). Before weathering, most mask fibers have a smooth surface, with only a small fraction containing fine particles. However, after weathering, the mask layers exhibit roughness, deformation, and even structural damage. Some C-H bonds break, forming double bonds, while the main polymer chains degrade, leading to a reduction in molecular weight and mechanical strength. This alteration in the chemical structure makes the fibers more brittle, ultimately turning them into microplastics. A single worn-out mask can release billions of microplastic fibers and particles upon entering the water. The middle layer of the mask is particularly susceptible to weathering due to its mechanical structure (Shen et al., 2021; Wang et al., 2021). Most released particles from all three mask layers measure less than 200 μm in size, and their size tends to increase over time. Notably, in the middle layer, this size distribution accounts for 91.2% of the total concentration. After 36 hours of weathering, the concentration of microplastics released into water increased by 70.73 μL/L for the outer layer, 60.36 μL/L for the middle layer, and 11.44 μL/L for the inner layer. Due to its greater resistance to weathering, the inner layer released significantly fewer particles than the other layers (Wang et al., 2021). High-risk groups exposed to health hazards include healthcare workers, informal waste collectors, and individuals living near landfill sites. Airborne microplastics are recognized as contributors to severe occupational diseases. For example, inhalation of microplastic fibers such as polypropylene and polyethylene has been linked to respiratory damage and chronic bronchitis (Haque et al., 2021; Torres-Agullo et al., 2021). Additionally, microplastics released by masks can directly enter the human body through respiration. The concentration of airborne microplastics is higher in urban areas than in rural regions, and their atmospheric distribution follows patterns similar to other air pollutants. Factors such as emission sources, meteorological conditions, transportation, dispersion, and removal influence their behavior in the environment (Shen et al., 2021; Torres-Agullo et al., 2021). One of the waste management methods is incineration, which is a thermal process. During the COVID-19 pandemic, the increase in plastic waste production, such as face masks, challenged the existing incineration capacity. Moreover, the release of hazardous gases like dioxins and furans from incinerators, if not properly controlled, has raised concerns about air pollution (Parashar & Hait, 2021). Another waste management method is landfill disposal. Microplastics released from face mask waste in landfills can act as carriers for antibiotic-resistant genes (ARGs), thus promoting the spread of ARGs into landfill leachate. This, in turn, provides a pathway for transferring these genes from landfills into groundwater (de Albuquerque et al., 2021). The accumulation of plastic waste, such as face masks, in urban areas, particularly in sewage systems, increases the risk of flooding due to clogged manholes caused by waste buildup. Additionally, blocked manholes become an ideal breeding ground for disease-transmitting insects, such as yellow fever mosquitoes, which can transmit diseases such as dengue, chikungunya, yellow fever, and Zika (de Sousa, 2020; Silva et al., 2020). Disposable surgical masks, when discarded in sanitary landfills or public areas, enter aquatic environments (Shen et al., 2021). A significant portion of the microplastics from these masks ultimately reach marine environments (for instance, numerous face masks were found on highway drainage in Nigeria and in the Hong Kong ocean) and become a new source of plastic pollution. For example, during an environmental survey conducted by a non-governmental organization (NGO), dozens of disposable masks were observed along a 100-meter stretch on the shore of Soko Island in Hong Kong (Abbasi et al., 2020; Silva et al., 2020).

On a coastal line, the physical abrasion caused by sand and water can exacerbate the release of microplastics from the masks (Wang et al., 2021). Currently, there are no regulations in many parts of the world, including the Arabian Peninsula, regarding strategies for managing microplastic pollution, which could potentially contribute to the continued transmission of pathogens like SARS-CoV-2 (Abbasi et al., 2020). Microplastics and plastic fragments from masks can create a multitude of environmental issues. Microplastics can accumulate in plankton, fish, and birds through the food chain and can be transferred to humans, where they have been found in the colon and even in the placenta (Hasan et al., 2023; Wang et al., 2021). Mask microplastics contain a variety of harmful compounds, such as organic pollutants, flame retardants, and additives like dyes and other chemicals. In the ocean, these microplastics absorb toxins and organic pollutants, which bind to the plastic's surface as a toxic film. As a result, they may be ingested by phytoplankton and zooplankton at the base of the food chain, and in turn, become food for other organisms. Since humans are at the top of the food chain, consumption of contaminated seafood, such as fish, shrimp, and crabs, could lead to the intake of microplastics and the toxic compounds they carry. These could accumulate in human tissues over time and cause serious health issues (Hamidianfar et al., 2025; Khoo et al., 2021; Selvaranjan et al., 2021). Bisphenol A, used as a stabilizer and antioxidant in polycarbonate plastics, can leach from plastics and act as an endocrine disruptor at low concentrations, causing toxicity. Cadmium, combined with mask microplastics, was observed in common carp (Cyprinus carpio), affecting biochemical and immune parameters in response to stressors (Silva et al., 2021). Microplastic particles can serve as a potential medium for pathogens, including viruses, bacteria, and fungi. Organisms can develop biofilms or form cavities on the surface of microplastics to aggregate. Zettel and colleagues observed a highly diverse microbial community on the surface of microplastics and named it the "plastisphere." Among these microbes, pathogenic species were identified, which caused Vibrio parahaemolyticus and Aeromonas salmonicida infections in humans and fish, respectively (Abbasi et al., 2020). Ingestion of plastic waste by various species causes physical wear and toxicity (due to the release of additives, adsorbed pollutants, and pathogens) in their digestive systems, which directly harms or weakens them, making them more vulnerable to other threats (Selvaranjan et al., 2021; Silva et al., 2020). For instance, Neto and colleagues reported the death of an adult Magellanic penguin (Spheniscus magellanicus) found on the coast of Jo Coahi, Brazil, which was likely caused by ingesting an FFP face mask. This mask was found in the penguin's stomach, which may have restricted its feeding activities and led to starvation (Silva et al., 2021). Several instances of wildlife entangled in disposable face masks have been reported worldwide, affecting species such as seagulls (Larus sp.), peregrine falcons (Falco peregrinus), ducks (Anas platyrhynchos), American robins (Turdus migratorius), crabs (Carcinus maenas), bats (Eptesicus serotiulpe), hedgehogs (Erinaceus europaeus), and pufferfish. These animals experience problems due to entanglement in the masks' straps, which can lead to immediate death through immobilization, suffocation, or drowning. Chronic effects such as restricted feeding, leading to starvation, facilitated hunting, exhaustion, suffocation, infections, severe injuries, or even amputation may also occur. In addition to entanglement, the availability of disposable face masks may have unforeseen effects. For instance, a disposable face mask was observed in the nest of a common cuckoo in Leiden, the Netherlands. The presence of such items in bird nests can threaten the birds' nutritional and developmental needs and alter the thermal properties and drainage of the nest, thereby affecting fertility. Even the ingestion of relatively small amounts of plastic waste by seabirds can have a significant negative impact on their morphology and blood calcium levels, along with increased concentrations of uric acid and amylase (Silva et al., 2021). In Colombia, a bird became trapped in a coronavirus-contaminated face mask discarded in a tree and ultimately died due to the mask winding around its body and beak (Fadare & Okoffo, 2020). The consumption of microplastics causes behavioral changes (such as crustacean burrowing activity), reduced feeding activity (in bivalves and crabs), stunted body growth (especially in crustaceans), decreased reproduction and embryonic growth (such as in crabs), induced inflammatory processes (in sea anemones), and oxidative stress (Silva et al., 2021). The pathway for the transfer of microplastics from face masks and other waste spans all the countries of the Arabian Peninsula to the Arabian Sea, Red Sea, Arabian Gulf, Gulf of Aden, and the Persian Gulf. The presence of mask debris and fragments in natural environments diminishes aesthetic and recreational values, thereby damaging the tourism industry. For example, in Oman, due to various marine systems like wetlands and estuaries, these waste materials hurt marine life, which may challenge the tourism industry (Abbasi et al., 2020; Selvaranjan et al., 2021).

3.3 Reducing Pollution Caused by Face Masks

In light of the environmental, social, and economic threats posed by plastic pollution, numerous international agreements have been established. Notable among these are the United Nations Convention on the Law of the Sea (UNCLOS), which addresses the control of plastic pollution in the marine environment, the Basel Convention and its 2019 amendment concerning the regulation of transboundary plastic waste movement, the International Convention for the Prevention of Pollution from Ships, which prohibits ships from dumping plastics into the sea, the Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection (GESAMP), and the United Nations Global Partnership on Marine Litter (GPLM). Both GESAMP and GPLM focus on land-based sources, the fate, and impacts of plastics and microplastics in marine environments. As plastic pollution is not constrained by political borders and has global impacts, international collaboration especially in the sharing of knowledge, technology, and funding is essential

(Silva et al., 2020). Following local national, or international recommendations and guidelines to prevent PPE (Personal Protective Equipment) pollution, such as face masks, and improper management, especially during the COVID-19 pandemic, it is advised that these contaminated wastes be sealed in two-layer colored waste bags for 72 hours (considering that the virus′s half-life is 5 to 6 hours). In addition, dedicated trash bins with specific colors for PPE waste should be provided in public areas to ensure proper collection, disposal, and recycling of these items (Allison et al., 2020; Parashar & Hait, 2021; Sangkham, 2020). In the absence of such a specialized collection mechanism for masks, they must be segregated again and follow general waste management strategies, which may lead to significant energy and cost wastage. However, adherence to this mechanism minimizes health issues, and the waste will be collected and handled safely by designated personnel (Allison et al., 2020; Sangkham, 2020). It should be noted that implementing this mechanism requires public cooperation, which cannot be achieved through informational campaigns alone. Public perception must be enhanced through environmentally-friendly actions by all stakeholders, including media, campaigns, scientists, policymakers, industry, and the general public, to encourage proper disposal of PPE items such as masks (Vanapalli et al., 2021). Additionally, the European Commission has incorporated a strategy for plastics within the circular economy, aimed at reducing single-use plastic products and increasing their reuse and recycling. This is known as the implementation of the R3 strategy, which stands for Reduce, Reuse, and Recycle (Khoo et al., 2021; Serafin et al., 2022). Effective public education on proper mask disposal requires targeted strategies and frameworks. A multi-channel approach, including social media campaigns, community workshops, and school programs, can raise awareness about the environmental impacts of mask waste (Sangkham, 2020). For example, Singapore′s ʻMask Go Where′ campaign used infographics and mobile apps to guide citizens to dedicated PPE bins, increasing compliance by 70% (Silva et al., 2020). The PRECEDE-PROCEED framework, which assesses predisposing, enabling, and reinforcing factors, can guide campaign design by identifying barriers (e.g., lack of access to bins) and motivators (e.g., environmental responsibility) (Haque et al., 2021). Collaborations with influencers and local leaders can further amplify outreach, particularly in underserved communities. According to the Environmental Protection Agency (EPA) report, out of the several tons of plastic waste generated annually, only 7% is recycled, approximately 8% is incinerated, and the remainder is landfilled (Khoo et al., 2021). Therefore, the management of mask usage and medical waste required stringent measures such as segregation, classification, storage, collection, transportation, and disposal as an emergency response to the significant surge in waste production during the pandemic (Parashar & Hait, 2021; Sangkham, 2020). During the pandemic, waste management infrastructure originally designed for steady-state operations with moderate waste flows was overwhelmed, leading to disruptions in normal functionality. Additionally, pandemic-related quarantines resulted in reduced transportation activities and a sharp decline in oil prices, which in turn reduced plastic recycling rates, creating a significant managerial challenge (Parashar & Hait, 2021). Effective management of plastic waste includes several strategies: monitoring waste production and determining treatment capacity, expanding disposal facilities, improving infrastructure, and increasing recycling capacity. When recycling is not feasible, plastic waste should be repurposed as raw material or used for waste-to-energy conversion. Furthermore, enhancing coordination among stakeholders, authorities, and local workers, along with encouraging education and training for waste collectors to adopt safe sorting and recycling practices, is essential for efficient waste management (Haque et al., 2021; Silva et al., 2020). The most widely used techniques for managing plastic waste globally include recycling, incineration, and landfilling. Shortly after the initial outbreak of COVID-19, many countries classified used PPE items, such as hospital and household face masks, as infectious waste that must be incinerated at temperatures above 1100 °C, with the remaining ash subsequently landfilled. While some countries and municipalities are equipped to manage waste properly, others are forced to implement suboptimal management strategies, such as direct landfill disposal or open burning. For instance, shortly after the outbreak of COVID-19, South Korea implemented special waste management measures on January 28, 2020, mandating that such waste could not be stored for more than 24 hours and had to be collected and incinerated on the same day (Selvaranjan et al., 2021; Silva et al., 2020). Automated AI-based waste sorting systems can enhance the efficiency, speed, and value of recycled products. However, major limitations in recycling face mask waste include polymer cross-contamination, the presence of additives and inorganic impurities, inconsistent or insufficient separation techniques at the source or during collection, and partial polymer degradation (Vanapalli et al., 2021). Globally, 16% of plastic waste is managed through mechanical recycling, 25% through incineration, 40% is disposed of in landfills, and 19% is mismanaged, leaking into the environment (Khoo et al., 2021; Vanapalli et al., 2021). Plastic waste disposal remains a societal concern due to the extensive use of various plastic polymers. To mitigate the environmental impact of plastics, enhancing recycling infrastructure and facilitating waste collection is crucial. While landfilling remains a common practice, it is not an effective solution for non-biodegradable plastics such as face masks. Instead, incineration with energy recovery is widely adopted in many countries as an alternative method for plastic waste treatment. However, this approach requires careful consideration due to the potential release of toxic compounds such as dioxins and furans (Haque et al., 2021). Thermal treatment or incineration is the preferred method for handling the large volumes of hazardous waste generated during the pandemic, including PPE such as face masks and gloves. Apart from thermal treatment, other waste treatment methods include pyrolysis, microwave irradiation, chemical disinfection, dry heat, hydrogen peroxide treatment, autoclaving, ultraviolet radiation, and ozone gas sterilization (Haque et al., 2021; Wang et al., 2021). During the pandemic, an effective yet emergency response involved decentralized waste management services, which temporarily stored waste before final disposal. Stored waste was pre-treated, processed, and volume-reduced through screening and grinding. This strategy was implemented in Wuhan, China (Haque et al., 2021). Based on waste volume, incineration is considered a practical option for processing over ten tons of waste per day, whereas alternative thermal techniques such as autoclaving and microwave irradiation are preferred for waste volumes below ten tons per day (Parashar & Hait, 2021). During the pandemic, the surge in plastic waste from PPE, such as face masks and gloves, led to an increase in medical waste production to 240 tons per day in Wuhan, China, overwhelming the city's maximum incineration capacity of 49 tons per day (Parashar & Hait, 2021; Vanapalli et al., 2021). The WHO guidelines recommend mandatory incineration of PPE at temperatures ranging from 900 to 1200°C (Klemeš et al., 2020). Additionally incineration facilities must be equipped with advanced air pollution control technologies to mitigate secondary pollution from hazardous gases, such as dioxins and furans (Parashar & Hait, 2021). Although incineration significantly increases CO_2 emissions and greenhouse gases, contributing to global warming (Vanapalli et al., 2021), it is worth noting that plastic waste has a thermal energy value comparable to conventional fuels (Klemeš et al., 2020). Another method for plastic waste disposal is landfilling, especially in both developed and developing countries. However, many of these nations still practice unregulated waste dumping, leading to spatial limitations, chemical contamination, and the risk of landfill fires. A CO_2 assessment study found that landfilling emits less CO_2 than incineration (Vanapalli et al., 2021). Polyethylene and polypropylene are among the most common polymers in municipal solid waste (MSW) and have the potential for recycling. However, contamination from corrosive compounds, heavy metals, or structural modifications may hinder recycling feasibility (Canopoli et al., 2020). Recycling and reuse are viable options for managing plastic waste; however, identifying the plastic type and its source is essential beforehand (Selvaranjan et al., 2021). Both formal waste workers who sort waste at facilities and informal workers, such as waste pickers, play crucial roles in recycling programs (Canopoli et al., 2020). Recycling methods include primary recycling (reuse), secondary recycling (mechanical), tertiary recycling (chemical and thermochemical), and quaternary recycling (energy recovery through incineration) (Canopoli et al., 2020). Mechanical recycling is considered relatively environmentally friendly, but it has limitations due to contamination, additives, impurities, improper sorting, and the degradation of plastic's mechanical properties after several recycling cycles (Canopoli et al., 2020; Vanapalli et al., 2021). Chemical recycling is regarded as the most promising option, with minimal environmental impact and the highest potential benefits (Haque et al., 2021). Additionally, the chemical energy of plastics can be recovered through incineration of medical waste with heat recovery (Klemeš et al., 2020). Recycling face masks using appropriate processes can help mitigate plastic pollution from discarded masks. Two primary methods are used for mask recycling: primary and secondary recycling. Primary recycling refers to reusing the product in its original form, while secondary recycling involves reusing thermoplastics present in the mask. However, the cost of a recycled mask may exceed that of a new one, and the filtration efficiency and quality of a recycled mask may be lower. Therefore, minimizing mask waste is crucial (Selvaranjan et al., 2021). The presence of mixed plastics can make it challenging to obtain homogeneous materials for high-quality product manufacturing. This issue can be partially addressed using separation technologies such as flotation, plasma gasification, spectroscopy, density differentiation, and X-ray fluorescence (Haque et al., 2021; Parashar & Hait, 2021; Selvaranjan et al., 2021). After separation, plastic waste must undergo impurity removal, quality assessment, and testing before being sold to manufacturing companies. These recycled plastics can then be used to produce valuable products such as engine oil, textiles, footwear, and concrete additives (Khoo et al., 2021; Selvaranjan et al., 2021). A life cycle assessment (LCA) study found that raw material recycling of mixed plastic waste emits 50% less CO_2 than incineration (Vanapalli et al., 2021). Estimates suggest that between 125,000 and 500,000 landfill sites in Europe contain potentially valuable secondary raw materials that could contribute to the circular economy (Canopoli et al., 2020). By using the recycling of mask waste, fuel and energy, carbon materials, and construction materials can be produced as follows: A) Fuel production and energy recovery: Energy recovery is the best option for disposing of hazardous polymer waste because it can meet partial energy demand and reduce disposal costs, CO_2 emissions, and greenhouse gases (Haque et al., 2021). Additionally, the fuels obtained from recycling significantly reduce CO_2 emissions compared to fuels produced from primary fossil sources (Vanapalli et al., 2021). The fuels produced in the pyrolysis process (decomposition under extreme heat ranging from 540 degrees Celsius to 830 degrees Celsius) are liquid, oil, gas, and coal as by-products (Khoo et al., 2021; Selvaranjan et al., 2021). Additionally, the quality of the liquid oil obtained from recycling is similar to crude oil (Vanapalli et al., 2021). The application of the products is in refineries, boilers, chemical industries, and even wastewater treatment (coal) (Khoo et al., 2021). When mask waste is non-recyclable, energy can be recovered through incineration. Some developed countries such as Denmark, Poland, and Sweden have employed advanced technologies to control air pollution during this process for waste treatment (Vanapalli et al., 2021). B) Production of materials from recycled materials: According to conducted studies, recycled polyethylene and polypropylene plastics (main components of masks) can be used with a maximum content of 5% for road construction materials (Khoo et al., 2021; Selvaranjan et al., 2021). And they can also partially replace cement and aggregates in construction materials. The study by Hama and colleagues in 2017 concluded that adding recycled plastic to concrete increases properties such as permeability and filling capacity (Selvaranjan et al., 2021). By using low-density recycled polyethylene, durable sand blocks can be produced. Additionally, during the study by Eco and colleagues, M20 grade masonry mortar can be produced by replacing 75% of sand with plastic. Additionally, a sustainable brick was produced with 52% mask waste, 45% paper waste, and 3% adhesive, which has the potential to replace traditional bricks. Another invention from mask waste is the production of air and moisture barrier layers and films, which are used in insulating building coverings. C) Production of carbon materials: Recycled plastics from waste masks can be considered a safe material and recycled carbon is suitable as a raw material for the production of petrochemical products, plastics, films, and composites. The process of producing carbon materials is an efficient and industrially scalable method, but it requires a high reaction temperature and has a low yield (Haque et al., 2021; Zhang et al., 2014). For the production of recycled carbons, the synthesis of iron/carbon nanotube nanocomposites with sponge-like structures can be mentioned, through the pyrolysis of polypropylene with a catalyst at a temperature of 600 degrees Celsius in a reactor. This nanocomposite has many applications in the fields of electronics, biosensors, energy storage, and reinforced composites for airplanes (Zhang et al., 2014). Additionally, compounds such as ethylene, propylene, and benzene can be recycled from the thermal decomposition of mask waste. The value of these products is estimated to be between 80 to 160 dollars per ton (Canopoli et al., 2020). Carbon-based materials are considered one of the practical adsorbents for CO_2 due to their high surface area, low cost, high flexibility for modifying pore structures, relative ease of regeneration, and surface performance. The production of activated carbon from waste mask precursors in a high-temperature, one-step carbonization process combined with KOH chemical activation results in high surface area and narrow pore distribution, making them an efficient adsorbent for CO_2 (Serafin et al., 2022). One of the effective strategies for mitigating face mask-related pollution is identifying methods for reusing respiratory and medical masks. It is preferable to reuse masks before disposal or recycling. However, when reusing masks, it is crucial to strike a balance between cleaning them effectively while maintaining their safety and functionality (Alcaraz et al., 2022). Studies have shown that SARS-CoV-2 can persist on plastic surfaces for up to 72 hours. Based on this finding, the U.S. government recommended that each healthcare worker receive five FFP respirators and use one per day in a specific sequence, storing it in a breathable paper bag at the end of each work shift. This approach ensures that at least five days elapse before reusing any given FFP respirator. However, this recommendation should be followed with caution, as FFP respirators are designed for single use and may become damaged, lose their protective properties, and become ineffective (Wang et al., 2021). Another alternative available to the public is reusable respirators, which are multi-layered and often equipped with high-efficiency particulate air (HEPA) filters. Some manufacturers claim that these masks can filter out dust, pollutants such as PM10 and $PM_{2.5}$, as well as bacteria and viruses through a unique three-layer filtration system. Additionally, general-purpose respirators with replaceable filters are available, which are suitable for filtering airborne viruses; however, their filters need to be replaced approximately every 69 hours (Allison et al., 2020). Reusable fabric masks can also serve as an alternative to disposable plastic-based masks, helping to curb plastic waste accumulation (Parashar & Hait, 2021; Urban & Nakada, 2021). However, fabric-based masks must provide the same level of protection as disposable surgical or N95 masks, although they generally offer lower filtration efficiency. Washed medical masks exhibit greater filtration efficiency than fabric masks (Alcaraz et al., 2022; Klemeš et al., 2020). Nonetheless, fabric masks have the potential to function as effective personal protective equipment (PPE). By combining electrostatic and physical filtration effects through layering, proper design, and correct usage, fabric materials can enhance filtration efficiency (Klemeš et al., 2020). The World Health Organization (WHO) has deemed these masks suitable for use by healthy individuals (Urban & Nakada, 2021). Thus, finding methods to disinfect, sterilize, and reuse masks without compromising their effectiveness is critical. The most promising methods include dry heat, moist heat, ozone gas, hydrogen peroxide vapor, and ultraviolet (UV) irradiation (Parashar & Hait, 2021; Wang et al., 2021; Xiang et al., 2020). Ultraviolet germicidal irradiation (UVGI) has been shown to inactivate numerous human pathogens, including coronaviruses when applied to FFP masks. However, both sides of the mask must be exposed to UV light, and this process does not degrade the polymers in the masks. The Spanish Society of Preventive Medicine, Public Health, and Hygiene recommends a dual-lamp system (top and bottom), 36W, with an exposure time of 148 seconds for this method. However, the Beijing International Medical Center has cautioned that "it is unlikely that UVGI will eliminate all viruses and bacteria on filtering facepiece respirators due to shadowing effects caused by the multiple layers of the respirator's structure" (Rubio-Romero et al., 2020), Another method involves hydrogen peroxide vapor, which has been recommended by both the Spanish Society of Preventive Medicine, Public Health, and Hygiene and the Netherlands National Institute for Public Health and the Environment for disinfecting and sterilizing FFP masks (except those containing cellulose), allowing for a maximum of two reuses. This approach preserves the mask's shape and filtration efficiency after treatment (Rubio-Romero et al., 2020; Xiang et al., 2020). Dennis et al. conducted a study demonstrating that an ozone concentration of 10-20 ppm for a minimum of 10 minutes effectively disinfects masks. One advantage of ozone gas is its rapid virucidal action. Furthermore, the Spanish Society of Preventive Medicine, Public Health, and Hygiene has indicated that moist heat can be used while maintaining a filtration efficiency of over 95% for up to three disinfection cycles. This method requires exposure to water vapor at 65 °C for 30 minutes to effectively sanitize and sterilize the mask (Rubio-Romero et al., 2020). Dry heat is another method that can achieve disinfection and sterilization while preserving filtration efficiency for up to three cycles. The Spanish Ministry of Labor and Social Economy, along with the Beijing International Medical Center, has shown that dry heat at 70°C for 30 minutes successfully decontaminates and sterilizes respirators (Rubio-Romero et al., 2020; Xiang et al., 2020). For sterilizing surgical and respiratory masks at home while maintaining their functionality and shape, dry heat can be applied using an oven at 60-70 °C for 30 min (Xiang et al., 2020). However, methods such as washing with soap and water, using alcohol, exposing to high temperatures, ethylene oxide, or bleach are not recommended for disinfection and sterilization, as they can alter the mask fibers, affect particle penetration levels, and even compromise the respirator′s integrity (Rubio-Romero et al., 2020). Additionally, chemical disinfectants are unsuitable for mask sanitation due to the potential for residual toxic and carcinogenic substances (Xiang et al., 2020). It is also important to note that the number of reuse cycles should be limited to ensure filtration efficiency is not compromised (Alcaraz et al., 2022; Allison et al., 2020). Reusing face masks through these disinfection techniques can alleviate strain on supply chains, reduce economic and environmental burdens, and lower waste generation by up to 93% while decreasing resource consumption by 28% (Allison et al., 2020; Haque et al., 2021). Another approach to reducing plastic pollution caused by face masks is the development of biodegradable masks. The production of environmentally friendly masks using high-performance biodegradable polymers with physical properties similar to plastic-based counterparts requires investment policies, with biorefineries serving as a biotechnological tool for obtaining raw materials (Silva et al., 2020; Vanapalli et al., 2021). The polypropylene used in conventional masks can be replaced with other biodegradable materials. For instance, coffee-based and hemp fiber-based face masks are already available as biodegradable alternatives. These masks offer high filtration capacity and physical properties comparable to plastic-based masks (Selvaranjan et al., 2021; Silva et al., 2020). Biodegradable masks are emerging as a sustainable alternative to polypropylene-based masks. Materials such as polylactic acid (PLA), derived from corn starch, and polyhydroxyalkanoates (PHA), produced by microbial fermentation, are being tested for mask production due to their biodegradability and comparable filtration properties (Samper et al., 2018). For example, hemp and coffee-based masks have shown filtration efficiencies above 90% while degrading within 6-12 months under composting conditions (Selvaranjan et al., 2021). Recent innovations include electrospun nanofiber masks made from cellulose acetate, which offer high breathability and biodegradability (Fadare & Okoffo, 2020). However, challenges remain, including scalability, cost (approximately 20-30% higher than conventional masks), and ensuring consistent filtration efficiency across environmental conditions. Pilot projects, such as those by BioCellection and Mask4All, are testing these materials in real-world settings, with preliminary results indicating a 30-70% reduction in CO_2 emissions compared to traditional masks (Silva et al., 2020). Biodegradable masks possess elasticity, filtration properties, and water resistance while also reducing CO_2 emissions by 30-70% compared to conventional plastics (Selvaranjan et al., 2021). The use of biodegradable polymers, commonly known as biopolymers, presents a viable substitute for plastic (Samper et al., 2018; Selvaranjan et al., 2021). Biopolymers can be derived from biomass production using agricultural sources such as polysaccharides, lipids, and microorganisms. Additionally, natural fibers including cactus, banana, avocado, lotus, reed, hemp, coffee, sugarcane, and bamboo exhibit the necessary characteristics for face mask production. Tea leaf waste, which contains polypropylene and polylactic acid properties, has also been utilized in the production of filtration components (Selvaranjan et al., 2021). Furthermore, wheat gluten biopolymer, a byproduct of the grain industry, can be used in mask production. Ultimately, it degrades into nitrogen-based components that serve as soil fertilizers (Silva et al., 2021). Switching to biodegradable masks and implementing advanced waste management systems involves economic trade-offs. Biodegradable masks, such as those made from PLA or hemp, are 20-30% more expensive to produce than polypropylene masks due to higher raw material and processing costs (Selvaranjan et al., 2021). However, their lifecycle benefits include a 30-70% reduction in CO_2 emissions and lower waste management costs due to composting potential (Silva et al., 2020). For waste management, investments in pyrolysis or automated sorting systems require upfront costs (estimated at $1-2 million for a mid-sized facility), but they yield long-term savings through energy recovery and reduced landfill expenses (Khoo et al., 2021). A cost-benefit analysis suggests that while initial costs are high, the environmental and health benefits such as reduced cleanup costs and healthcare expenses from microplastic-related illnesses outweigh these over a 5-10-year period (Vanapalli et al., 2021). During the COVID-19 pandemic, global policies on medical and plastic waste management varied widely. The WHO recommended incineration of PPE at 900-1200°C to prevent pathogen transmission, a policy adopted by countries like China and South Korea (Klemeš et al., 2020). The European Union′s Circular Economy Action Plan emphasized reducing single-use plastics, including masks, through the R3 strategy (Reduce, Reuse, Recycle), leading to initiatives like the EU Plastic Strategy (Khoo et al., 2021). However, in developing nations, such as Nigeria, the lack of regulated waste management systems led to open dumping, exacerbating microplastic pollution (Mokuolu & Timothy, 2021). Our proposed reduction strategies, such as promoting biodegradable masks and decentralized waste management, are grounded in these policy frameworks. For instance, biodegradable masks align with the EU′s focus on sustainable materials, while decentralized systems, as implemented in Wuhan, China, address capacity constraints during waste surges (Haque et al., 2021). These strategies aim to balance environmental protection with public health needs, supported by evidence of reduced CO_2 emissions and waste leakage (Vanapalli et al., 2021). Practical implementation of waste management strategies has been demonstrated in several regions. In South Korea, a special waste management policy implemented in January 2020 mandated same-day incineration of PPE waste at temperatures above 1100 °C, reducing environmental leakage by 85% (Silva et al., 2020). In Singapore, the National Environment Agency introduced dedicated PPE disposal bins in public areas, coupled with public awareness campaigns, resulting in a 70% increase in proper disposal rates (Sangkham, 2020). Additionally, a pilot project in the Netherlands utilized pyrolysis to convert mask waste into liquid fuel, achieving a 60% energy recovery rate (Khoo et al., 2021). These case studies highlight the importance of infrastructure investment, public cooperation, and innovative technologies in effective waste management.

4. Conclusion

This review study examined the use of plastic-based face masks, their various types, ecological and environmental impacts, and methods for reducing face mask waste. Additionally, the structure and composition of face masks were analyzed. A scenario was presented regarding mask-related pollution, particularly microplastic contamination, and the challenges arising from improper disposal. However, the environmental consequences of plastic mask disposal remain complex, and their long-term effects are not yet fully understood. Given that these environmental impacts have already contributed to a global ecological crisis, urgent practical measures must be implemented to mitigate the environmental issues caused by face mask pollution. Management challenges and proposed approaches such as recycling face masks into energy, fuel, carbon-based materials, and construction materials as well as alternative solutions like developing and increasing the production of biodegradable face masks, offer potential ways to balance high demand while reducing plastic pollution. Furthermore, innovative and improved waste strategies, along with effective waste management policies, can help address mask pollution in atmospheric, terrestrial, and aquatic environments. These findings enhance our understanding of environmental pollution caused by face masks and the methods to mitigate it, allowing us to consider various factors and adopt appropriate waste management strategies to prevent contamination. Ultimately, to avert a global crisis stemming from face mask pollution, stakeholders must raise public awareness, develop and implement relevant policies, and promote international agreements regarding the production, usage, and disposal of face masks. Future studies could explore the role of multi-stakeholder collaboration, involving governments, manufacturers, and environmental organizations, to develop integrated policies and initiatives for mitigating face mask pollution, thereby enhancing the practical implementation of sustainable solutions.

Authors' Contributions

Anvar Asadi: Conceptualization; Supervision; Project administration. **Shakiba Amiri:** Writing-original draft preparation. **Maryam Ahmadi, Roya Mahmouditabar:** Writing-original draft; Investigation. **Sabah Beigrezaee:** Methodology; Writing-review and editing; Visualization.

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Ethical considerations

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