environments

Review

Environmental and Economic Impacts of Mismanaged Plastics and Measures for Mitigation

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Abstract: The mismanagement of plastic materials has grown to become a mounting global pollution concern that is closely implicated in unsustainable production and consumption paradigms. The ecological, social, and economic impacts of plastic waste mismanagement are currently transboundary in nature and have necessitated numerous methods of government intervention in order to address and mitigate the globalized and multifaceted dilemmas posed by high rates and volumes of plastic waste generation. This review examines the current landscape of a plastics economy which has operated with a linear momentum, employing large quantities of primary resources and disincentivizing the functioning of a robust recycling market for collecting plastic waste and reintegrating it into the consumer market. This contextualizes an increasing plastic pollution crisis that has required global efforts to address and mitigate the ecological risks and socio-economic challenges of mismanaged plastic waste. A timeline of government interventions regarding plastic pollution is described, including numerous international, regional, and local actions to combat plastic waste, and this is followed by an examination of the relevance of the extended producer responsibility principle to improve plastic waste management and obligate industry to assume responsibility in waste collection and recycling.

Keywords: plastic pollution; marine litter; food packaging; single-use plastics (SUPs); recycling and reuse; extended producer responsibility (EPR)

Citation: Diggle, A.; Walker, T.R. Environmental and Economic Impacts of Mismanaged Plastics and Measures for Mitigation. *Environments* **2022**, *9*, 15. https://doi.org/10.3390/environments9020015

Academic Editor: Dimitrios Komilis

Received: 29 December 2021
Accepted: 18 January 2022
Published: 21 January 2022

1. Introduction

Plastics have become ubiquitous in the global economy and are integrated into the functioning of many industrial sectors [1]. Many plastic applications are added to long-term stocks, while in contrast, plastic packaging materials have a very short life cycle and are currently discarded as waste in large volumes [1,2]. Large volumes of primary plastics are produced and discarded within the same year, resulting in millions of tonnes of primary industrial resources that are not recovered and reintegrated back into the economic market [1,3]. Growth in the production and consumption of disposable packaging materials currently contributes to most domestic waste streams internationally, as packaging waste accounts for an estimated 15–35% of household solid waste around the world [4].

Improper management of waste packaging materials is an increasingly burdensome task for communities and citizens to address. The material complexity of the packaging waste stream restricts the efficient functioning of secondary recycling markets, and the pace and scale of primary plastics production has hampered the capacity of recycling industries to produce substantial feedstock at a quality and scale necessary to compete with virgin plastics, inhibiting a thriving secondary market for plastic packaging [1,5,6]. Furthermore, inadequate plastic recycling has caused the leakage of land-based plastic waste into terrestrial and aquatic environments, through insufficient or nonexistent waste management infrastructure [7]. Since the introduction of plastic material to the consumer market, a burgeoning plastic pollution crisis has been occurring on land and at sea [8]. This review seeks to examine the ongoing impacts and risks of plastic pollution in the natural environment, and the available governance instruments that have been employed in order to effectively mitigate the risks and the further accumulation of plastic pollution.

2. Impacts of Plastic Production

The global value chain for plastics spans numerous industries and complexifies the total life cycle of plastics production, use, and disposal. The value chain consists of a complex network of stakeholders operating in the following industrial sectors described by Barrowclough & Birkbeck [9]:

- Raw material extraction and provision of material feedstocks;
- Refining raw inputs to produce feedstock for production of plastics;
- Converting plastics into plastic resins or fibers;
- Manufacturing intermediate and final plastic products;
- Plastic use by all final consumers including brands, institutions, retailers, and distributors;
- Collection, sorting and transportation of plastic waste;
- Plastic waste treatment in landfill, incineration, recycling, or dumping;
- Plastic reuse as secondary materials or in waste-to-energy approaches.

According to the International Energy Agency, the production of virgin plastics has increased over tenfold globally since 1970 and has exceeded the growth of any other group of bulk materials produced by the chemical sector, including steel, cement, aluminum, and ammonia [10]. According to estimates by the Ellen MacArthur Foundation (EMF) [3], plastic consumes between 4 and 8% of global oil production, equal to the oil consumed by the global aviation industry. Oil demand for plastic production is expected to outpace that for road passenger transport by 2050, and the projected combined CO_2 emissions from both production and embedded carbon amounts to 287 billion metric tonnes (Bt) annually by the end of this century, comprising more than one third of the allotted carbon budget under a 2 °C climate warming scenario [10]. The production of plastics has grown at an exponential rate, permitted by a highly government-subsidized petroleum industry since the mid-20th century.

Plastic dominates consumption choices and prevails across the global supply chain [1,10]. In response to the currently decreasing demand for oil and gas for energy for transportation, and the decarbonization of electricity generation, the fossil fuel industry has been expanding investments in plastic production [11,12]. Investments in new refineries and ethane-cracking facilities are now on the rise across the United States, to increase its domestic capacity to produce chemical feedstock for the production of plastic materials [12,13]. The United States currently holds approximately 40% of the global capacity to produce ethane-based petrochemicals, and its market share of steam cracking facilities is projected to rise to 22% by 2025 (20% higher than 2017 levels) [10]. Ethane is considered a preferable, lower-cost domestic alternative to other plastic feedstocks such as naphtha, originally accessed from stocks in India and China [13]. These facilities are known to emit high levels of carbon dioxide (CO_2) in their production of plastic feedstock and are of concern for public health regarding air quality, water contamination, and environmental degradation surrounding production facilities [12,14]. Virgin plastics production is thus projected to rise amidst a backdrop of a plastic mismanagement crisis.

An estimated 9.2 Bt of virgin plastic was produced between 1950 and 2017, and an estimated mere 9% of the quantity produced has been recycled within that time period, leading to a crisis of overproduction as well as of resource loss and waste mismanagement [1]. Based on global estimates from Geyer [1], around 36% of plastic production is employed for packaging, accounting for 158 million metric tonnes (Mt) of the total plastic resin produced in 2017. The production rates of plastic resins in 2017 are shown in Table 1 based on analysis by Geyer [1].

Table 1. Estimated primary plastic production in 2017 by resin type (by mass) [1].

Polymer Resin Type	Estimated Primary Plastic Production in 2017 (%)
#1 Polyethylene terephthalate (PET)	8%
#2 High-density polyethylene (HDPE)	13%
#3 Polyvinyl chloride (PVC)	9%
#4 Low-density (LDPE) and linear low-density polyethylene (LLDPE)	16%
#5 Polypropylene (PP)	17%
#6 Polystyrene (PS)	6%
Other plastics and additives	31%

Alongside the 158 Mt produced in 2017, a total of 152 Mt or 46% of plastic waste generated during the same year was packaging [1]. Plastic production reached a total of 368 Mt in 2019 [15] and production rates have increased annually. Rates of plastic waste generation are projected to continue to increase during the next decades due to projected growth in plastic production, in human population, and in plastic consumption, but they are also dependent on global waste generation rates, improvements in overall waste management, recycling technology and governance, material reduction and substitution, and progress towards circular economy goals for plastic materials [16,17]. Currently, the high rates of virgin plastic production have outpaced development of adequate recycling infrastructure and technologies, which are out of step with increasing demands for plastic packaging.

3. The Reality of Plastic Recycling

The origins of the term and concept of recycling are rooted within the oil processing industry, to describe the process of re-refining petroleum materials to reduce the quantity of waste [18]. Once the term was popularly re-employed in the 1960s and 1970s, it became a descriptor for general material reuse and reclamation, and eventually became a commonplace term for the collection of separated waste streams [18].

The packaging industry is dependent on extractive industries to produce steel, aluminum, glass, paper and cardboard, and plastic. Metal and glass packaging materials often do not require the addition of primary materials into their recycling processes and are therefore suitable for repeated recycling that retains the original material properties intact, while plastic packaging recycling processes usually require the inclusion of additional primary materials to produce secondary materials [19]. While recycling technologies have been developed to decrease the quantity of virgin resources necessary to produce packaging materials, current economic and technical dynamics are significant in shaping resource flows within the packaging industry.

Currently, the goal of plastic recycling is to reduce the need for primary plastic production, as well as to recover the value in materials that have fulfilled their functional purpose. The variety of many plastic types makes recycling difficult, largely due to multi-material configurations. Recyclability can be restricted by a range of product features, including product format, material, size, color, and transparency, as well as the surface presence of inks, adhesives, and labels [20,21]. Due to their perceived low or inconsistent quality, recycled plastics can trade at discounts of up to 50% lower than the price of some corresponding primary plastic categories [5]. The myriad types of plastics on the market with a range of chemical and physical properties inhibits the functioning of efficient plastic recycling. Additionally, recycled plastics are continually in economic competition with the virgin plastics market, which has a higher relative material efficiency compared with secondary plastic production, due to the ongoing availability of lower-cost feedstock [6]. Enkvist and Klevnäs [5] describe the contradiction at play in improving secondary plastics where "a fragmented and small-scale recycling industry cannot produce the consistent quality and volumes required for large-scale use, even as lack of demand holds back the investment that would enable such production in the first place" (p. 84).

Various methods are used to treat plastic waste. Two main methods of recycling are available in mechanical and chemical form. Mechanical recycling, also termed back-to-polymer recycling, allows for the recovered material to be remanufactured or downgraded into a new product with a different function. Chemical recycling, also termed back-to-monomer recycling, concerns the recovery of a product into its chemical constituents, permitting closed-loop recycling that maintains a material's original quality. Closed-loop recycling is possible when a resin "is returned at the end of its initial lifetime in a fit state to fulfill the service for which it was originally produced" [10] (p. 23). Open-loop recycling, by contrast, remanufactures a product with a loss in physical quality and properties [10,22]. Various recycling options available for plastics are otherwise categorized into primary, secondary, tertiary, and quaternary recycling by Bocken et al. [23], and are further described in Table 2.

Table 2. Overview of plastic recycling methods [23].

Recycling	Description
Primary recycling (mechanical recycling)	Employs the mechanical recycling process to retain original quality of material properties (known as closed-loop recycling within a circular economy)
Secondary recycling (mechanical recycling)	Employs the mechanical recycling process resulting in lower-quality material properties (known as downgrading within a circular economy)
Tertiary recycling (chemical recycling)	Employs the chemical recycling process to the material's chemical constituents to retain original chemical properties (known as depolymerization and repolymerization in a circular economy)
Quaternary recycling (energy recovery and incineration)	Employs thermal recycling and energy recovery through incineration of materials (not considered recycling in a circular economy)

The OECD [20] distinguishes between two important factors that are relevant in defining recycling capacity, clarifying further the discrepancy between perceived and actual recyclability. A material's technical recyclability is based on the currently existing recycling technologies available, while practical recyclability is subject to greater regional differences across the world, given that each country has access to different recycling and waste management infrastructure largely shaped by available public funds, market conditions, and socio-economic determinants [20].

Cognizant of the many factors hindering recovery of plastics and production of secondary plastics, it has been recognized that plastic recycling produces the lowest CO_2 emissions compared to other methods of plastics production. Globally, mechanical recycling is the most available method of plastic recovery, and chemical recycling rates still remain quite low [1]. Enkvist and Klevnäs [5] determined that current primary plastic production produces 5.1 tonnes of CO_2 per 1 tonne of primary plastic (both in production and embedded carbon use), compared to the production of secondary plastics via mechanical recycling, which produces 1.4 tonnes of CO_2 emissions per 1 tonne of recycled plastic. Additionally, looking forward, they projected that mechanical recycling would produce only 0.1 tonnes of CO_2 emissions per 1 tonne of secondary plastic produced, based on projections for 2050 regarding increased decarbonization in recycling technology [5]. From a material efficiency standpoint, plastics recycling is deemed a valuable manufacturing option, while being fraught with barriers to achieving circularity with respect to plastics.

Currently, recycling is not functioning at the scale that is necessary to adequately process the quantity of plastic waste that is currently discarded globally. Therefore, the production of plastic resin does not align production with the realistic capacities of recycling infrastructure. Contextualizing this challenge, Gordon [24] states that "the benefits of recycling [...] are based on a series of assumptions that may not match the reality of how these systems operate and the impacts of the materials that flow through them" (p. 28).

Plastic Waste Exports

Due to inhibitive technical and economic barriers impacting plastic recycling, recycling has become a substantial economic and technical matter of resource management through the 20th and 21st centuries. The economic and technological barriers currently restricting closed-loop recovery of plastic waste have placed a burden on municipal waste programs that has left communities struggling to address stockpiles of solid waste in recycling bins, due to a lack of stable and long-term end markets for recycling, as well as domestic capacity to process waste locally. As a remedy to combat a domestic issue of increased recyclable waste, many countries across the world have facilitated an international trade in plastic waste amounting to a total of USD 3.3B in trade value, according to the United Nations Conference on Trade and Development (UNCTAD) [25].

For many years, the recycling trade in global scrap plastic materials was predominantly based in China, later sweeping across the globe to other markets that would accept designated materials to manage [26,27]. East Asia and Pacific countries imported the vast majority of plastic waste between 1988 and 2016, accounting for 75% of total imports [28]. Until the Chinese government restricted plastic scrap imports in the early part of 2018, many recycling programs relied on exports to the Chinese recycling market [29]. Through its National Sword policy, China shed its previous role as the world's largest importer of recyclable waste by banning 24 different types of materials from foreign shipments, thereby eradicating many nations' main export market for their recyclable materials [29,30]. Smaller recycling markets in Southeast Asia attempted to fill the void left by China and began importing larger quantities of plastics and other recyclable materials to fulfill the overseas demand, and countries including Malaysia, Thailand, and Turkey were soon inundated by waste materials [6,31]. Brooks et al. [28] estimated that the trade implications of China's restrictions will displace a total of 111 Mt of plastic waste by 2030.

Pacini et al. [32] examined the import and export patterns of styrene, ethylene, PVC, and mixed plastics waste within the global plastic scrap trade network during 2018, which amounted to a total quantity of 2738 declared intercontinental and transcontinental transactions between a network of 111 countries. The global plastic scrap trade in 2018 dramatically declined by 45.5% from the years prior to the Chinese import ban, as many countries involved in plastic waste exports in the past turned to stockpiling their high volumes of plastic waste locally, increasing landfill usage [33]. Waste recycling capacity is lacking in many importing countries, and landfill methods are the more common waste management approach in recycling markets located in Malaysia [33,34]. Ratifications to the international Basel Convention under the United Nations Environment Programme, which regulates the transboundary shipment of hazardous wastes between countries, have attempted to limit the shipment of plastic waste overseas to countries lacking environmental protocols for effective recycling or safe operational conditions in recycling facilities [26]. Within this reality, transplanting recycling challenges by the transboundary shipment of wastes to emerging economies and recycling markets with low or inadequate access to recycling infrastructure creates ongoing social and ecological risks.

The global waste trade has resulted in profound inequities through the transfer of stockpiled plastic scrap waste from the Global North to Asian, African, and Latin American nations [35]. Many regions of the Global South do not have access to even the most basic waste collection services, especially in rural regions, creating large quantities of waste plastic that are not formally collected and managed even before foreign waste imports add to an existing stockpile [6,36,37]. The work of informal waste workers and cooperatives around the world has contributed to local waste management, recycling, and litter reduction in substantial ways in the face of a lack of available waste infrastructure [36,38,39]. Informal waste work in collection, handling, and recycling employs an estimated 15 to 20 million people globally, predominantly workers who are women, children, elderly, or migrants [34,40,41]. Informal waste work has been on the front line of the plastic pollution crisis since its origins. Particularly for packaging waste, informal waste workers can play a crucial role in mitigating plastic waste emissions into terrestrial and marine environments [39]. Given these challenges, the current state of waste generation and recycling is hindering the operation of a circular economy for plastics.

4. Plastic Leakage into Marine and Terrestrial Environments

Discarded plastic materials created a burgeoning pollution crisis in ecological systems soon after the production of consumer plastics began. Thompson et al. [42] examined plankton samples that were collected regularly from various points along coastlines of the UK and Iceland dating back to the 1960s, and among the collected plankton samples found various polymers with increasing abundance over time. Among the earliest scientific accounts of a burgeoning pollution issue that would later be known to impact birds, fish, and other wildlife was that from two American marine biologists in 1972, Carpenter and Smith [43], who documented findings of plastic in the Sargasso Sea in concentrations of approximately 3500 particles and fragments per square kilometer (km^2). Since then, studies have documented the presence of plastic debris at some of the highest points on Earth, e.g., the surface of Mount Everest at the China-Nepal border [44], and at the lowest, within oceanic trenches [45,46].

Forty years after Carpenter and Smith's findings, Eriksen et al. [47] published an oceanic survey that estimated that 5.25 trillion plastic particles, weighing an estimated 268,940 tonnes, were floating as debris in the world's oceans, ranging from 0.33 mm (mm) to above 200 mm in size. Their expedition surveys spanned five subtropical gyres, as well as several smaller waterbodies and coastlines around the world, and their findings estimated plastic particle densities ranging between 1000 and 100,000 particles per km^2, reaching up to 890,000 particles per km^2 in the Mediterranean Sea [47]. In the same region as Carpenter and Smith's study, plastic particle densities were most prevalent as small and large microplastics and based on the density estimates made by Eriksen et al. floating plastic debris had increased substantially. One year later, in 2015, a study estimated a much higher quantity of plastic debris present in the world's oceans, ranging from 15 to 51 trillion plastic particles on the ocean's surface, weighing between 93,000 and 236,000 metric tonnes [48]. While further studies have proposed increasing estimates and various methodologies for measuring the amount of plastic debris in the oceans, these two examples demonstrate the challenges and diverging methods used in quantifying the presence of plastic pollution in the marine environment, using different volume and density metrics to capture the scale and character of marine plastic debris.

There is now a vast and growing body of literature documenting the ecological, social, and human health effects of litter and debris caused by mismanaged plastic waste leaking into the biosphere [7,49–51]. Pathways of plastic pollution emerge from various sources on land and at sea [7,52]. Sea-based sources of marine pollution emerge from commercial fishing industries, through both active fishing gear and abandoned and derelict fishing gear, caused by a lack of collection and on-land disposal protocols to retrieve gear that may continue to catch unintended species on land and at sea, entangle marine mammals, prevent mobility, and shed fragments over time through degradation [53–55]. Abandoned, lost, and discarded fishing gear can cause the by-catch of unintended aquatic species when not retrieved, including aquatic species that are at risk [54]. Estimates of land-based pollution have stated that plastics are also emitted in much greater volumes from mismanaged waste in inadequately functioning waste disposal sites, as well as via informal and uncontained dump sites. It is estimated that the most significant entry points for plastic entering waterways emerge in coastal cities and towns that are lacking in waste infrastructure or regular waste collection services, emitting an estimated 8 Mt of plastic waste into marine environments annually [7]. If current rates of plastic production, consumption, and disposal are maintained, Borrelle et al. [16] predict that the global quantity of plastic waste entering aquatic ecosystems could reach up to 90 Mt annually by 2030, with the highest rates from upper-middle-income and middle-income countries.

Plastics can become environmental pollutants in fragmented form and as larger and intact plastic litter known as macroplastics [47]. Plastic fragments in their smallest forms are classified into the two main categories of primary and secondary microplastics. Primary microplastics occur either as manufactured nurdles, which are small-scale plastics used as feedstock for commercial plastic production, or as microbeads for use as rinseable exfoliants and abrasives in cosmetic products; the use of the latter has now been banned in many countries including Canada, the US, and the UK, due to a lack of catchment filters in wastewater treatment operations [56–59]. Secondary microplastics, by comparison, are produced by the breakdown of larger intact plastics that gradually fragment. Secondary microplastics fragment from exposure to environmental weathering, sunlight, and wave movements, leading to dispersal both upon surface water and throughout the water column [60].

4.1. Marine Plastic Pollution

As of 2021, it is estimated that there have been over 100,000 studies produced analyzing the impacts of marine litter on each level of the ecological web [8]. By 2018, over 1400 species of marine fauna had been documented to have been negatively impacted by plastic debris [49]. In aquatic environments and on shorelines, plastics expose many mammals, fish, birds, reptiles, and plants to risks from entanglement, collision, and/or ingestion of debris [20,55,61]. Plastic entanglement can lead to decreased mobility for wildlife, increased vulnerability to striking by ship traffic, external abrasions, and fatal constriction or choking [20]. Ingestion of plastics poses a range of potential risks to organisms, leading to digestive blockages that may lead to starvation, prevent regular nutrition, and lower food stimulus [49,61]. Plastic debris is known to act as a vector and a sink for persistent chemicals upon surface areas, including chemical compounds such as plastic additives and brominated flame retardants, in addition to other industrial and microbial contaminants in the surrounding marine environment including heavy metals, polycyclic aromatic hydrocarbons, polychlorinated biphenyls, polybrominated diphenyl ethers, antibiotics, and endocrine-disrupting chemical compounds, which when ingested can result in sorption of persistent toxins into the organs and tissues of marine life [62–64]. Plastic debris has also been found to act as an aquatic raft that allows for the transportation of biota, microbes, and chemical contaminants from one ecosystem to another, due to their properties as vectors and their rougher surface area which accommodates a higher volume of matter compared to other natural aquatic rafts such as wood and microalgae [65]. These properties have potentially detrimental impacts via the more frequent migration of invasive species, or "colonizers", from one region to another via aquatic transport [55,66], contributing to the widespread formation of microbial assemblages on plastic debris, which has led to what has been termed the "plastisphere" [67,68]. Some microplastic debris has greater buoyancy and is transported along the surface water via wind and oceanic currents, whereas plastic with greater weight may descend deeper into the water column [47]. This leads to potentially compounding effects on species throughout the marine environment, infiltrating the marine food chain. Plastic movements throughout the water column can be further facilitated by deposition on the seabed by organisms that have ingested and excreted plastic particles, resulting in increasing quantities of microplastics that may accumulate deeper in the water column and within aquatic sediment [42,47,69].

All known species of sea turtle have been documented to have ingested plastic sheets and films, due to their dietary patterns and susceptibility to mistaking plastic debris for a variety of regular marine prey [61]. Fish species in freshwater, estuarine, and marine ecosystems have had documented interactions with plastics. Based on a review of 108 studies surveying interactions between fish and plastics, Azevedo-Santos et al. [70] determined that at least 427 fish species have been documented to ingest plastic particles. Plastic ingestion has been globally documented among mussels, oysters, clams, shrimps, lobsters, squid, and many fish species, with potentially dangerous implications for commercial fisheries [71] and human consumption of seafood species that have ingested marine plastic particles [72].

Bird species in both marine and terrestrial environments have been documented to interact with plastic debris in each hemisphere, causing a range of potential physical and toxicological risks [64]. Seabirds have been some of the species most impacted by marine plastic debris, especially those in the petrel and shearwater families [73] which ingest large quantities of surface debris, mistaking it for their regular diet of plant matter and fish eggs. Seabirds have thus been characterized as a sentinel species for exposure to marine plastic pollution, due to their long migration paths and feeding habits across numerous marine environments throughout their lifetimes [49,74]. Intergenerational transfer of plastic particles has been documented from adult seabirds to their nestling chicks via regurgitation, resulting in plastic accumulation in the gut of immature seabirds that may cause intestinal blockage, perforations, and ulcerations, inhibiting growth and feeding [73,75]. Due to current rates of plastic ingestion and increased exposure pathways, as well as the expected continued increase in plastic production, Wilcox, van Sebille, and Hardesty [76] projected that 95% of all seabird species will have ingested plastic debris by the year 2050.

4.2. Terrestrial Plastic Pollution

Terrestrial bird species are relatively understudied compared to seabird species. Some birds of prey, including some species of hawk and vulture, have been documented to ingest macroplastics and microplastics, both from their prey and from scavenging practices surrounding waste disposal sites, but little knowledge has been documented about interactions of smaller terrestrial birds with plastic debris [64].

While land-based pollution has received attention as providing pathways towards marine plastic pollution, it is noted that the study and analysis of the ecological impacts of plastic pollution within terrestrial and freshwater ecosystems [77,78] is lacking. Macroplastic debris enters the terrestrial environment as litter and is most abundant in areas lacking adequate solid waste management; when subject to environmental variables it can enter other environmental pathways towards rivers and coastlines. Macroplastic debris is intact plastic material and is less subject to the same degradation as within marine environments [55]. Wildlife interactions with macroplastic debris can include low-risk, benign, or potentially beneficial encounters, as some wildlife species employ fragments or intact plastic materials for nesting materials and makeshift shelter, including various mammal and bird species [77]. More dangerous or fatal interactions can take place via entanglement and ingestion, depending on the nature and condition of the debris and its impact on wildlife habitat and health [60]. Terrestrial plastic debris also impacts agricultural livelihoods and the health of livestock. This has been documented within Western Africa and Central Asia, where plastic bags are commonly ingested by roaming cows and goats, and plastic materials are commonly found in the manure and remains of sheep, poultry, and cows [20,79,80].

4.3. Economic Costs of Plastic Pollution

Costs of marine plastic pollution are multifold, causing an estimated annual economic loss between USD 6–19B to 87 coastal countries around the world whose economies depend on fisheries and tourism industries [81]. Since the costs required for organizing and funding formal waste management systems require large economic investment in infrastructure (in recycling facilities and sanitary landfills), public information, transportation, and human resources, it has been unfeasible for many local governments in low-income countries to make these investments, and thus they are forced to grapple with the other social and economic costs of mismanaged household waste [34,82]. The economic repercussions of plastic pollution create pressures that are both direct and indirect in nature, spanning loss to tourism revenues, impacts on fisheries and aquaculture stocks, and increased demand for government expenditure on litter cleanup efforts, as well as indirect impacts on aspects of public health [81].

5. Public Responses and Political Action

Public and political concern has increased towards the plastics industry due to the perception and recognition of the harmful impacts of plastic waste. The perception and critical responses to plastics and their implication in environmental damage can be traced back to the origins of some of the first disposable plastic packaging materials. Beginning in the 1970s, pollution caused by plastic products was being increasingly documented by scientific researchers and vocalized in the media as an ecological threat to marine life [83]. In particular, Kinkela [83] traces the introduction of the polyethylene six-pack plastic beverage ring, developed in 1959 by an American manufacturer, used for the sale of aluminum beverage containers sold in multipacks. The six-pack beverage ring emerged as one of the first packaging materials of synthetic origin deemed problematic by the American public, due to increasing evidence and media coverage displaying littered American waterways and the entanglement of fish, birds, and sea lions [84]. This dialog garnered increasing public attention towards the plastics industry, as well as political interventions calling for increased regulation of plastic manufacturers.

Industry responses to public concern about mounting environmental litter caused by plastic packaging have promoted a consumer-centered structure of accountability in managing and reducing plastic pollution, which has normalized an approach of individual responsibility and community cleanups. Both Kinkela [83] and Lerner [27] have investigated the emergence of industry-sponsored public campaigns such as the "Keep America Beautiful" campaign developed in 1953, to encourage citizen engagement as the most effective means of improving recycling rates and ensuring litter prevention [27,85,86]. Such campaigns have been critiqued by environmental groups, as these framings of plastic consumption and litter have attempted to position consumers as the actors best suited to prevent a continuing pollution crisis [87].

Role of Citizen Science Cleanups

Worldwide beach cleanups undertaken by citizens and environmental organizations have contributed to public and political understandings of marine debris by quantifying and characterizing the presence of plastic pollution in the natural environment, empowering citizens to engage in environmental stewardship and contribute to immediate efforts to reduce environmental pollution [84,88,89]. De Frond et al. [62] posit that by preventing the entry of plastic debris into oceans, coastal cleanups simultaneously function as effective chemical pollution prevention measures by reducing the introduction of chemicals embedded within plastic products into the marine environment. Such citizen-led efforts also critically contribute to citizen science efforts to identify and record litter and debris in the environment, characterizing the scale of terrestrial pollution, which is not possible to the same extent once litter becomes mobilized by wind or aquatic forces. Hidalgo-Ruz and Thiel [90] examine how citizen science studies have contributed to scientific understandings of marine litter, which have focused most on the distribution and composition of marine litter, as well as on interpretations of marine litter's interactions with marine biota and its toxic effects, transport, and degradation. Citizen cleanups are thus important components of risk identification, as well as a crucial step in preventing the entry of litter into ecosystems.

Coordinated efforts to manage litter through citizen-led cleanup activities have become well-established intervention methods. Current shoreline cleanup programs include the Ocean Conservancy's International Coastal Cleanup (ICC), Ocean Wise and the World Wildlife Fund's Great Canadian Shoreline Cleanup (GCSC), the Great American Shoreline Cleanup (GASC), and Break Free from Plastic (BFFP), which all mobilize and equip volunteers to collect data and information about plastic debris. Data collection on the composition and quantity of litter provides valuable information on the most prevalent and mismanaged materials that are escaping waste collection systems and entering the environment as debris. Annually released data from the ICC's cleanups document that seven of the ten most collected litter categories are food packaging materials [91]. Similarly, the GCSC [92] also compiles the most common litter items collected across Canadian cleanups and records that food packaging materials constitute over half of the materials collected, including food wrappers, bottle caps, beverage cans, plastic bottles, plastic bags, and other packaging. Additionally, various methods to identify the primary industrial sources of plastic pollution have increased in popularity and in turn have popularized the use of brand audit methodologies, in which cleanup volunteers identify and record the producers of the most prevalent littered items to create an ethic of corporate accountability within cleanup efforts. Since 2017, brand audits undertaken by groups like BFFP around the world have found consistent proof that a defined group of global consumer goods brands contribute to plastic pollution on a large scale, which motivates efforts to assign correct accountability to actors along the plastic packaging value chain [35,87]. As the BFFP states, "For years, the messaging around plastic pollution and litter has been focused on community cleanups and individual responsibility for managing waste. Yet in this latest effort to add brand audits to cleanups, we are seeing a shift in the way consumers are thinking about waste. People are beginning to see the connection between plastic pollution on the ground and the corporations that overpackage food and healthcare products" [87] (p. 23).

Audits are undertaken regularly by volunteer-led cleanup initiatives, and findings identify the materials that are contributing to increased marine pollution and are continuously escaping waste collection systems or bypassing waste management entirely as litter. Citizen science outcomes have effectively influenced and informed government policy on plastic pollution around the world [93–95]. While citizen-led efforts have proven to be central in managing and characterizing pollution caused by mismanaged plastic materials, the pace and scale of plastic pollution has warranted increasing political responses, which will be discussed in the following sections.

6. Global Governance of Marine Pollution

Early legislative attempts to measure and mitigate litter emerging from human activities took hold during the late 20th century, beginning in the 1970s [83]. In response to mounting scientific documentation of marine pollution caused by anthropogenic sources, various international bodies have proposed strategies and frameworks to limit the sources of pollution in the marine environment [96]. The Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter 1972, known as the London Convention, was adopted by the International Maritime Organization (IMO) and came into force in 1975, seeking to control marine pollution caused by industrial and chemical wastes dumped at sea [97] and designating some categories of wastes that require authorization for disposal [98]. In 1996, the London Protocol was proposed by the IMO to modernize and replace the London Convention by adding additional stringencies that prohibit all waste dumping and the export of wastes by using expanded compliance measures and preferred alternative methods of waste prevention and reduction including product reformulation, cleaner production technologies, input substitutions, and closed-loop recycling [99]. The IMO's enactment of the International Convention for the Prevention of Pollution from Ships (MARPOL) addressed measures to control the emission of garbage from ships into oceans, in addition to other sources of air and chemical pollution emitted from ships. MARPOL's addition of Annex V, Prevention of Pollution by Garbage from Ships came into effect in 1988 [98].

In 1994, the United Nations Convention on the Law of the Sea (UNCLOS) forged an international agreement for the protection of ocean resources and the marine environment [100]. Article 194 in UNCLOS requires states to take measures to prevent, reduce, and control sources of marine pollution [100]. In 1989, the United Nations implemented the Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and their Disposal to prevent the export of toxic wastes between countries. Amendments to the Basel Convention were made in 2019 to specify the non-hazardous plastic materials that can be exported for recycling, ensuring plastics are uncontaminated, are unmixed with other non-recyclable materials, and will be recycled in an environmentally sound manner [101]. Following the earlier adoption of the Basel Convention, the Bamako Convention on the Ban of the Import into Africa and the Control of Transboundary Movement and Management of Hazardous Wastes within Africa was negotiated by 16 nations in Africa to prevent the import and incineration of any hazardous waste, banning inland and ocean dumping. This came into force in 1998 [102]. Numerous regional conventions on marine protection include measures to prevent marine pollution in specific geographic areas: the Barcelona Convention 1976 (Mediterranean region); Abidjan Convention 1984 (West and Central African states); the Kuwait Convention 1989 (Persian Gulf states); the Helsinki Convention 1992 (Baltic Sea states); the Bucharest Convention 1994 (Black Sea states); the OSPAR Convention 1998 (European states along the northeast Atlantic Ocean); and the Tehran Convention 2006 (Caspian Sea states) [96].

In the early 2000s, international coordination around the topic of marine plastic pollution became more stringent in the agenda of the United Nations [9]. In 2004, the UN General Assembly (UNGA) delivered the first resolution regarding marine debris at its annual gathering, which marked a significant step in acknowledging marine pollution through a global focus [9,103]. The Honolulu Strategy in 2011 was a framework proposed by the UNEP and the National Oceanic and Atmospheric Administration (NOAA), with the three goals of reducing pollution from land and sea, as well as reducing the accumulation of debris on shorelines and in aquatic habitats, proposing strategies to improve waste and stormwater management on land and reduce loss of gear, cargo, and vessels at sea, as well as strategies for litter reduction and management [104]. The Manila Declaration was implemented in 2012, where 65 signatories committed to national policies to reduce pollution from marine litter and from agricultural fertilizers, and to undertake improved wastewater management, noting the importance of international coordination regarding land-based pollutants in the marine environment [105].

In 2012, the UN launched the Global Partnership on Marine Litter (GPML) during the UN Conference on Sustainable Development, which functions as a multi-stakeholder and multi-sector partnership for developing knowledge, information, and collaboration between governments, intergovernmental organizations, regional bodies, the private sector, civil society, and academia [106]. Marine plastic debris and microplastic pollution was included as a resolution in the first session of the United Nations Environmental Assembly (UNEA) in 2014, acknowledging the range of sources of plastic debris and their impacts on marine health, and recognizing the need for government and international measures [107]. Efforts to address marine pollution are integrated into the 2030 UN Sustainable Development Goals Agenda, in SDG 14.1, aiming to "prevent and significantly reduce marine pollution of all kinds, in particular from land-based activities, including marine debris and nutrient pollution" by 2025 [108]. Ongoing international action is taking place to address the scale and scope of plastic waste. At the fifth session of the UNEA, participating member states articulated the need to negotiate a global, binding agreement to address marine litter and plastic pollution, and this remains top of the agenda in advance of the resumed fifth session of the UNEA in Nairobi, Kenya in 2022 [109].

7. Local, Regional, and National Approaches to Plastic Waste

Increasingly, governments are taking simultaneous measures to address plastic overproduction, mismanagement, and pollution by focusing on defined strategies and focus areas. For decades, a waste-centric approach has been employed by governments to address the risks and challenges of plastic pollution, while less focus has been placed on the prevention, production, and consumption stages of the plastics life cycle [9]. Pales and Levi [10] describe the shortcomings within attempts to mitigate the impacts of plastic packaging production and use, underlining the need "to recognise and address the heavy externalities that product design choices impose on recycling [...] and there is an urgent need to evaluate the costs and benefits of different options to address it—whether the gradual introduction of product regulation, voluntary agreements, standards, industry design protocols, financial incentives, or in other ways" (p. 94).

Currently, there is a wide variety of potential actions that local, regional, and national governments may choose to take towards plastics that span the production, use, maintenance, and disposal stages. There are numerous political focal points in the following thematic categories that Barrowclough and Birkbeck [9] distinguish:

- Cleaning up environmental pollution;
- Reducing waste leakage;
- Reducing consumption;
- Increasing recycling and reuse;
- Investing in alternative or new markets for plastic waste;
- Reducing plastic production;
- Reducing pollution across the life cycle.

7.1. Plastic Bans, Levies and Taxes

Bans, levies, and taxes are increasingly implemented policy instruments that focus specifically on the consumption and/or production stages of plastic materials, to monitor and reduce the quantity of problematic and nonessential materials that are introduced to the market. The bases for enacting such restrictions are subject to local and regional determinants, and are usually shaped by a combination of economic, social, and environmental factors in the local context. To date, many subnational, national, and regional restrictions have been legislated on every continent for a range of plastic products and materials that have resulted in detrimental environmental and socio-economic impacts in the natural and human landscape as litter, including plastic microbeads, plastic bags, and a range of single-use plastic materials [58,59,79,89,110,111].

As opposed to interventions that focus on the disposal-oriented nature of plastics management, the implementation of bans, levies, and taxes can regulate the upstream plastics value chain. The scope of restrictions chosen by government varies across the world and may focus on one or several life-cycle stages. The UNEP [89] delineates four potential areas along the life cycle of plastics in which regulations may be implemented, spanning market entry (regulating manufacture and production of a product), retail distribution (regulating the consumer acquisition and use of a material), post-use or disposal, and trade regulations. Depending on the scope of the restrictive measures, governments may select a total or partial ban that focuses on certain product classes or problematic materials, in addition to using taxes or financial incentives for the manufacture of designated materials to lessen virgin material use or to support recyclable and reusable products [89]. Additionally, national laws may ban or limit the free distribution or use of specific product classes or materials, which may be facilitated using a tax or fiscal incentives to retailers and businesses to encourage reusable alternatives to plastic materials [89]. Disposal restrictions are normalized in many national laws but are implemented in different ways. Restrictions may regulate the return, collection, or disposal of materials, assigning responsibility to the manufacturer, retailer, or consumer, and may also assign specific fees or taxes for the disposal of a material [89]. Lastly, trade restrictions concern the import or export of materials, regulating the entry of specific products into the market, as well as the global waste trade in scrap plastic [89].

Most recently, some stakeholders across the plastics value chain have pursued various legal actions in response to such legislation, in attempt to prevent local and national governments from passing regulations that seek to minimize the import, sale, and use of designated plastic materials that have been deemed environmentally harmful and problematic. These legal actions, otherwise termed pre-emption bans, make it illegal for cities or states to pass legislation that restrict specific plastic materials. Many plastic industry lobbyists representing the American Progressive Bag Alliance and the Plastics Industry Association have successfully implemented pre-emptive measures across the

United States to limit the capacity of governments to pass legislation to ban, levy, or tax plastic materials [112].

Such instruments are an important option allowing governments to exercise jurisdictional autonomy and propose their own methods of controlling the production, import, distribution, use and/or disposal of plastic materials within the economy, which in turn has resulted in a patchwork of bans, levies, and restrictions around the world, enacted for a mosaic of plastic products deemed unnecessary or harmful [96]. Some bans, such as Kenya's stringent plastic bag ban, include severe penalties for noncompliance, whereas in other jurisdictions there is a lack of monitoring protocols in place to track and assess the impacts of the legislation [8]. There is a large jurisdictional variance in the scope of bans and the methods for their implementation, and it is argued that the piecemeal nature of individual bans, levies, and taxes limits governments from addressing the risks of plastics over their full life cycle [113]. Additionally, these legislations are making increasing strides towards limiting single-use plastics in food and retail, but progress in new legislation stalled, and at times was reversed, by political reprioritization during the global COVID-19 pandemic, due to an increasing slant towards the use of plastic packaging for hygienic and protective purposes [114].

7.2. International and National Strategies for Plastic Waste

In June 2018, the Ocean Plastics Charter was initiated during Canada's G7 presidency in Québec alongside France, Germany, Italy, the UK, and the EU. Current partners span industry, organizations, and governments committed to five goals in the realms of design, production, and after-use markets, collection and management, sustainable lifestyles and education, research, innovation and new technologies, and coastal and shoreline action [115]. There are currently 27 countries that are partners in the Ocean Plastics Charter as well as partners in many sectors in business, industry, non-profit organizations, and academia [116]. The charter works towards 100% reusable, recyclable, or recoverable plastics by 2030, aiming for increased recycled plastic content by 50% by 2030 through the support of secondary markets, recycling, and elimination of unnecessary plastic items [115].

The EMF has emerged as one of the foremost proponents of a globally aligned circular plastics economy; it proposed a global Plastics Pact in 2018 that sought the membership of industry, organizations, and governmental signatories, to build transboundary public–private partnerships that permit collaboration and expertise-sharing to harmonize solutions and to fuse efforts that could benefit other jurisdictions. There are currently ten countries partnered in the Plastics Pact Network: Canada, Chile, France, Kenya, Netherlands, Poland, Portugal, South Africa, the UK, and the US, as well as regional partners including the European Economic Area, Australia, New Zealand, and the Pacific Island Nations [117]. The Plastic Pact Network requires signatories to commit to individual targets in five areas to achieve more sustainable production, consumption, and reuse networks for plastics [117] by:

- Eliminating unnecessary and problematic plastic packaging through redesign and innovation;
- Transitioning from single-use to reusable materials;
- Ensuring plastic packaging is reusable, recyclable, or compostable;
- Increasing reuse, collection, and recycling or composting of plastic packaging;
- Increasing the recycled content in plastic packaging.

National plastic strategies have been under development by many nations around the world, aimed at committing to an improved recycling economy and limiting the pathways of plastics into the natural environment [118]. One of the first wide-ranging strategies considering the full life cycle of plastics was developed in the EU. The EU's plastics strategy includes a single-use plastics ban, which seeks to take broad steps towards a circular economy for all plastics by achieving increased recycling targets, prioritizing reusability, and avoiding disposal, as well as by mandating increased recyclability principles in product design, specifically for PET bottles [95]. The European Commission (EC) contextualizes citizen science data gathered by shoreline cleanup programs as a key proponent in enacting their single-use plastics ban, which includes restrictions on such plastic items as cutlery, plates, straws, beverage stirrers, and polystyrene food containers [95].

The need for a unified national approach to restricting problematic plastics, improving domestic recycling capacity, and pursuing a circular plastics economy has been identified in many countries, including Canada [119,120]. In Canada alone, plastic production and plastic resin manufacturing is a CAD 35B industry; however, in 2016, sales of domestically recycled plastics in Canada accounted for only 3.5% of those of primary virgin plastics [119]. The Canadian government has begun to develop approaches towards innovating and investing in improved plastic waste strategies and addressing pollution, in attempts to embrace the environmental and economic benefits of a circularized plastics economy. The Canadian government moved to restrict a preliminary number of single-use plastic items including plastic checkout bags, beverage stir sticks, six-pack rings, cutlery, straws, and some food service ware, also partly informed by national citizen science data identifying the materials most persistent as plastic litter [94]. Additionally, as of May 2021, plastic manufactured items were added to Schedule 1 of the *Canadian Environmental Protection Act 1999*, designating plastic as a potentially toxic substance in Canada due to its ecological impacts when emitted as litter, and granting government the regulatory power to develop appropriate risk management measures [121–123].

Additionally, the Canadian Council of Ministers of the Environment (CCME) approved the Canada-wide Strategy on Zero Plastic Waste, which proposed targets and plans to limit and eliminate the most problematic plastic materials and increase the reuse and recycling of plastics [94]. The CCME's [124] Canada-wide Action Plan on Zero Plastic Waste has prioritized several action areas including implementing extended producer responsibility (EPR) for plastic recycling nationwide, focusing on single-use and disposable products, defining national performance requirements and standards, as well as introducing incentives for a circular economy, infrastructure and innovations investment, public procurement and green operations.

Due to the increasingly large patchwork of national and regional strategies to combat an international problem that defies borders, there is a growing consensus that there is an urgent need for a globally binding treaty on plastics to bridge the divide between individual nations' objectives and the need for wider international collaboration and momentum. Simon et al. [113] illustrated the need to coordinate action to pursue consistent solutions and to forge a globally aligned plan to address each step along the life cycle of plastic production, use, and disposal.

8. Extended Producer Responsibility Principle for Packaging Waste

The seminal 1987 Report of the Brundtland World Commission on Environment and Development [125] referenced the importance of addressing pollution, and the risks of transboundary shipments of waste in the Global South. In particular, the report noted that pollution as a form of waste could be rectified using economic instruments to apply polluter payment principles. It recognized the importance of motivating investments in efficiency to reduce waste generation and pollution by charging fees or penalties for noncompliance. In this vein, industrial stewardship is an important opportunity for governments to improve product systems and introduce regulatory methods for waste reduction.

A taxpayer-funded recycling model has been a conventional method of waste management around the world. Beginning in the late 20th century, in many regions of the world, authorities grappling with increasing volumes of solid wastes were faced with the dilemma of effectively increasing recycling and diverting residentially generated waste from landfill and minimizing the life cycle impacts of products at their disposal [20]. Products of greatest concern such as waste electrical and electronic equipment (WEEE), automobiles, household appliances, and hazardous household waste required new forms of coordination and life cycle analysis to develop improved end-of-life management strategies, to mitigate their entry into the natural environment through illegal dumping, abandonment, and landfill disposal [126].

Conversations about shifting the responsibility for managing materials at their end-of-life phase began in jurisdictions that were encountering these growing waste challenges. Thomas Lindhqvist, a Swedish academic in the field of industrial environmental economics, was among the first advocates for an alternative political approach to managing discarded material goods. In the 1990s, the EPR principle was first articulated as a waste management approach by Lindhqvist and his colleagues in a report to the Swedish Ministry of the Environment [126]. EPR is formally defined as "a policy principle to promote total life cycle environmental improvements of product systems by extending the responsibilities of the manufacturer of the product to various parts of the entire life cycle of the product, and especially to the take-back, recycling and final disposal of the product" [126] (p. v). The principle has the ultimate goal of developing "more environmentally adapted products and product systems" [126] (p. i). The EPR principle is an effective method of involving producers in the waste management process to account for environmental, economic, and social externalities within the design of otherwise linear product systems.

In the EPR model, businesses are responsible for paying the costs of end-of-life management of the materials they introduce into the marketplace, incentivizing recovery-based material streams and intending to stimulate improved environmental impacts through better product designs [22,126]. Since its development, the concept of EPR has been applied to many product industries such as automobiles and WEEE, and it has proven to be successful at creating networks of post-consumer material collection and recovery. EPR for the packaging waste stream requires industries to finance, in part or in whole, the end-of-life management of materials that they provide in the market once they are discarded, alleviating tax funding otherwise required to finance the recycling system.

The earliest responses to improve management practices for packaging waste came into force through the European Union Directive 94/62/EC on Packaging and Packaging Waste, which was introduced to EU member states in 1994 [127]. This policy marked the beginning of a wide-ranging government response to the issue of packaging waste in the world, targeting packaging waste across Europe. Since that period, numerous political and economic instruments have been developed, pivoted towards solutions that require producers to exert greater leverage in addressing problematic materials in the marketplace.

8.1. Models of Producer Responsibility

While mandatory, fee-based EPR for packaging waste is the central waste policy instrument of focus in this review, numerous other policy instruments can be employed in various forms that in turn qualify as a function of EPR. These different instruments offer ways to minimize or restrict certain waste materials, and to increase waste diversion through a range of product take-back programs, regulatory approaches, voluntary industry practices, and economic and informative instruments [128]. As illustrated in the next section, several models are available through voluntary participation, as well as through more formal governmental intervention mandating producer participation. Across the world, there are currently many applications of each of these instruments across various industrial sectors. Within a waste policy framework, the diverse regulatory and economic instruments described by Yu, Hills and Welford [128] in Table 3 are employed by both government and industry for the sustainable management and stewardship of materials, to address the mismanagement of waste resources, limit the pathways that allow migration of pollutants into the environment, and extend oversight to aspects of the end-of-service phases for discarded products [129].

Table 3. Extended producer responsibility (EPR) policy instruments [128].

Type of EPR Approach	Applications
Regulatory approaches	Minimum product standards; prohibitions on certain hazardous materials or products; disposal bans; mandated recycling.
Voluntary industry practices	Voluntary codes of practice; public/private partnerships; leasing and servicing.
Economic instruments	Deposit/refund schemes; advance recycling fees; fee on disposal; material taxes/subsidies.
Informative instruments	Reporting to authorities; marking or labelling of products and components; information provision to stakeholders (e.g., consumers and recyclers).

Early implementation of some of these instruments took place in the United States and Canada for used beverage containers through deposit/refund programs, long before more formalized conceptualizations of EPR were proposed by Lindhqvist and applied to regulation by European waste authorities [82]. Based on a review by Kaffine and O'Reilly [129], Canada and the US were among some of the earliest adopters of regulated deposit/refund schemes specifically for beverage containers, beginning in the 1970s. The first beverage container recycling scheme dates back to a deposit/refund scheme in Oregon in 1972, followed by Vermont in 1973, Saskatchewan in 1973, Michigan and Maine in 1978, and Iowa in 1979. Many other US states and Canadian provinces quickly began to follow suit, applying other instruments to recycling schemes for vehicle tires, batteries, hazardous products, household devices, and WEEE [129].

8.2. Defining Responsible Producers of Packaging

Pinpointing producer responsibilities within a network of many actors along a globalized supply chain for consumer goods is necessary in order to assign correct accountability, to achieve the objectives of a product stewardship program. For example, clarifying the role of producers in the food industry is essential in the development of EPR programs for packaging, since food brands, grocery stores and retailers, food outlets, and restaurants all produce or distribute food products in packaging materials to customers [20]. While obligated producers in EPR programs for packaging are often defined as the fillers of packaging, as opposed to the manufacturers of packaging itself, there remains an ongoing dialog aimed at engaging actors further up the plastics value chain [6,20].

8.3. Implementation of the EPR Principle for Packaging Waste

Packaging materials (including beverage containers) account for about 17% of the total EPR programs worldwide, while 35% of programs cover WEEE, 17% cover tires, and 20% cover a collective category of used oil, paint, chemicals, large appliances, and light bulbs [129]. In Figure 1, the EMF [130] has mapped the landscape of EPR programs for packaging existing in 2020, when there were approximately 45 mandatory, fee-based programs in operation.

Governments are motivated by different sets of factors in pursuing producer responsibility for packaging waste. By implementing EPR programs for packaging, the financial burden on taxpayers is relieved for the financial source of administering waste management programs. The purpose is to increase recycling rates, reduce landfill usage, and contribute to feedback loops between industry and the recycling market for improved product designs. These goals are even more pertinent in regions where waste infrastructure is lacking or nonexistent for collecting, processing, and recycling packaging materials, identified as one of the most significant sources of plastic litter on land and emissions into rivers and oceans [7,34]. Each region of the world has taken steps towards implementing EPR for packaging waste. These actions complement ongoing policies for plastic bans.

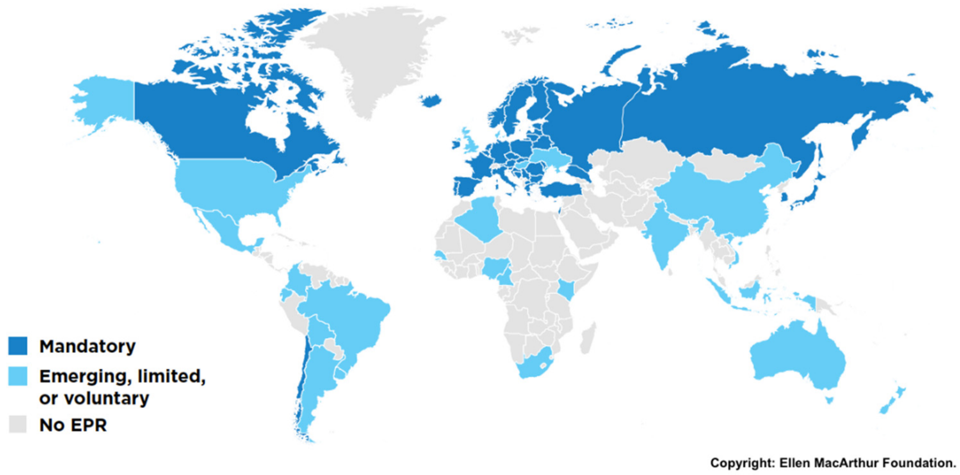

Figure 1. Overview of packaging EPR schemes implementation around the globe in 2020 [130].

Based on the EMF's use of "emerging", "limited", or "voluntary" terminologies to classify nations with different designs of EPR programs implemented for packaging, the range indicates the variance of legislation, policy approaches, types of EPR instruments in place, and specified material coverage [130]. It is difficult to ascertain the full global scale of EPR implementation for packaging materials at a granular level, as legislative information from many national environmental authorities is unavailable, and many nations are in the early stages of program proposals and planning. While this landscape provides a general scope, a regional review of existing EPR programs for packaging materials was conducted within a quickly moving landscape of national waste policies pursuing greater involvement from producers in waste management.

8.3.1. Africa

Implementation of EPR for packaging waste in African nations has had varying applications. Fee-based EPR programs for packaging have been minimal to date, but a number of countries operate voluntary programs aimed at specific packaging materials, including deposit/refund programs for plastic bottles. Several new EPR programs for packaging have been proposed across Africa, spanning different regions and islands, that are pursuing mandatory financial contributions from producers in the effort to reduce pervasive packaging pollution.

Legislation has been approved for fee-based, mandatory EPR for packaging in South Africa as of May 2021, through the national Ministry of Forestry, Fisheries and the Environment's adoption of Section 18 in the *National Waste Management Act*, which covers paper, packaging, and some single-use products [131,132]. South Africa has had a voluntary EPR program in place for waste materials since 2000, wherein some plastic packaging materials had been covered by a group of national organizations organizing collection of various plastic materials on the market [133].

Kenya's Ministry of Environment and Forestry also passed legislation to approve a fee-based, mandatory EPR program for packaging materials in 2020 and developed legislation for the formation of producer responsibility organizations in 2020 [132]. The *Extended Producer Responsibility Law* under the *Environmental Management and Co-ordination Act* is expected to lead to program development in 2021 [134]. Additionally, Tunisia and Namibia have developed EPR frameworks but are currently without any program implementation. Ghana and Cameroon both operate limited EPR programs for packaging covering a narrow range of packaging materials, and Nigeria currently operates only a voluntary EPR program for some packaging materials [132]. Within Africa, there are ongoing attempts to implement EPR for packaging in the future.

8.3.2. Asia

Current implementation of EPR for packaging is varied across Asia [135]. Japan, South Korea, and Taiwan each have mandatory, fee-based EPR programs for packaging materials. Japan's EPR program for packaging began with the *Act on the Promotion of Sorted Collection and Recycling of Containers and Packaging* in 1995 [136]. Japan's program had been deemed effective over the first decade of its implementation, as packaging recycling rates rose 27% between 1997 and 2010 [137]. South Korea's program began in 2003 with the implementation of the *Act on the Promotion of Saving and Recycling Resources* [138]. Taiwan enacted an EPR program for packaging materials in 1998, in the *Waste Disposal Act* [139]. Additionally, India approved an EPR program specifically for plastic packaging materials in 2020, through the *Rules for Plastic Waste Management* [140].

Numerous non-mandatory initiatives are managed by recyclers and actors in the private sector across Southeast Asia, including the Philippines and Indonesia [82]. There are increasing measures, but as of 2021 there were no mandatory EPR programs for packaging in operation. The Association of Southeast Asian Nations (ASEAN) has proposed a regional plastic waste strategy, with several targets to reduce marine pollution and improve recycling rates in the geographic region, which includes the recommended implementation of a mandatory EPR program for packaging [141].

Australia has operated a voluntary industry program for packaging since 2010 through the Australian Packaging Covenant, which seeks to make environmental improvements to packaging materials. Signatories are required to pursue an action plan and report annually but are not implicated in a mandatory EPR program [135,142].

8.3.3. Latin America

Based on available information and legislative documentation, several countries in Latin America including Chile, Venezuela, and Colombia have passed mandatory EPR programs for packaging [143]. Chile approved a mandatory EPR program for packaging through the *EPR Decree for Packaging* in June 2019 [144]. Venezuela approved a mandatory EPR program for packaging in 2020 in *Resolution No. 0191* [145]. Colombia's Ministry of Environment approved EPR legislation for packaging materials in 2018 through *Resolution 1407* [146]. Other nations are pursuing mandatory programs, including Argentina, while other nations such as Uruguay, Brazil, Bolivia, and Ecuador currently have voluntary programs in place that cover a defined selection of packaging materials [143].

8.3.4. Europe

The European Union (EU) took bold regulatory steps to manage and minimize packaging waste in the 1990s and adopted EPR as one of the main policy instruments within an overarching strategy aimed at minimizing landfill use and recycling waste [147]. There is a significant regulatory structure to minimize the quantity of waste entering landfills in the EU and implement recycling targets, largely motivated by the limited geography available for landfill infrastructure within a densely populated region [148].

With the passing of EU Directive 94/62/EC on Packaging and Packaging Waste in 1994, the EU took regulatory steps towards the greater recovery and landfill diversion of increasing volumes of household packaging waste that many European nations were discarding on an annual basis. Germany had already begun developing an EPR program for packaging waste in 1991, with the implementation of the German Packaging Waste Ordinance. Packaging materials regulated by EU Directive 94/62/EC comprise paper and cardboard, plastics, wooden materials, metallics, aluminum, steel, glass, and other packaging materials [127]. The directive did not originally mandate that member states must implement a mandatory EPR program for packaging as part of their compliance with the Directive, but since 1994 most member states have developed mandatory EPR schemes to manage packaging waste by obligating producers to finance recycling programs for household waste [147]. Last amended in 2018, Article 7 in EU Directive 94/62/EC requires all member states to implement a mandatory EPR program for packaging waste by 31 December 2024, obligating the few remaining states that have not yet developed a program [127].

The EU Directive 94/62/EC mandates current overall recycling targets for packaging at 55% until 2025, with a plastic recycling target set at 25% by weight [149]. Most European member states that have adopted an EPR program for packaging have documented plastic recycling rates that meet or exceed the EU's current recycling targets [150]. New targets will increase to require that at least 65% by weight is recycled by December 31, 2025, with 50% targets for plastic recycling, differentiated by material. Additionally, targets will increase five years later on December 31, 2030, requiring that at least 70% by weight of all packaging waste is recycled, including a 55% recycling target for plastic.

Table 4 shows that the five EU member states that documented the highest plastic recycling rates in 2019 were Lithuania (69.6%), Czechia (61%), Netherlands (57.2%), Sweden (53.2%), and Slovakia (52.8%) [150]. Depending on the application in the country, the organization of collection programs, and various factors influencing program efficiencies, each country creates different conditions for the operation of their recycling programs.

Table 4. Recycling rates of plastic packaging waste for monitoring compliance with policy targets [127,150].

EU Member State	Average Packaging Recycling Rate	Plastic
Belgium	84.2	47.4
Bulgaria		
Czechia	71.2	61
Denmark	71.2	36.2 (e)
Germany	63.2 (b)	43.3 (b)
Estonia	66.2	40.6
Ireland	62.5	27.5
Greece	60.1 (e)	37.6 (e)
Spain	69.6	51.5
France	65.6	26.9
Croatia	48.9	35.7
Italy	69.6	44.7
Cyprus	66.8	50.5 (e)
Latvia	62.4	35.4
Lithuania	61.9	69.6
Luxembourg	71.5	33.4
Hungary	47.3	33
Malta		
Netherlands	80.7	57.2
Austria	65.4	30.8
Poland	55.5	31.5
Portugal	62.8	35.6
Romania		
Slovenia	67.1	50.3
Slovakia	67.5	52.8
Finland	70.6	42
Sweden	63.9	53.2

Mandatory, fee-based EPR program for packaging. Limited or no mandatory, fee-based EPR program for packaging. Flags: e—estimated; b—break in time series.

Lithuania and Czechia had the highest plastics recycling rates in the EU in 2019, but very limited analysis is currently available on the management and performance of both member states' programs. Lithuania's and Czechia's success in waste management has been stated to be due, in part, to their small populations, and the OECD attributes their high recycling rates to the successful implementation of a deposit/refund system for plastic beverage containers [151]. Meanwhile, the Netherlands has the third-highest plastics recycling rate among EU member states. The Netherlands has made significant strides in EPR for packaging since its program implementation in 2008. Afvalfonds Verpakkingen operates the Dutch EPR program for packaging, and Kennisinstituut Duurzaam Verpakken (KIDV) (Netherlands Institute for Sustainable Packaging) operates to assist obligated companies to undertake improved packaging designs and to select packaging materials that permit easier recyclability and/or reusable designs. The Institute employs their Recycle Check procedure which analyzes the individual components of a company's choice of packaging design to inform producers of the impacts that their packaging material would place on current sorting and recycling capacities in the Netherlands [152]. The Recycle Check program has a specific focus on flexible plastic packaging. Additionally, the Institute offers their Sustainable Packaging Compass tool for flexible and rigid plastic packaging materials. The tool is used to analyze three different pillars of improved design: recyclability, circularity, and environmental impact [153].

8.3.5. North America

The US was one of the earliest adopters of EPR for many materials as early as the 1970s, using advanced-disposal fees for beverage containers as well as for hazardous wastes and WEEE. Currently, Oregon and Maine have approved fee-based, mandatory EPR programs for packaging waste. Oregon approved the *Plastic Pollution and Recycling Modernization Act* in 2021, and Maine approved *LD 1541, An Act to Support and Improve Municipal Recycling Programs and Save Taxpayer Money* in 2021 [154,155].

Canada currently has five provincial EPR programs for packaging in implementation. The first program was implemented in Ontario in 2004, followed by Québec in 2005, Manitoba in 2010, British Columbia in 2014, and Saskatchewan in 2016 [156]. New Brunswick approved legislation for an EPR program for packaging in 2019, becoming the first province in Eastern Canada to do so, while local governments and stakeholders within other Canadian provinces have proposed legislation and are undertaking public consultations, including Nova Scotia and Alberta [157–159]. Harmonized implementation of EPR for packaging waste in Canada has been recognized as a crucial step towards improved overall plastic waste management and a circular plastics economy [124,156].

9. Conclusions

The risks of plastic mismanagement are increasingly recognized as a threat to wildlife on land and at sea, to global environmental health, and to human livelihoods. Direct and cumulative risks within ecological systems have been increasingly documented, and it has become evident that the persistence of plastic pollution in aquatic and terrestrial environments could have profound implications for the long-term subsistence of wildlife around the world.

There is currently a complex landscape of government approaches and responses to plastic pollution, and current actions address different aspects of the plastic life cycle. Citizen-led actions based on individual cleanup efforts and citizen science have been central in prompting the development and implementation of restrictive measures including material bans, levies, and taxes that seek to limit and control the quantity of problematic consumer plastic products within the consumer marketplace. Restrictions have also led to the implementation of large-scale national and international plastic strategies that aim for a united agenda in efforts to mitigate plastic pollution. Currently, policymakers within the international community have recognized the dire need to contend with a pollution issue that inherently defies international borders, and to forge a globally aligned strategy to achieve material changes regarding improved plastic production and use, for the sake of ecological and human wellbeing, and economic security.

Producer responsibility and private sector engagement are crucial components in achieving transformation along the plastic value chain and pursuing a reuse-oriented economy for plastics. The EPR principle seeks to obligate industry, within the wider life cycle of plastic materials, to bear financial and/or physical responsibility for plastic waste management, specifically for the recycling of plastic packaging waste. Implicating producers in the functioning of waste management programs would guarantee regular waste collection and disposal services, achieving a crucial first step towards improved plastic management. The environmental and economic benefits of the EPR principle for improved plastic recycling are clear, and the principle is continuing to gain momentum around the world as an effective and vital waste policy to ensure industrial accountability in the plastic pollution crisis.

Author Contributions: Conceptualization, A.D. and T.R.W.; investigation, A.D.; writing—original draft preparation, A.D.; writing—review and editing, A.D. and T.R.W.; visualization, A.D.; supervision, T.R.W. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: No new data were created or analyzed in this study. Data sharing is not applicable to this article.

Conflicts of Interest: The authors declare no conflict of interest.

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