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Plastic production, consumption, and global release pathways

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Abstract

Over the past few decades, the rise of plastic production and consumption has significantly redefined the way materials are used globally, with 460 million tons of plastic produced annually, and nearly half of all plastics ever manufactured being produced since 2000. This paper delves into the trends of plastic production and consumption, and how the four main polymers, polyethylene, polypropylene, polystyrene, and polyethylene terephthalate, are responsible for the majority of the global output, with polyethylene dominating the market. In developing economies, rapidly growing urbanization and economic growth in regions such as Asia, Sub-Saharan Africa, and Latin America are sending an increasingly spiraling demand to developed nations' markets, which have reduced their consumption. The main ways that we can control the leakage of plastic into the environment are also scrutinized. With the alarming revelation that over half of the plastic produced remains unmonitored and ends up in our terrestrial, freshwater, marine, and atmospheric surroundings. The climate effects of plastics are addressed by highlighting carbon emissions along the entire life cycle, from the excavation of fossil fuels to burial. Coming together, the proof in this paper highlights that the growth of plastic production is going unchecked and demands international coordination to tackle the problems that are coming as a result.

Keywords: Global plastic market trends, Polymer life cycle assessment, Plastic waste management, Microplastic pollution pathways, Fossil fuel-based carbon emissions

1. Introduction

The adoption of completely synthetic polymers-starting with Bakelite in 1907 and then moving forward with the invention of polyethylene (1933), polypropylene (1954), and poly (ethylene terephthalate) (1941)-stands as one of the most significant developments for the manufacturing process during this time since the Industrial Revolution [1]. Plastics are lightweight, corrosion-resistant, non-conductive through electrical means, and very durable; those characteristics have allowed for transformational

developments like sterile medical disposables to prevent hospital-acquired infections, lightweight auto parts resulting in less fuel consumption, flexible packages allowing longer food shelf life, and insulating foams used to reduce energy requirements in buildings [1, 2]. Overall, plastic production increased globally from 1.7 million metric tons (Mt) in 1950 to 460 Mt in 2022, with an annual average growth rate of 8.4%, surpassing other bulk commodities such as steel, cement, and alloys [3, 4].

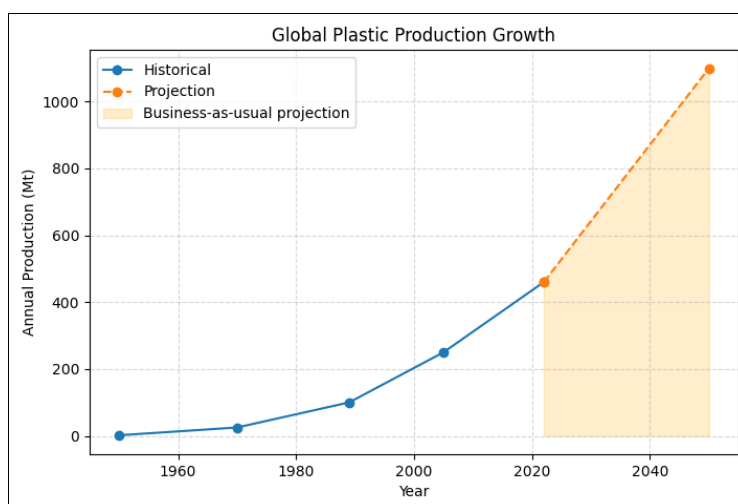


Fig 1: Global plastic production grew from 1.7 Mt in 1950 to 460 Mt in 2022, an 8.4% compound annual growth rate. Under current trends, production will reach 1,100 Mt by 2050

All the benefits associated with plastics have also contributed to an unprecedented environmental hazard. In fact, many "commodity" forms of plastic will not decompose over any period of closure; for example, a polyethylene shopping bag can remain intact for many hundreds of years while slowly breaking down into smaller components without undergoing any chemical processes to produce completely mineralized forms of itself [5]. The plastics economy currently operates using a linear model known as the "take, make, dispose," whereby 95% of plastic packaging produced is dumped after one use, usually in less than 6 months [6]. Out of 9.5 billion tons of plastic produced globally in total up until 2022, around 6.7 billion tons are wasted; however, only 9% of this waste has been recycled, only 12% have been incinerated; with the rest (79%) either sent to landfill or dumped into the environment [3, 7].

The understanding of plastic pollution through scientific study has improved rapidly in the last 10 years. Early investigations were focused upon visual observations (of litter at beaches), as well as animals being entangled within plastic (such as seals, turtles, and whales) [8]; however, research has expanded to include other issues, such as macro and microplastic ingestion, and their documented effects (i.e., reduced feeding, intestinal blockage, and adsorbed particulate contaminants being translocated) within organisms in marine environments [9, 10]. More recent studies are now showing that microplastics have been identified within human blood, placenta, and lungs, leading investigators to conduct even more research to discover whether or not they are dangerous to human health [11, 12]. In addition, the previous viewpoint that plastic pollution only affects oceans is being challenged by new information indicating that microplastics have been discovered not only in oceans but also in snow from the Arctic and remote topography, as well as within agricultural soils that are far removed from urban areas [13, 14].

2. Global Plastic Production: Trends, Composition, and Regional Patterns

2.1 Historical production trajectory (1950-2022)

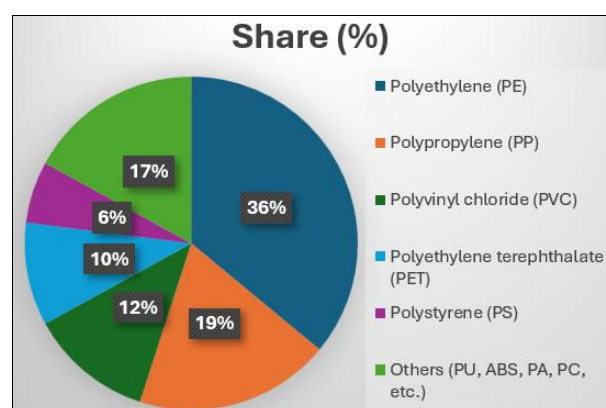
The contemporary era of plastic manufacturing began in earnest after World War II, when many factories created from synthetic rubber, explosives, and high-octane fuel for WWII were converted over to commercial production [15]. Plastic production soared from 1.7 Mt in 1950 to 25 Mt in 1970, 100 Mt in 1989, 250 Mt in 2005, and 460 Mt in 2022 [3, 4]. An 8.4% compound annual growth rate (CAGR) over the same period is staggering-steel's global production rate grew at just 2.5% CAGR over the same period [3]. The global production decline for plastics was temporary due to the impact COVID-19 had on the automotive and construction sectors, which caused a decline in demand for plastics; however, production increased to 430 Mt in 2021 and again to 460 Mt in 2022 due to strong demand for packaging related to e-commerce and personal protective equipment (PPE) [16, 17]. The consumption of disposable plastics in the healthcare market grew an estimated 250-300% during the pandemic [17].

The total production of plastics from 1950 until 2022 is approximately 9.5 billion tons [3]. This can be visualized as laying down all of the plastic produced during this time as an equivalent number of squares with dimensions of 0.5 mm

thick plastic film laid out flat, covering a total area equal to approximately two Argentinas. Out of the total amount of plastic produced, approximately 30% of the total amount produced remains in the form of buildings, cars, machinery, and other long-lasting products; the remaining 70% (approximately 6.7 billion tons) has been disposed of by the end of 2022 [3, 7]. The mass of the amount of plastic currently disposed of is greater than the mass of the total human population on Earth (approximately 0.4 billion tons times 10) by a factor of 10.

2.2 Polymer types: production shares and material properties:

There are five different types of plastic known as commodity thermoplastics: polyethylene (PE), polypropylene (PP), polyvinyl chloride (PVC), polyethylene terephthalate (PET), and polystyrene (PS). They account for 83% of the plastic produced [18, 4], with PE having the largest share at 36%, followed by PP at 19%, PVC at 12%, PET at 10%, and PS at 6%. The other 17% is made up of polyurethane (PU), which has 5%, acrylonitrile-butadiene-styrene (ABS) with 2%, polyamide (nylon) with 2%, polycarbonate (PC) with 1%, and an assortment of other specialty polymers [18, 19].



Note. Data from Plastics Europe (2022) and [17].

Fig 2: Global plastic production by polymer type (2022). Polyethylene (PE) accounts for the largest share (36%), followed by polypropylene (PP, 19%), polyvinyl chloride (PVC, 12%), polyethylene terephthalate (PET, 10%), and polystyrene (PS, 6%). The remaining 17% comprises other polymers, including polyurethane (PU), acrylonitrile-butadiene-styrene (ABS), polyamide (nylon), and polycarbonate (PC).

Polyethylene's dominance stems from its low production cost and versatility. High-density polyethylene (HDPE)-density 0.94-0.96 g/cm³-is used for rigid containers (milk jugs, shampoo bottles, detergent bottles). Low-density polyethylene (LDPE)-density 0.91-0.93 g/cm³-is used for films, bags, and flexible packaging. Linear low-density polyethylene (LLDPE)-a copolymer with higher tensile strength-is used for stretch wraps and heavy-duty bags [19]. Polypropylene has a higher melting point (160-170°C vs 105-115°C for PE) and is favored for heat-resistant applications, including dishwasher-safe containers, automotive components, and living hinges (e.g., flip-top caps) [20]. PVC is denser (1.30-1.45 g/cm³) and contains chlorine, making it more fire-resistant but also more problematic in incineration due to hydrogen chloride and dioxin emissions [18].

Table 1: Major polymer types: properties, applications, and recyclability

Polymer	bbrev	Density (g/cm ³)	Melting Point (°C)	Typical Applications	Recyclability	Approx. Degradation Half-life (Marine)
LDPE	LDPE	0.91-0.93	105-115	Shopping bags, films, squeeze bottles	Low (downcycled)	>500 years
HDPE	HDPE	0.94-0.96	120-130	Milk jugs, shampoo bottles, pipes	Moderate	>500 years
PP	PP	0.90-0.91	160-170	Food containers, automotive parts, and living hinges	Moderate	200-500 years
PVC	PVC	1.30-1.45	100-260 (broad)	Pipes, window profiles, cables, and flooring	Very low	Unknown (can release HCl)
PET	PET	1.38-1.39	250-260	Beverage bottles, polyester fibers	High	~450 years
PS	PS	1.04-1.05	240	Disposable cutlery, CD cases, insulation foam	Low	>500 years
PU	PU	0.50-1.25 (varies)	170-190 (decomposes)	Foam insulation, seat cushioning, adhesives	Very low	Unknown

Cite sources: [4, 17, 5]

2.3 Regional production patterns

China supplies 32% of the global plastic supply, with 18% coming from North America, 15% from Europe, 9% from the Middle East and Africa, and 17% from the remainder of Asia [4]. With massive investment in petrochemical infrastructure, China's share of global production has increased from 15% in 2005 to 32% in 2021, largely reflecting the availability of abundant supplies of coal-based feedstocks [4].

The United States has seen what can be described as a plastics boom or renaissance since 2010, owing to the availability of low-cost ethane derived from shale gas. Ethane, which is the primary feedstock for ethylene, is produced via hydraulic fracturing in Ohio, Pennsylvania, and Texas, and has historically traded in the US for \$200-300 per ton, compared to \$600-800 per ton in Europe [21]. As of the end of 2022, there are another 15 Mt of ethylene cracking capacity on the US Gulf Coast and an additional 10 Mt of capacity either under construction or planned.

The US has become a net exporter of plastic resins, primarily to Latin America and Europe [22]. In part due to rising energy costs (especially after 2022) and increasing chemical regulation from REACH (Registration, Evaluation, Authorization and Restriction of Chemicals), Europe's share of world production has decreased from 20% in 2010 to 15% in 2021 [4]. In addition, the European Union's Plastics Strategy mandates that plastic products contain recycled content [23]. As a result, numerous European companies have announced they will close older cracking facilities and either transfer that production to the Middle East (where associated gas is an inexpensive source of ethane) or to the United States.

2.4 Primary vs. secondary (recycled) production

As of the end of 2021, the worldwide output of secondary (recycled) materials was a mere 35 million tons, only accounting for 8% of all materials produced [24]. Only mechanical techniques can be used to recycle plastic materials, using washing, shredding, melting, and extruding processes to create new consumer products. Each time a plastic material undergoes a thermal process (melting, etc.), the polymer chains that make up the material are degraded, resulting in a decrease in molecular weight and physical/mechanical properties. The majority of plastics can only be reused by mechanical means between 2-3 times before they reach the end of their useful life for most applications [25]. For this reason, a majority of recycled

plastics are "downcycled" into lower-value applications (i.e., bottles become carpet fiber, films become composite wood) and cannot be recycled infinitely. There are physical methods that can be used to recycle plastics (i.e., pyrolysis, depolymerization, gasification), and these methods can result in producing virgin quality monomers from plastics; however, they currently are not economically feasible as global capacity is less than 1 million tons, and the energy requirements for each of these processes are extremely high (typically 10-20 MJ/kg output) [25]. Thus, in general, the plastics industry is remaining linear as all virgin materials are extracted, processed into new consumer products, and then subsequently disposed of after a brief consumptive cycle.

3. Plastic Consumption by Sector

3.1 Packaging: the dominant but short-lived sector

Packaging uses more than 42% of all types of plastics (193 Mt in 2021) and, therefore, is the largest user of plastic, followed by construction (14%), textiles (12%), and automotive (11%) [6, 26]. Examples of packaging are: rigid containers such as bottles and tubs, flexible films like shrink wrap and bags, and protective foams (e.g., polystyrene and polyethylene). One of the defining features of this type of plastic is its very short life cycle—on average, the time it takes for a package to be consumed and thrown away is less than six months [27]. For bottles produced for beverages, the time between filling the bottle and throwing it away may be as little as 15 minutes when the bottle is consumed "on the go" (e.g., at sporting events or festivals) [27]. Of all the plastic packaging produced, approximately 95% is disposed of after its initial use, and only 5% has any other use (e.g., refillable bottles, reusable crates) before disposal [6].

As e-commerce grows, the consumption of packaging has also grown significantly. In the period from 2015 to 2022, global e-commerce sales increased threefold: from \$1.5 trillion in 2015 to \$4.5 trillion in 2022, along with the usage of plastic mailing bags, air pillows, bubble wrap, and tape [28]. With an estimated 860 million plastic shopping bags used in 2021, Amazon generated over 200,000 tons of plastic waste [28]. Many companies are now using paper alternatives. However, "when you consider the carbon footprint" of paper bags per unit volume for production and transport, it is approximately 2-3 times higher than that of plastic [29]. Additionally, paper bags still require moisture barriers for many applications [29]. The use of compostable plastics (e.g., PLA) is increasing; however, the plastic

requires an industrial composting facility that exists at 55-60°C with high humidity to decompose properly, and is a contaminant in the conventional recycling stream ^[6].

3.2 Building and construction: the long-lived reservoir

The construction sector consumes 18% of the world's plastic consumption and has a projected consumption of 83 million tons of plastic in 2021 ^[26]. The most prevalent plastic used in construction is PVC, which is used to make pipes (water supply, sewage pipes, electrical installation, gas mains), window frames, electric cable, floor coverings, and roof membranes. Polyurethane foam enables insulation through rigid and flexible forms, whereas polyethylene film is used for moisture-containing membranes ^[30, 19].

In contrast to the use of plastics in packaging, the time between when construction plastics are manufactured and when they begin to be disposed of (as waste) can be measured in decades - 30 to 50 years on average for pipes and window frames, and 100 years or more for pipes buried underground ^[30, 3]. Therefore, the vast majority of construction plastics produced between the years 1970 and 2000 remain in use today. The initial destruction of all of these construction plastics began to occur between 2040 and 2070, and the challenges associated with improperly managing all of this waste stream and providing continued recycling for construction plastics are underestimated ^[30].

The reuse of recycled products will be possible through the recycling of demolition debris, but it will be very expensive to separate contaminated demolition products (e.g., paints, adhesives, fire-retardants, and heavy metals). In addition, there are significant difficulties associated with separating mixed types of plastics (i.e., PVC from polyethylene, or polyurethane foam from metal fasteners) ^[19].

3.3 Transportation: lightweighting and end-of-life vehicles

In 2021, the automotive sector used approximately one-tenth of global plastic output (46 Mt) ^[30]. Passenger automobiles built in 2022 typically use between 150 and 200 kg of plastic parts and account for between 10% and 12% of their total mass as plastic ^[30]. The majority of plastics used in vehicles (approximately 35%) are made from polypropylene (i.e., dashboards, bumper fascia, interior trim, and door panels). Other plastics used to manufacture automobile components include polyurethane (i.e., seat and headrest cushioning) at 20%, polyamide (i.e., engine cover and air intake manifold) at 15%, and PVC (i.e., electrical wire insulation and underbody coating) at 10% ^[30]. Reducing the mass of an automobile by substituting metal for plastic (lightweighting) leads to decreased fuel usage and CO₂ emissions. For every 10% decrease in automobile mass, fuel economy increases by 6% to 8% ^[31]. However, recycling at the end of a vehicle's life (ELV) remains

challenging. Automotive shredder residue (ASR) is a mix of plastics that are generally either sent to landfills or burned for energy. Of the total quantity of plastics used in automobile manufacturing, only 5% to 10% of plastic will be recycled and reused as parts for another vehicle; a significant amount will be downcycled and used in lower-grade applications, such as sound-deadening materials or mats used in construction ^[31].

The European Union's ELV directive mandates that 95% of all automobile manufacturers' waste be recycled; yet, if energy recovery via incineration is included in the ELV recycling percentage, material recycling rates are drastically less than anticipated ^[30].

3.4 Textiles: synthetic fibers as a diffuse microplastic source

Synthetic fibers account for 15% of global plastic consumption (69 Mt in 2021) ^[32]. Polyester (PET) dominates with 60 Mt, followed by polyamide (nylon, 8 Mt), acrylic (3 Mt), and polypropylene (used in nonwovens, 2 Mt) ^[32]. The textile sector has grown rapidly: synthetic fiber production increased from 5 Mt in 1980 to 69 Mt in 2021, surpassing cotton production in 2005 ^[33]. Polyester now accounts for 52% of global fiber production, compared to cotton's 23% ^[33].

The environmental release pathway for textiles is unique and diffuse. During laundering, synthetic garments shed microfibers-typically 100-500 mg per kg of fabric per wash ^[34]. A single fleece jacket (100% polyester) can shed 1,000-2,000 mg of microfibers over its lifetime, equivalent to 50,000-100,000 individual fibers ^[35]. Factors affecting shedding include fabric type (fleece sheds more than woven), age (older garments shed less), wash temperature (hot water increases shedding), and detergent type (powders cause more abrasion than liquids) ^[34]. Wastewater treatment plants capture 85-95% of these fibers, but the absolute number discharged is enormous: a plant serving 500,000 people can release 50-100 million microfibers per day ^[36]. These fibers are too small to be filtered by conventional sand or membrane systems without advanced tertiary treatment (e.g., ultrafiltration or reverse osmosis) ^[36].

4. Waste Generation and Management Infrastructure

4.1 Mass balance

The 460 million tons of plastic that are produced every year, around 350 million tons flow into the waste stream in the same year they were produced ^[3]. The other 110 million tons are put into use for buildings, cars, machinery, etc., where they will be stored for years or even decades. In 2022, the total in-use storage of plastics was about 2.8 billion tons ^[3, 24]. The amount of waste generated each year (350 million tons) is equivalent to the weight of 35,000 Eiffel Towers or 2.3 million blue whales ^[7].

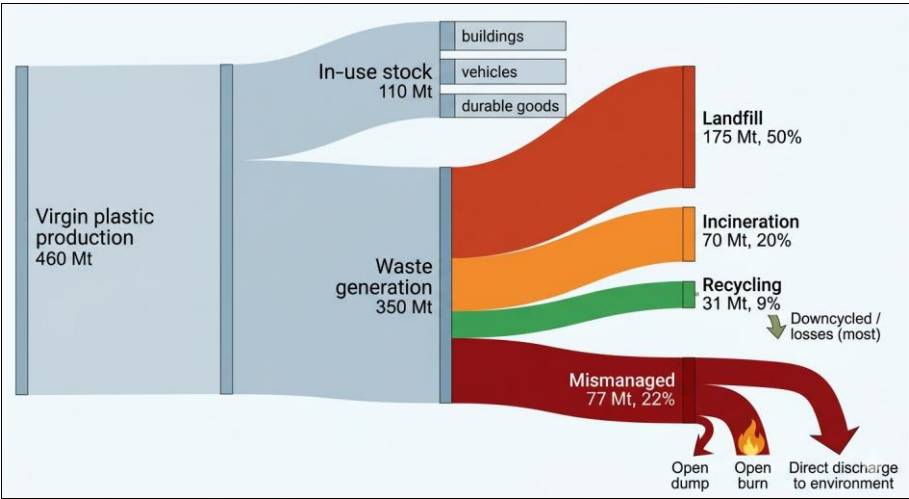


Fig 3: Diagrammatic representation of global plastic flow

4.2 The Global Waste Management Pathways (2019)

You've probably heard that waste management statistics vary by region, but what you may not have known is that some countries are significantly better at managing waste than others. For example, high-income (OECD) nations (excluding Mexico and Turkey) recycle 22% of their waste, incinerate 32%, landfill 38%, and mismanage 8% of their waste [24]. However, when we account for the waste exported for recycling, much of which is actually mismanaged in the destination countries, the effective mismanagement rate for these nations rises from 8% to 15% [29]. Conversely, low- and middle-income countries (excluding China) have quite different waste management profiles, recycling 6%, incinerating 4%, landfilling 35%, and mismanaging 55% of their waste [24, 38]. Due to the absence of an adequate waste collection system,

particularly in peri-urban and rural areas, plastic waste is often disposed of in uncontrolled heaps (which may contribute to the spread of infectious diseases and pollute surrounding waterways), incinerated in backyards or landfills (which generate noxious dioxins, furans, and black carbon), or placed in ditches and gutters [38]. In China, waste management has significantly improved. In 2015, China mismanaged 35% of its plastic waste, but by 2020, following massive investments in incineration capacity (over 350 plants with a total of more than 1 million tons per day of capacity), it had reduced mismanaged plastic waste to 12% [39, 24]. However, incinerators in China still have insufficient capacity, and many are operating below acceptable emission levels, releasing fine particulate matter (PM2.5) and dioxins into the environment [39].

Table 2: The Global plastic waste management by different regions (2019)

Region / Country Group	Landfill (%)	Incineration (%)	Recycling (%)	Mismanaged (%)	Notes
High-income countries (OECD excl. Mexico / Turkey)	38	32	22	8	Exports not accounted; effective mismanagement ~15%
Low- & middle-income countries (excl. China)	35	4	6	55	Lacks formal collection in many areas
China (pre-2015)	~45	~10	~10	~35	Rapid improvement after 2015
China (2020)	~20	~55	~13	~12	Massive investment in incineration
Global average	50	20	9	22	~350 Mt total annual waste

NOTE: Source of this data is from OECD (2022).

4.3 The Collapse of The Global Recycling Markets: National Sword Policy

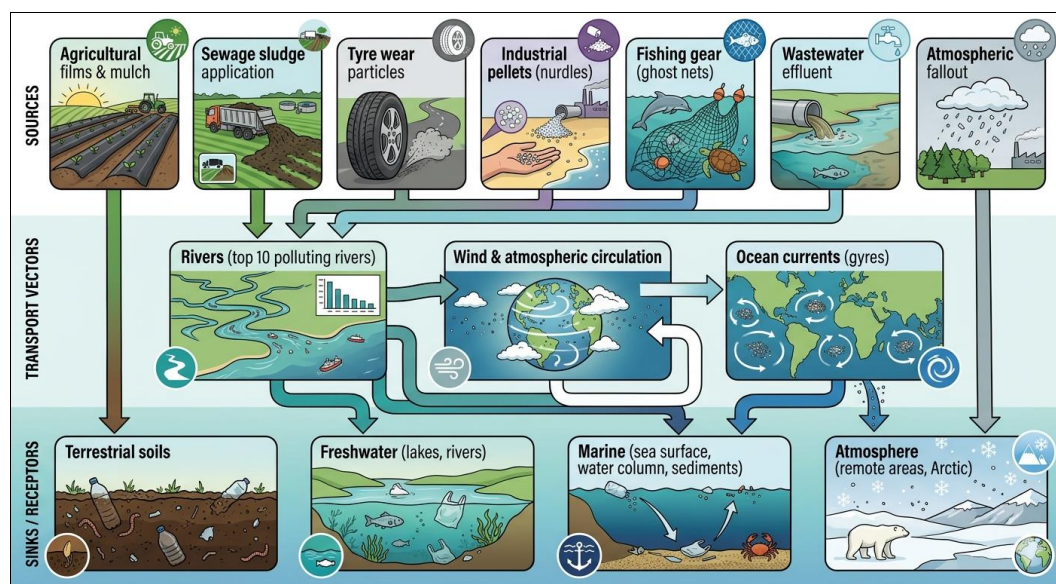
High-income countries exported a staggering 50-70% of their collected plastic waste for recycling in China up until July 2017. In fact, in 2016 alone, China received 8.5 million tons of imported plastic waste [40]. Nevertheless, due to consistently poor quality of many bales due to contamination (food remnants, mixed polymers, non-recyclables, hazardous waste), roughly 20-30% of each load ended up being contaminated [40]. Therefore, China's implementation of the National Sword Policy in July 2017 effectively ended the importation of 24 categories of solid waste, including most post-consumer plastics, into China. The ban was fully implemented on January 1, 2018 [40]. Once the ban took effect, the impact on the global recycling rate measured in terms of domestically processed materials

virtually collapsed. In the UK, for instance, the effective recycling rate fell from 46% to 29% when compared to 2017, when the UK exported 800,000 tons of plastic waste to China [41]. With the closures of the port in China, much of the waste going to China was directly redirected toward other developing Asian countries, which were already violating any environmentally acceptable procedures and had extremely low processing capabilities [42]. A Greenpeace report issued in 2020 indicated that approximately 50% of plastic waste exported from the EU to Turkey was illegally dumped and/or burned, frequently being disposed of in open fields or along roadways [42]. Illegal dumping of plastic waste processing in Malaysia was reported to be responsible for water pollution (rivers turning white and opaque from plastic residue) and related respiratory illnesses in nearby communities [43].

5. Environmental Release Pathways

The major release pathways of plastics in the environment

are shown in figure 4.



NOTE: Information taken from [12, 13, 51, 49, 46]

Fig 4: This diagram shows pathways of plastic release to the environment.

5.1 Release pathways of plastic in terrestrial environments

In many areas of the world, the primary receptor for plastic pollution is soil; however, much less research is conducted on terrestrial pollution compared to oceans. Some of the key terrestrial pathways include:

Agricultural Film Residues: Mulch films have been accumulating at a rate of 50-250 kg/ha/year [44], and the concentration of microplastics within soils in the Xinjiang region of China is reported to be between 200-500 particles/kg (after ~10-20 years) [45]. In the Almería region of Spain (intensive greenhouse agriculture), some agricultural fields are reported to have up to 1,000 kg/ha of accumulated plastic debris [44].

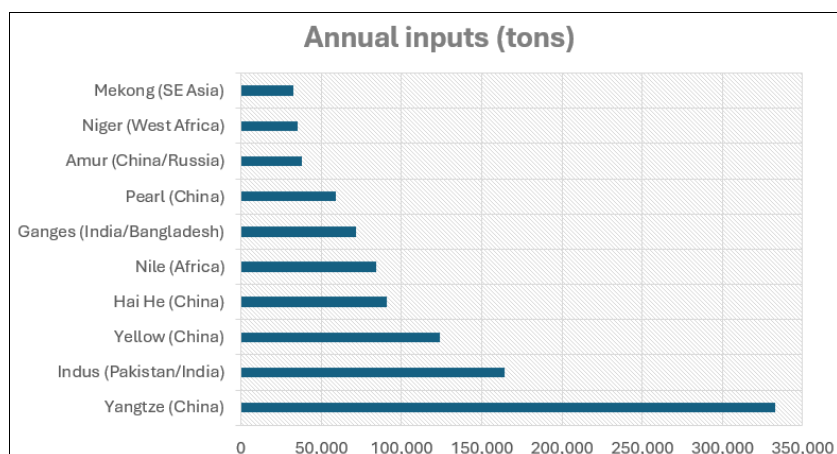
Sewage Sludge Application: Approximately 85-99% of microplastics are removed from influent within wastewater treatment plants and concentrated into sludge (biosolids) [46]; however, in Europe and North America, roughly 50% of these biosolids are applied to agricultural land as fertilizer (the remaining biosolids are either incinerated, landfilled or used for land reclamation) [46]. Applying biosolids at rates of 5-10 tons of dry sludge per hectare per year introduces approximately 50,000-100,000 microplastics per square meter of soil per year [47]. A long-term study conducted in Switzerland indicated that soils that received biosolid applications contained ~0.5-1.5 g of microplastic per kilogram of dry soil after 25 years of biosolid application [48].

Tyre wear particles account for a significant amount of microplastic pollution. It is estimated that each individual in developed nations produces 1 kg of tyre wear particles annually (in countries including the United States of

America (USA), the European Union (EU), and Japan) [49]. The tyre itself loses about 10% to 30% of its weight and will release tyre wear particles into the environment during its lifetime as it wears away from use. Tyre wear particles are transported from roads to the surrounding soil via both water (rain runoff) and wind. Concentrations of tyre wear particles in roadside soils can range from 5 to 10 g/kg at distances less than 10 m from major highways, up to 20 g/kg at locations such as intersections and roundabouts where braking and acceleration occur frequently [50]. The composition of tyre wear particles contains a complex blend of different materials and chemicals such as rubber polymers (i.e., styrene butadiene rubber, natural rubber), carbon black, zinc oxide, sulfur, and polycyclic aromatic hydrocarbons (PAHs) [49].

5.2 Release pathway of plastic in freshwaters

Rivers provide the main pathway for plastic waste that comes from land to enter the ocean. The ten largest rivers in the world that contribute the majority of plastic waste into oceans are located primarily in Asia and Africa and account for an estimated 1.15 million to 2.41 million tons of waste each year [51, 52]. The Yangtze River alone contributes an estimated 333,000 tons per year [53]. The top ten rivers (Yangtze, Indus, Yellow, Hai He, Nile, Ganges, Pearl, Amur, Niger, Mekong) account for approximately 90% of plastic waste that enters oceans from rivers [51]. These rivers are located in some of the most densely populated and rapidly developing areas, and the regions they flow through typically have inadequate infrastructure to handle large volumes of waste. In addition, during floods caused by monsoon rains, large amounts of accumulated waste are mobilized.



NOTE: This data is from [51, 52]

Fig 5: Top 10 rivers that contribute to the ocean plastic pollution (in tons).

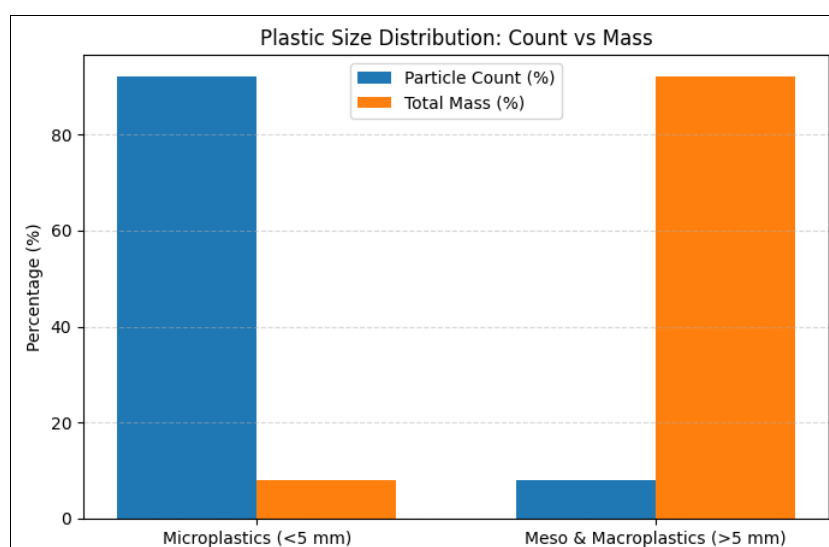
Urban wastewater treatment plants, while removing 85-99% of microplastics from influent, still discharge billions of particles per day into receiving waters due to the sheer volume of flow. A typical secondary treatment plant with a flow of 100,000 m³ day⁻¹ (serving ~300,000 people) discharges 10-100 million microplastic particles daily, even with 95% removal efficiency [36, 37]. These effluents create microplastic "hotspots" in rivers downstream of treatment outfalls, with concentrations up to 10 times higher than upstream background levels [37]. Stormwater overflows—which bypass treatment plants during heavy rain—are an even larger source, releasing untreated sewage and microplastics directly into rivers. In the United Kingdom, stormwater overflows discharge an estimated 3.5 Mt of untreated sewage annually, containing billions of microplastic particles [36].

5.3 Marine release pathways

The marine plastic inputs originate from 3 primary sources: land-based waste mismanagement, which is (82%), fishing (10%), and shipping or aquaculture (8%) [38, 39]. Microplastic

release from fishing nets, fishing lines, and trapes are major reason for microplastic input in certain regions, with an estimated value of 640,000 tons discarded annually [40]. "Ghost nets" (abandoned, lost, or discarded fishing nets) continue to trap fish, marine mammals (dolphins, whales), sea turtles, and seabirds for decades. A single ghost net can kill up to 3,000 marine animals over its lifetime [40].

The five subtropical gyres—North Pacific, South Pacific, North Atlantic, South Atlantic, and Indian Ocean—accumulate floating plastics due to convergent surface currents (Ekman transport and geostrophic flow). The Great Pacific Garbage Patch (GPGP), located between Hawaii and California, contains 79,000 tons of plastic distributed across 1.6 million km²—an area three times the size of France [41]. Unlike popular imagery of solid "islands", the GPGP is a diffuse soup: "92% of particle count is microplastics (<5 mm), but 92% of the total mass is from larger debris (>5 mm). Of that macroplastic mass, approximately 75% consists of derelict fishing gear (nets, lines, ropes, buoys) [41].



Note. Data from [58].

Fig 6: Composition of the Great Pacific Garbage Patch (GPGP) by particle count versus total mass. Although microplastics (<5 mm) dominate particle numbers (92%), larger debris (>5 mm) accounts for 92% of the total mass. Of the macroplastic mass, approximately 75% consists of derelict fishing gear (nets, lines, ropes, buoys)

Microplastics in the GPGP have been colonized by marine organisms (bacteria, diatoms, barnacles, bryozoans), forming a novel "plastisphere" ecosystem that can transport invasive species across ocean basins ^[41].

5.4 Atmospheric transport pathways

Recent research has identified atmospheric transport as a significant pathway for microplastic transport, particularly for fibers <100 µm. Microplastics have been detected in remote mountain catchments (Pyrenees, 365 particles m⁻² day⁻¹), in Arctic snow (14,000 particles per liter of snow), and in the French Pyrenees at an altitude of 2,800 m (53 particles m⁻² day⁻¹) ^[13, 14, 42]. Atmospheric modelling suggests that road dust (from tire wear and brake wear) and agricultural soils (from sludge application and film residues) are major emission sources, with transport distances exceeding 1,000 km ^[42]. A study in the western United States found that 4% of atmospheric deposition of microplastics came from transboundary transport (e.g., from Asia), while the remainder was regional ^[43]. Microplastic fibers have been found in the atmosphere of remote oceanic regions (e.g., the Arctic), indicating that long-range transport is ubiquitous ^[14].

5.5 Industrial pellet loss

Pre-production plastic pellets (nurdles)-typically 2-5 mm diameter cylinders-are lost throughout the supply chain during manufacturing, transport, and handling. Estimates suggest that 50-200 billion pellets (5,000-20,000 tons) are released annually in Europe alone (2012) ^[44]. During any loading or unloading, plastic pellets can be spilled from containers, and when facilities are washed, they can enter drainage systems or be released during maritime accidents, like X-Press Pearl in May 2020, which discharged around 1680 tons of pellets in the Indian Ocean ^[45].

Once released in the environment, pellets will adsorb hydrophobic contaminants such as PCBs, DDT, PAHs, and nonylphenol at concentrations up to 1 million times ambient water levels ^[46]. They are ingested by seabirds (e.g., the Laysan albatross, where pellets account for up to 90% of stomach contents in some colonies), fish, sea turtles, and marine mammals, serving as vectors for toxin transfer up the food web ^[46].

6. Fragmentation and Secondary Microplastic Generation

Primary microplastics in the atmosphere make up anywhere from 15-31% of harmful pollutants, including industrial abrasives (utilised in sandblasting, cleaning of ships or before 2020 (banned in EU, USA, Canada and other nations) with use of beauty products that originally contained microbeads), textile fibers (lost through washing, not just through wearing), and particle wear from tires ^[64, 65]. Secondary microplastic is generated from the breakdown of larger pieces of microplastic; therefore generally (69 - 85% total by weight) comprises the bulk quantity of microplastics in the environment ^[65].

The rate at which plastic breaks down is dependent upon a variety of factors: the type of plastic, exposure to ultraviolet (UV) light (sunlight), physical wear from abrasive actions, temperature, and the presence of a biofilm. In aquatic environments, the photo-oxidation process begins with the

UV light (sunlight) being absorbed by the polymer, breaking the long-chain molecules into smaller pieces and generating free radicals that continue to break down the polymer. A single standard 500 mL bottle of polyethylene terephthalate (PET), the water can be broken down into the between 10,000 and 100,000 pieces, of microplastic in the ocean within a 2 to 5-year period ^[66]. Expanded polystyrene (EPS) foam will be reduced even faster than PET foam. One EPS foam cup can create more than 1 million pieces of microplastic within 1 year. By breaking down the cellular structure of the EPS foam in both UV light and through wave action ^[67].

Nanoplastics (<1 µm) represent the least understood microparticle and are considered to be one of the most dangerous microparticles due to their potential ability to penetrate cell membranes, the blood-brain barrier, and the placental barrier ^[68].

Currently, there are a number of new methods for detecting nanoplastics in the environment (e.g., soil, water, and biota) under development. However, all of the available methods (i.e., pyrolysis-GC-MS, Raman spectroscopy, and electron microscopy) have not been sufficient to provide for the usual detection of nanoplastics, and no consensus protocol has been developed ^[69]. Current estimates have suggested that nanoplastics may comprise between 10 - 20% of the total number of particles, which contained in some types of environmental materials, but this number is still very uncertain ^[68].

7. Regional Disparities and Environmental Justice

Plastic Production, consumption, and disposal are all different regions of the world. High-income countries (16% of the global population) produce almost half of the world's plastic waste (46%). Low-Income countries (9% of the global population) produce almost no plastic waste (3%) ^[70, 24].

However, the international trade in waste has historically shipped the environmental impacts, of waste from high-income countries to middle-income countries. Before China's National Sword ban, for example, the United Kingdom exported 800,000 metric tons (Mt) of waste to China each year, the United States exported 1.2 Mt, Germany (0.7 Mt), and Japan exported 0.5 Mt ^[40, 41].

Since 2018, much of this waste was diverted to countries like Vietnam, Malaysia, Thailand and Turkey. A 2021 study of EU plastic waste exported to Turkey found that over 50% of the exported waste was mismanaged, either dumped or burned improperly ^[43]. In Malaysia, illegal plastic waste processing has caused significant water contamination (rivers that are opaque white from plastic residue and heavy metals above safe levels) ^[71]. In Indonesia, imported plastic waste has outstripped local recycling capacity leading to open burning that releases dioxins and furans into the environment ^[72]. These current developments are examples of environmental injustice, where low-income countries with less regulatory oversight are left responsible for the human and environmental health costs attributed to high-income countries' plastic consumption.

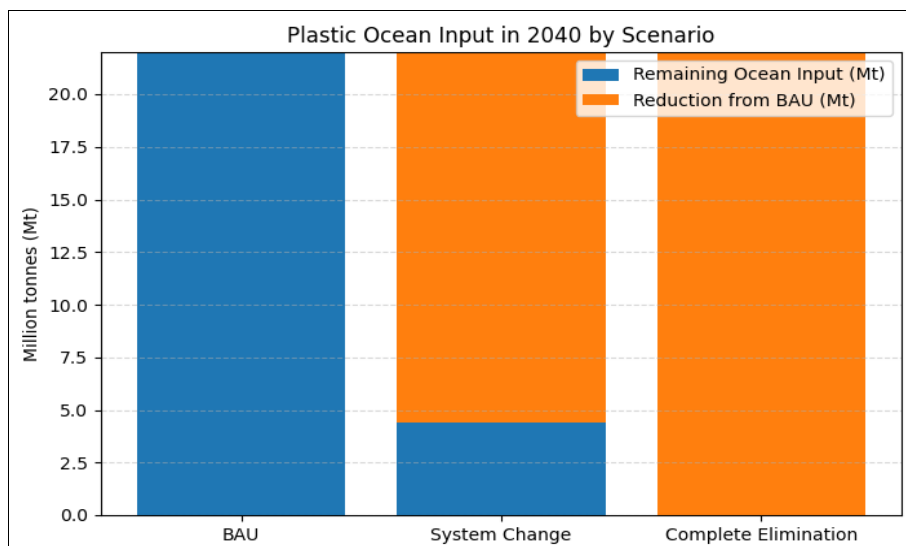
8. Future Projections and Scenario Analysis

Under business-as-usual projections (current production growth of 8.4% CAGR and current waste management

trends), global plastic production will reach 1,100 Mt by 2050, with cumulative waste reaching 12 billion tons^[3, 6]. Ocean plastic inputs, which were 11 Mt in 2016, would rise to 22 Mt by 2050—a doubling of annual inputs^[47].

The Pew Charitable Trusts and SYSTEMIQ (2020) modelled eight intervention scenarios, ranging from business-as-usual to "system change" that combines: (1) reducing plastic production (by eliminating unnecessary packaging and single-use items), (2) substituting with alternative materials (paper, compostables, glass, metal), (3)

designing for recyclability (mono-material packaging, elimination of problematic additives), (4) expanding waste collection in low-income countries (from current 60% to 90% of the population), (5) increasing mechanical recycling capacity (by a factor of 5), and (6) reducing waste exports^[47]. Even the most aggressive scenario (system change) would only reduce annual ocean plastic inputs by 77% relative to 2016 levels—meaning 4.4 Mt yr⁻¹ would still enter the ocean in 2040^[47].



NOTE: The data is taken from^[73]

Fig 7: Projected annual ocean plastic inputs under different scenarios (2020-2040). Under business-as-usual (BAU), annual inputs double from 11 Mt (2016) to 22 Mt by 2040.

According to the study, additional measures are needed to completely eliminate plastic pollution, such as requiring recycled content (e.g., 30% in new packaging), implementing deposit-refund systems (on bottles and containers), and creating extended producer responsibility (EPR) programs that will make producers financially responsible for the management of their products after use^[47].

9. Conclusion

Plastic production has grown exponentially to 460 Mt annually, with packaging (42%) dominating consumption and generating waste within six months. Of the 350 Mt of annual plastic waste, 22% is mismanaged—neither recycled, incinerated, nor landfilled—leading to environmental release across terrestrial, freshwater, marine, and atmospheric pathways. Major release routes include: river transport (1.15-2.41 Mt yr⁻¹ to oceans), agricultural film residues (50-250 kg ha⁻¹ yr⁻¹), wastewater effluent (billions of microplastic particles per day per plant), and atmospheric deposition (up to 365 particles m⁻² d⁻¹ in remote areas). Fragmentation generates secondary microplastics that dominate environmental particle counts (69-85% of total). Regional disparities in production, consumption, and waste management capacity create environmental justice concerns, as waste exports shift pollution burdens from high-income to low-income countries. The collapse of global recycling markets following China's National Sword policy has exposed the fragility of export-dependent recycling systems.

Addressing this crisis requires systemic transformation from linear to circular material flows: reducing virgin plastic production, mandating recycled content, redesigning products for durability and recyclability, expanding formal waste collection in low- and middle-income countries, and implementing extended producer responsibility. Without such action, business-as-usual projections indicate ocean plastic inputs will double by 2050, and cumulative plastic waste will reach 12 billion tons, with consequences for ecosystems and human health that are only beginning to be understood.

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