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Review

A Review of Landfills, Waste and the Nearly Forgotten Nexus with Climate Change

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Abstract: Landfills have been considered the most convenient approach for dealing with waste from time immemorial, even though some have led to disasters of catastrophic proportions. Moreover, recent findings by the International Panel on Climate Change (IPCC) suggest that the decomposing fraction of landfill waste that generates greenhouse gases (GHGs) may not be adequately accounted for and could become a critical issue in our effort to restrict atmospheric temperature increases to 1.5 °C above pre-industrial levels. (According to the IPCC, the maximum atmospheric temperature rise is a factor of cumulative net CO_2 emissions as well as net non-CO_2 radiative forcing. These anthropogenic forcing agents include methane, nitrous oxide and other trace gases from landfill sites. In that sense, landfills can tip the balance from 1.5 towards 2 degrees of warming). This paper draws on data from a number of countries for review and is a timely reminder that society needs to develop a more environmentally and socially sensitive set of methods that could ultimately replace landfills. The paper first examines problems connected with landfills and evaluates alternatives such as incineration, biomass burning and mechanical biological treatment, which generally present their own problems. The paper then considers the range of materials conventionally dispatched to landfill, dealing with them in the context of a zero-waste philosophy. The conclusions propose more disciplined waste management to embrace collective accountability, wherein those who create the waste—chiefly, households and businesses—would be expected to deal with it responsibly. With attitudinal changes and education, supported by regulatory measures, it should be possible to reach the long-term objective of zero waste and the retirement of the traditional landfill.

Keywords: wet waste; landfills; methane; waste management; zero waste; systemic change

Citation: Blair, J.; Mataraarachchi, S. A Review of Landfills, Waste and the Nearly Forgotten Nexus with Climate Change. *Environments* **2021**, *8*, 73. https://doi.org/10.3390/environments8080073

Academic Editors: Yu-Pin Lin and Manuel Soto

Received: 8 January 2021
Accepted: 22 July 2021
Published: 30 July 2021

1. Introduction

The growing urban population and the strong correlation between greatly increased per capita wealth since World War II and waste generation have globally produced immense amounts of waste. It was reported that global waste generation is on a trajectory that would surpass a total of 11 million tonnes a day by 2100 [1]. In 1960, Americans produced 1.22 kg/person/day of municipal solid waste (MSW), but by 2015, that had increased to 2.03kg/person/day and with population growth, a total of 238 million tonnes (Mt) of waste annually [1]. Around 90 per cent of this waste could be reused, recycled or composted instead of landfilled or burned, but the United States (US) landfills 52% of the MSW generated, incinerates 13% with energy recovery, recycles 26 per cent and composts 9% [2].

In comparison, during 2016–2017, Australia generated a total of 67 Mt of waste, 57 Mt of which is regarded as core waste [3]. Within the core waste category, 13.8 Mt of MSW, or 20.6% of the total, represents 1.6kg/person/day. Some 40% of the MSW is landfilled, while incineration with energy recovery accounts for 0.03%. Recycling represents 58% of the total MSW in 2014/2015, which remained the same up to 2018. During this period, Australia's adjusted MSW recycling rate was about 45% [3,4].

Landfilling waste has been an automatic choice for dealing with large quantities of MSW—indeed waste of all types—from time immemorial. However, the potential of the decomposing fraction of landfill waste to generate harmful landfill gases is an important factor in our effort to restrict global warming and limit the atmospheric temperature increase to 1.5 °C above pre-industrial levels [5]. Global temperature rise has resulted from radiative forcing caused by carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and other anthropogenic forcing agents, some of which can be derived from landfills [5] and in the case of N_2O, are significantly more potent in warming the planet than methane. Figure 1 demonstrates that if there is no reduction of non-CO_2 radiative forcing by 2030, there would be a very limited chance of restricting atmospheric temperature increase to 1.5 °C. Landfills contribute significantly to non-CO_2 GHGs, thus leaving the world more vulnerable to quicker temperature rise. IPCC's warning that this could be the straw that breaks the camel's back is well justified [5].

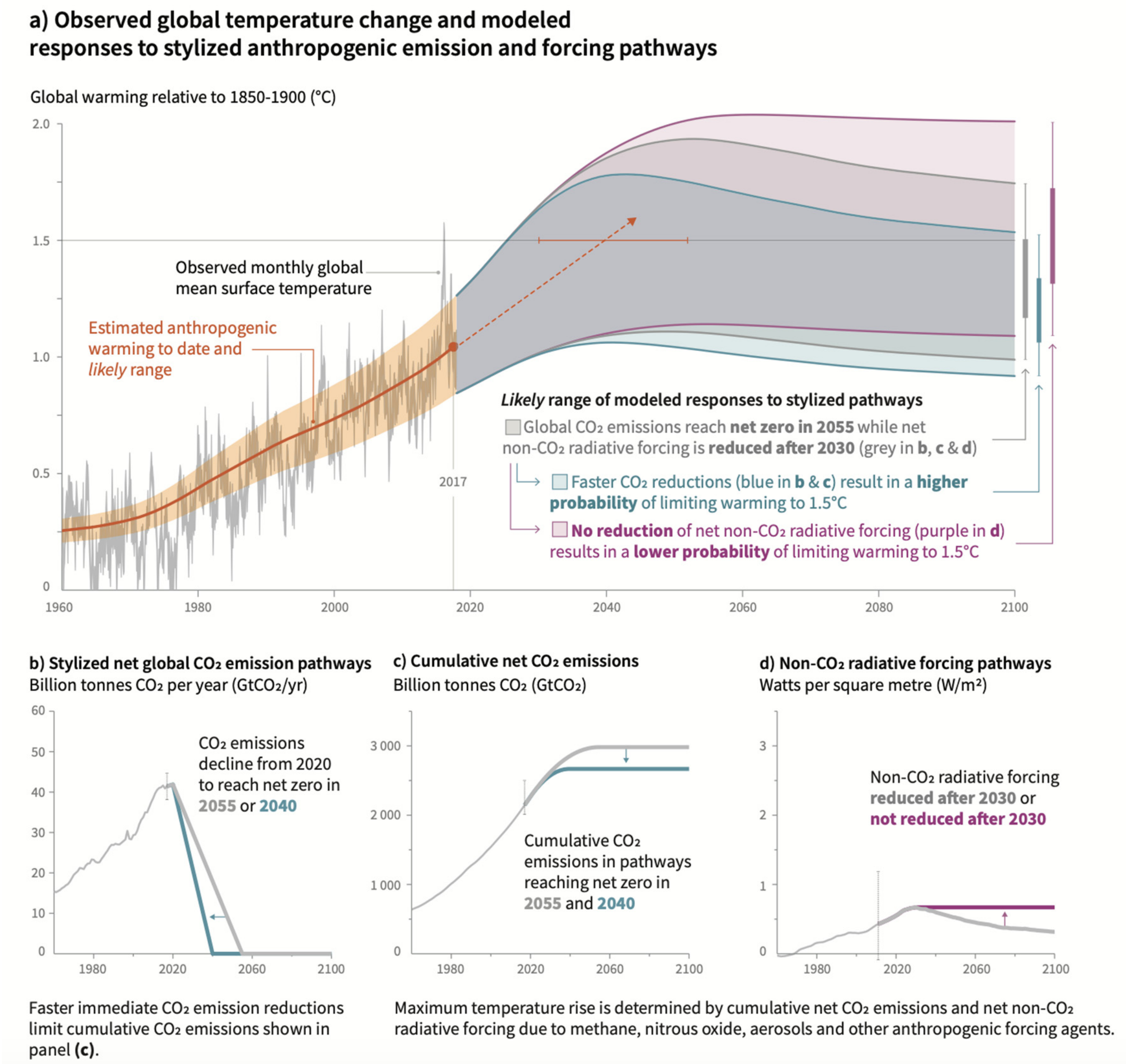

Figure 1. Cumulative emissions of CO_2 and future non-CO_2 radiative forcing determine the probability of limiting warming to 1.5 °C (reproduced from Figure SPM.1 in [5]).

In the United States, landfills are the third-largest source of CH_4, accounting for approximately 15.1% of these emissions in 2018. Emissions are derived from 1498 landfills which generate some 108 million metric tonnes (mmt) of CO_2e, consisting of CO_2 (10.5 mmt), CH_4 (97.8 mmt) and N_20 (0.4 mmt) [6]. Landfill gases typically contain 45–60%

methane and 40–60% carbon dioxide [7,8] and small amounts of non-methane organic compounds and trace gases. Irrespective of worldwide effort to minimise waste generation by practising recycling and reuse, the risk to climate change posed by landfill gas is yet to be managed at adequate levels. Global CH_4 generated in landfills accounts for 35 to 73 Teragrams (tg) CH_4/yr compared with yearly global total CH_4 emissions of 500 to 600 Tg(CH_4/yr) [9].

The most widely used approach for estimating GHG generation from the waste sector is the waste model developed by the IPCC [10]. The methodology used by the IPCC for estimating CH_4 emissions from solid waste is based on 'first order decay' principles. Behind the methodology is the premise that the degradable organic component releases CH_4, CO_2 and N_2O at predictable rates during the decay process, with emissions gradually declining as the carbon decomposes. The model gives methodological guidance to estimate carbon-based gas emissions from landfills as well as biological treatment of solid waste, incineration and open burning of waste and wastewater treatment and discharge [9].

Thus, the objective of this paper is to demonstrate why landfill gases are critical in reaching climate targets and proposing a way in which landfills may ultimately be retired from service. Our review draws on data from a number of countries though it tends to focus on information from the US and Australia because there is active reporting on the waste industry in the former country, in both scholarly and less formal publications. The review has been carried out using the desktop research methodology approach to examine the appropriate literature, covering the waste management subjects raised in the paper. The review embraces both the scholarly and non-academic literature, the latter consisting of reports from government agencies and a considerable range of non-government organisations, both international and national, in the attempt to gain up-to-date commentary and research. Note that MSW collection systems vary widely across cultures and countries in what household and business waste is collected and how it is collected, and there are promising door-to-door collection initiatives identified by Zero Waste Europe (https://zerowasteeurope.eu/2010/09/zero-waste-and-separate-collection (accessed on 10 April 2021)). However, given the focus of the research, collection systems per se are not considered in this study.

Figure 2 presents the structure and organisation of the paper. The paper briefly introduces landfills as waste management infrastructure as the world sees them today and discusses alternative, though conventional, ways of dealing with waste. The world has already seen the alternatives, and the problem has not been about their capacity for more sustainable waste management methods but the reluctance of responsible authorities to use them to replace existing landfill practices. For example, incineration generally, biomass incineration and mechanical biological treatment, when used within an integrated system of waste management, will offer opportunities to greatly reduce the need for landfills. In the long term, it may be possible to eliminate them, although that will need further creative research to deal with incineration ash and its toxicity [11]. Although most alternatives present their own raft of pollution and logistical problems, the paper argues that in a system of waste management that is entirely localised, that is citizen-based within a government frame of regulations, these obstacles can be overcome. The primary premise of the proposed approach is that waste needs to be dealt with at the source, and the onus for its management is shared between the individual, their immediate community and the local council. Those who create the waste, both residents and businesses, will be expected to deal with it responsibly, including composting, rigorous home-based sorting, an expanded range of recyclables and a strong level of producer responsibility. With attitudinal changes promoted by local government and supported by regulatory measures, it should be possible to reach the long-term goal of zero waste. This is a proposal that will not be implemented quickly but which offers significantly fewer environmental impacts as well as a greater degree of security for the long-term availability of resources.

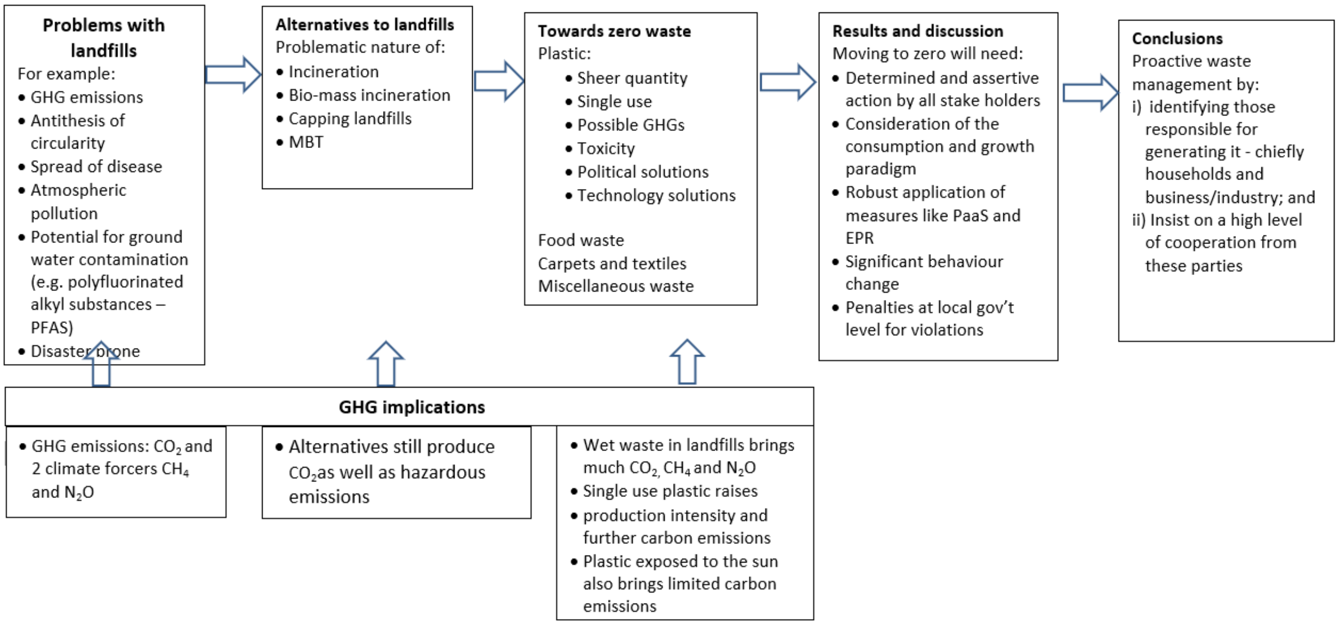

Figure 2. Landfills, GHGs and the focus and structure of the research.

2. Review of Problems Arising from Landfills

Landfills are sites identified for dumping and/or burying waste and are the most common and the oldest organised form of waste disposal in the world. Modern landfills are more sophisticated and designed and operated under strict government regulations. However, such compliance regimes are limited to more developed countries, and in most countries where rapid urban population growth is the norm, landfills have been and are still virtual dumping grounds for waste rather than well-engineered waste disposal sites. Open waste sites with scavenging are regular features of the rapid urbanisation and limited infrastructure services in these countries.

Although quantifying landfill methane emissions is problematic [12], interest in reducing them from landfills has grown, partly a result of the increasing awareness of the overall quantities of emissions, as well the feasibility of reducing them. The Kyoto Protocol may have been instrumental in linking carbon emissions with waste since many of the protocol's mitigation efforts were aimed at trapping methane from landfills. Methane is a key greenhouse gas, second only to CO_2, with a global warming potential recently estimated by the United Nations Framework Convention on Climate Change [13,14] to be 56 times greater over a 20-year time period. Targets for the first commitment period of the Kyoto Protocol covered emissions of the six main greenhouse gases: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulphur hexafluoride (SF_6) [13])

GHG emissions from landfills mainly originate—though not exclusively—due to the degradation of wet waste. Wet waste consists primarily of food and green waste, but other organic materials such as paper and cardboard in the municipal solid waste (MSW) stream may contribute if they are not recycled. As wet waste is covered on the landfill by additional accumulation, methanogens proliferate below the surface in the absence of oxygen and produce CH_4, the potent GHG [8,15]. In the US, for example, 21% of fresh water supplies represent the water used to grow vegetables that are not consumed and which are destined for landfills. It is more than just the food that is wasted but also the resources that went into growing, harvesting and transporting it to market. Then, after dispatching it to landfills, it decomposes with the continuing problem of GHG production in the form of carbon dioxide and methane [16].

Over 60% of global methane emissions come from human activities [17]. Human activities emitting methane include leaks from natural gas systems and from livestock, emissions that are projected to grow 13% between 2010 and 2030. Methane is also emitted by natural sources such as natural wetlands, coastal mangroves and melting permafrost. In Europe, an estimated 30% of anthropogenic methane arises from landfills [12,18]. Global anthropogenic methane emissions are projected to increase by 15 per cent to 7904 Mt of CO_2 by 2020 from 6875 Mt of CO_2 in 2010. Landfills account for 11% of total global CH_4 emissions, so leaving them unattended certainly works against mitigating climate change risks [5,19].

In addition to producing GHGs, landfills generate several other environmental and social impacts. The first law of thermodynamics suggests considerable potential for recycling manufactured products such as plastic, glass and metals [20]. However, economics often stand in the way, making it difficult to profit from tangible materials such as glass and impossible to recycle some of the plastic resin codes such as polystyrene or polypropylene or separate the mixed materials of many products into their parent constituents. The result in the last case is that almost all mixed materials are regarded as contamination, at which point they are sent to landfills or incinerated. Since it has not been possible to price the value of a declining resource [21,22], landfilling will often be the cheapest management solution for these waste problems. Landfills are the antithesis of circularity, representing the rather embarrassing results of most countries' linear economies, conspicuous consumption and cavalier use of finite resources [23–25]. Moreover, in addition to systemic issues connected with resources, there are other localised problems, for example, the creation of unhygienic conditions detrimental to public health, a source of food for stray animals and wildlife, the possibility of poor groundwater quality in the vicinity of a landfill and physical safety issues for people living in their locale.

As opposed to being landfills, waste is often mounded up into garbage mountains, and without proper care, they can become unstable collapsing garbage mounds which can threaten the lives of people living in close proximity [26,27]. The most recent incident of garbage collapse is in Sri Lanka, where fifteen families in the vicinity of the Karadiyana garbage mountain in Sri Lanka's Western Province had to be evacuated from the collapse danger zone [28]. These families were much luckier than the 17 people who were killed by a lethal avalanche of waste in Mozambique's capital city, the collapse triggered by heavy rains [29].

Regarding groundwater quality, waste placed in landfills is subjected to infiltration from precipitation which is contaminated on its passage through the landfill materials. The resulting leachate may reach adjacent groundwater, especially where a landfill is improperly sealed or not sealed with a geo-membrane. Leachate constitutes a complex mixture of hazardous and toxic chemicals such as dissolved organic matter, inorganic salts, organic trace impurities and heavy metals. Groundwater quality in the vicinity of landfills is often poor as a result of the leachate penetrating into the groundwater, and since the aquifer is used for potable water supplies, it is potentially hazardous to human and animal health [30,31]. Associated with groundwater quality in the vicinity of landfills is a group of chemicals known as per- and polyfluorinated alkyl substances (PFAS). They are a group of human-made compounds manufactured since the 1950s and used widely in industrial processes and consumer products. Interest has arisen relatively recently as a result of their widespread use in everyday products and media coverage about their possible health and environmental impacts. Conventional treatment processes cannot remove PFAS in leachate, and there are analytical challenges simply in detecting the chemicals in leachate and gas samples [32,33].

3. Review of Alternatives to the Landfill Solution

There are numerous alternative ways of managing municipal solid waste (MSW), although they can only partially compensate for the inherent short-sightedness of employing landfills since most substitutes possess their own disadvantages in impacting environmental quality and raising human health concerns. Several of the options are discussed in more detail below.

3.1. Incineration

One of the more common alternative waste treatments is incineration, and it has been practised in various forms for many years. Varying from its most primitive form thousands of years ago to mechanical and electric incineration methods after the industrial revolution in the west has always been a part of the options practised everywhere. Incineration as a form of disposing of waste has a long history in the USA, for example, as well as an equally long history of resistance by the communities the incinerators are situated in. However, incineration is significantly more expensive at AUD8.33 /MWh than AUD4.25/MWh for pulverised coal and AUD2.04/MWh for nuclear, the second and third most expensive forms of energy generation [2]. MSW incineration in the USA seems to have been in decline for a variety of reasons connected with ageing plants which are costly to operate and maintain, some interest in zero waste aims, concern over air pollution and public health risks as well as incineration's GHG contribution to climate change [2].

There is little waste incineration in Australia, which has been limited mainly to burning biomass from forestry and agricultural operations. However, research on sugarcane fields in Australia, Brazil and Thailand has shown that biomass residues left on the fields provide ecosystem services such as nutrient recycling, soil biodiversity, water storage, carbon accumulation and a degree of control of soil erosion and weeds [34], so it does seem appropriate to discontinue this form or incineration. Regarding general waste and the sheer quantities in Australian capital cities, recent suggestions that the country may have to resort to incineration have drawn considerable criticism. One of the critics is the industry body, the Waste Management Association of Australia, which suggested that if the technology detracts from a focus on reusing and recycling resources, then it is doing us a disservice and needs to be viewed as one of the lowest options on the hierarchy of waste disposal [35].

Incinerators emit much CO_2, and the mixed waste will (during storing, for example) release small quantities of CH_4 directly to the atmosphere, although any CH_4 remaining would be converted to CO_2 during incineration. However, MSW incinerators emit a wide range of air pollutants, some at a greater rate than fossil fuel power plants, as well as discharging four of the most harmful pollutants to human health: NOx, lead, $PM_{2.5}$ and mercury. Despite these apparent social and environmental hazards, roughly half of all municipal waste in Sweden is used to feed sophisticated incineration systems that have been developed to provide electricity and district heating to Swedish households. Certainly, the winter temperatures in these northerly latitudes justify artificial heating, and if waste incineration were abandoned, the energy source would probably be fossil fuels. In any event, the incinerators are strictly monitored to adhere to Sweden's rigid emissions standards. However, the growth in household waste and the rising content of non-biogenic materials directly impacts incinerator emissions with more materials containing toxic chemicals, bringing the potential for more hazardous air pollution [2]. Moreover, relying on incineration to 'solve' a waste problem would do nothing to alleviate countries' consumption of virgin materials. In addition to being the polar opposite of circularity, incineration could create a dependence on garbage as a fuel source and could be a perverse incentive to produce even more waste, although there is no evidence that this has happened in the past [35,36].

Bio-mass incineration has been practised as an informal waste disposal practice for thousands of years and is still prevalent in many parts of the world, especially in the tropics. It is practised by farmers and traditional owners for cultural purposes, cultivation and economic needs [37,38] and includes disposing of garden waste in backyards and using fuelwood for domestic cooking [39]. However, incinerating bio-mass means the soil cannot benefit from decomposing organic matter and soil enrichment as well as the other ecosystem services noted above. There are multiple adverse environmental impacts of biomass incineration, too, including all major facets of global changes such as ozone depletion, tropical deforestation, acid deposition and increased atmospheric concentrations of gases that trap heat and contribute to rising global temperature. There are also pollutants such as particulate matter, which add to concerns that increased exposure will raise morbidity and mortality rates in the vicinity of the incineration plants [40] [5] (p. 10) or [6] (pp. 101–105).

Bio-mass incineration is generally criticised as a waste management practice unless burning results in energy generation. Even then, there is a tendency to use waste to energy as a waste management solution [41] rather than a renewable energy source which may be why [42] (p. 2) suggests inefficiency abounds in bio-mass plants in that 'a huge amount of exhaust heat from incineration plants remains unused'. Indeed, in the Australian Capital Territory, any form of thermal treatment of waste such as incineration, gasification and pyrolysis is not allowed [43]. This is far from the case globally with recent research by [44] in Iceland evaluating the global warming, acidification and eutrophication impacts of gasifying organic wastes and the efficiency of producing electricity from the combustion process. The authors compared the results against conventional waste incineration and concluded that producing electricity from waste gasification integrated with combined heat and power was more environmentally friendly than conventional waste incineration in all three impact categories. This is primarily because gasification technology has a lower level of exhaust emissions of significant air pollutants and a higher amount of carbon retained in the ash [44].

3.2. Capping Landfills

Capping landfills is a technique used to seal them off when they reach their full capacity to prevent methane from escaping into the atmosphere. Landfill capping is not a landfill substitute per se but does enable one adverse outcome of landfills to be moderated. Capping involves placing a gas-tight membrane over the waste, allowing the organic fraction to decompose and produce CH_4, which can either be incinerated to CO_2 or captured and piped to a generator for energy. As of February 2019, there were 619 operational landfill gas (LFG) to energy projects in the USA and approximately 480 landfills that were considered good candidates for energy generation. The approach had been in occasional use by municipalities managing landfills but became more common with the advent of the 2005 Kyoto Protocol as a way of earning carbon credits [45] until the termination of the Protocol in 2012. In Australia, landfill gas energy recovery occurs in all states and territories on a small scale and roughly in proportion to population size [3].

Lastly, landfills that have reached their maximum capacity and which are capped then present themselves as a land-use problem since they are, literally, a wasteland, a form of contaminated land, unusable for decades. However, a beneficial use has been established for closed landfills in Europe and North America with a pilot in Australia by [46], which is to use the landfill's flat surfaces to install photovoltaic panels and generate solar energy [47,48]. Establishing photovoltaic (PV) arrays often requires extensive land areas and hence suffers from competing land uses. Thus, the conjunction of unwanted land with the space needs of PV is very convenient, as long as the potential for settlement in the landfill is taken into account and the potentially explosive nature of CH_4 remaining in the landfill.

3.3. Mechanical Biological Treatment

Mechanical biological treatment (MBT) is a form of waste pre-treatment technology, employing plant that sorts and treats the material entering as a flow of garbage. The operation removes the few recyclables remaining in the waste after dual-stream kerbside handling and either composts or anaerobically processes the organic component to reduce volume and destroy pathogens before dispatch to landfill. Europe had some 570 MBT plants in 2017, with the number growing after the European Union created a landfill directive that required members to gradually phase out landfilling all biodegradable waste, and the policy was reinforced by imposing very high landfill taxes [49,50]. An issue in the past with MBT is that it can easily become a form of dirty materials recycling, especially where comingled recycling collection takes place, with the result that much of the MBT output ends up in landfills. The Department for Environment, Food and Rural Affairs [51] suggests that new generation plants have seen an improvement in output quality, indicating there are now proven examples of successful operation and bankable viability [51]. However, a later report on MBT [52] (p. 3) indicates that for local councils, 'MBT led Residual Waste solutions have proved to be more expensive' than energy from waste-based alternatives.

A number of local government authorities in Sydney are seeking a long-term, secure and reliable alternative waste technology solution that maximises resource recovery and are sending their waste for processing to an MBT facility in Woodlawn, 250 km south of Sydney. The plant is designed to separate organics from mixed household waste to produce compost which will be used to rehabilitate a former mine site in the area. Stage 1 of the MBT facility can process up to 144,000 tonnes of waste per annum, transported by rail and road from Sydney. Based on waste audit data, approximately 50–60% of the waste received will be diverted from landfills. After the organic material is recovered and converted into compost, the remaining waste is delivered to the bioreactor for further energy recovery [53].

4. Towards Zero Waste and a Circular Economy

4.1. Problematic Plastic

Recycling can be seen as a tool to save energy and water, and in the former case, recycling will reduce fossil fuel emissions and CO_2 and thus mitigate climate change risks [54]. However, some apparently recyclable materials often find their way to landfills, plastics being one industrial product whose management is so problematic that it tends to be treated as waste after a single use. Demand for some polymers such as polystyrene is very low, and even the eminently recyclable polyethene terephthalate (PET) beverage bottles in the USA contain only seven per cent recycled content. Since the US EPA began monitoring plastics recycling in 1994, the rate has never exceeded 9.5%, which was reached in 2014 [55]. More recently, [56] (p. 1) has pointed out that since 2017, the price of mixed plastics on the open market in Australia has declined 'from about AUD$325/tonne to AUD$100/tonne', considerably reducing plastic's recyclability.

Meanwhile, the use of plastic packaging is rising [57–59], explained by its value in reducing food waste, population growth and market expansion [60]. Global plastics production reached 380 Mt in 2015, having doubled in 20 years [61]. With increasing plastic production and throw-away cultures comes increased plastic waste, and careless disposal has led to an accumulation of vast quantities of plastic bags, containers and bottles in oceans and on land [62,63]. Much appears in the environment as litter, but substantial quantities are incinerated or deposited in landfills. Even in technically advanced and environmentally conscious Europe, some 50% of plastic waste is still destined for landfill disposal, and more plastic is destined for energy recovery (39.5%) than for recycling (29.7%) [63,64].

Plastic is far more than a quantity problem, however [63]. As the Centre for International Environmental Law (CIEL) says, plastic pollution across the globe is suffocating our planet, and key points in its lifecycle, especially the incineration phase, are helping to drive the Earth toward a climate catastrophe [65]. The organisation has also demonstrated 'that plastic on the ocean's surface continually releases methane and other GHGs, and that emissions increase as the plastic breaks down further' [65] (p. 3). Some commonly used plastics, such as low-density polyethene, produce methane and ethylene at high rates when exposed to solar radiation [66]. While the behaviour of plastic inside a landfill is uncertain, it will be exposed to solar radiation on the surface of a landfill for some time, thus yielding hydrocarbon gases. Although plastic does not decompose, it does degrade over time, breaking down into finer and finer pieces of micro-plastic [64,67]. Thus, the surface area available for further photo-chemical degradation increases and is likely to accelerate gas production [66]. Moreover, the microplastics resulting from the breakdown process can be inhaled as we breathe the air or ingested in the case of marine creatures. The authors also point out that higher hydrocarbon production rates are expected for plastic exposed to air compared to plastic in aquatic environments in warm climates [66]. However, the authors also note that the methane release rate measured in their research is likely to be an insignificant component of the global methane budget despite the quantity of waste plastic produced globally.

A third issue connected with plastics is their toxicity, both during and at the end of life [66]. A number of chemicals are added to plastic products to enhance polymer properties and improve functionality, but their slow degradation releases a variety of chemicals to contaminate soil, air, water and food, widely documented in the literature [63,68]. Research that has investigated the chemical composition of plastic has concluded that there are 906 chemicals probably associated with plastic packaging and possibly as many as 3377 substances potentially in use. Some 63 of the 906 chemicals rank highly for human health hazards and 68 for environmental hazards according to the European Chemicals Agency [62], and 34 of the 906 chemicals are recognised as endocrine disrupters by the United Nations Environment Programme. The additives in both soft and hard plastic packaging can migrate into food or from sensitive uses, such as children's toys [63,69]. Probably the most relevant to ecology and human health are Bisphenol A, phthalates and brominated flame retardants [68]. Chemicals can also be released from plastics during the recycling and recovery processes and incineration, in particular, will release toxic gases such as dioxins, furans, mercury and polychlorinated biphenyls into the atmosphere unless there is strict combustion quality control.

There is now rising awareness of the generation of secondary microplastics and nanoplastics in airsheds [70,71] and the release of hazardous chemicals during manufacturing and use [72,73]. Moreover, all five post-manufacturing destinations of plastic—improper disposal as litter in the environment, recycling, landfill, incineration and, as we will see in a later section of the paper—reincarnation as fuel, release toxins and GHGs to varying degrees. In the latter case, it undermines goals to arrest the growth of carbon emissions and jeopardises global efforts to keep climate change below 1.5 degrees of warming.

4.2. Reducing Plastic Waste

There have been several attempts by developed countries to solve their intractable plastic waste problems. First, waste may be treated as an externality and sent to a developing country so that it can utilise its 'competitive advantages'. This normally consists of cheap labour, weak environmental regulation and limited enforcement [74], a dubious ethical response on the part of the country exporting its waste. Ironically, some of the waste sent from developed countries such as Canada, Australia and the USA has been too contaminated to recycle, which has meant that much of the waste has been incinerated or landfilled. The concepts of extended producer responsibility (EPR), in which producers have responsibility for the environmental costs and disposal of post-consumer products, need to evolve to a global level in the form of 'extended exporter responsibility' [74] in which countries must also take responsibility for their waste post-consumption. Closed borders, on the contrary, mean that each country has to replicate infrastructure and technical know-how, which would not be necessary if the principle of 'competitive advantage' were utilised ethically.

More recently, receiving countries such as the Philippines and Indonesia have returned container shipments based on their level of contamination. Unfortunately, shrunken manufacturing industries in waste-exporting countries mean that local capacity to use recycled content in new products has been reduced. However, the international waste trade confrontation between the Philippines and Canada that happened in 2019 has, ironically, had a productive outcome for the latter country. It has become a leading example of turning a trade conflict into a chance to truly focus on recycling and creating a domestic circular economy [75].

A more draconian attempt to grapple with plastic pollution is the European Union's pledge to ban single-use plastics, and as caretakers of the world's largest island, it is time for Australia's leaders to step up and join other countries who are taking action [76]. Thus, an Australian Senate committee of enquiry into waste and recycling in 2018 specifically urged the establishment of a circular economy, recommending prioritising waste reduction and recycling above waste-to-energy and phasing out petroleum-based single-use plastics by 2023 [77]. Senate recommendations are not necessarily implemented, but a separate initiative has arisen in South Australia, which led the state to pass legislation in 2020 to ban single-use plastic products such as straws, cutlery and stirrers, and takeaway coffee cups and plastic bags may follow [78].

A recent initiative in the Municipality of North Sydney in New South Wales, Australia, is preparing to ban single-use plastics and is currently taking submissions on the subject. The proposal only applies to employees in Council's offices, however, which falls far short of [79] suggestion that reducing plastic pollution can be achieved at low cost through a combination of leveraging local regulations, requiring retailer responsibility, collaborating with waste industry partners and engaging with citizens (see Table 1). Although this sounds like far-fetched idealism, San Francisco is already a long way down the path to achieving its stated goal of being circular—a zero-waste city by 2020. Problematic products such as styrofoam and polystyrene have been banned city-wide in nearly all forms, including food and takeaway containers, coffee cups, coolers and packaging [80] and plastic bags were banned in 2007. However, the business element of reducing and eventually eliminating plastic use will be a substantial barrier for any but the most progressive and environmentally responsible government agency, but some of the necessary steps are elaborated and presented in Table 1.

4.3. Technology-Based Solutions to Plastic Waste

Generally speaking, the great majority of plastics that are recycled are processed mechanically; that is, they are shredded, melted and then pelletised so they can be extruded into new plastic products [81]. While the renowned circularity intellectual and designer William McDonough is exceptionally positive about implementing strategies for moving plastics recycling from a current figure of 11% to 90% by 2050 [82], the process cannot be continuously repeated and is technically considered as down-cycling. However, the plastics industry is avidly searching for new recycling approaches that can cope with the clean-up, recovery and re-use of decades of plastic production and waste accumulation. Recently, several companies in the USA, including those involved in the Alliance to End Plastic Waste (https://endplasticwaste.org (accessed on 15 April 2021)), have been employing chemical recycling processes that return the plastics to their original monomers or building blocks to make new plastic that is virtually identical to the virgin feedstock derived from fossil fuels [81]. The circularity that comes from chemically based recycling, including the ability to handle a much wider range of plastic resins, is creating a reputational demand for 'recycled' plastic in the USA and Canada, with the supply of the recycled monomers greatly outpacing demand. The move is also connected with CO_2 and reducing the plastic industry's footprint with the chemical technique.

A second and technological approach to reducing the consumption of conventional plastics relies on substitution with biological forms. One of the earliest bio-plastics, known as 'Mirel', was manufactured from a fermentation of corn sugar injected with genetically engineered bacteria. A sample product—a gift card—completely biodegraded in home compost in about 40 days [85]. A professional life cycle analysis was carried out on Mirel, the conclusion being that it 'can provide 200% reduction in greenhouse gas emissions along with an over 95% reduction in the use of non-renewable energy as compared to petroleum-based plastics' [85] (p. 2).

More recently, a replacement for petro-chemical plastic has been polylactic acid (PLA). It is also derived from renewable resources, such as corn starch, tapioca roots or sugarcane and is increasingly available for single-use consumer products similar to petroleum-based plastic cups, cutlery, straws and lids [86]. However, at end-of-use, PLA is not readily recyclable and is likely to be landfilled under the assumption that PLA is a carbon sink. This no longer appears to be correct with research by [84] (p. 166) indicating that certain types of PLA may generate 'significant quantities of methane in an anaerobic landfill environment' at 'mesophilic and thermophilic temperatures'.

Table 1. Strategies and tactics for reducing plastic pollution.

Strategies	Tactics and Actions
(i) Locally imposed bans and fees on single-use plastics; (ii) Legislative toolkits developed for communities and states to create ordinances to restrict or ban plastic items.	Some single-use plastic items, e.g., straws, bags and polystyrene often of low value and unprofitable to collect and recycle. Eliminate single-use with: (i) Better quality alternative materials, e.g., bamboo straws; (ii) Re-usables, e.g., personal cloth bags [1].
Provide facilities to lead to the voluntary reduction of dominant elements of the plastic waste stream: single-use disposable bottles, plastic bags and food containers.	(i) Promote public water refill stations; (ii) Promote reverse vending machines and support container deposit in public places; (iii) Water refill stations; (iv) Incentivise to ensure that no bottle is left behind, e.g., cash refund, prizes (Abu Dhabi), transit tickets (Istanbul), telephone cards (Kuala Lumpur).
Provide facilities to reduce the disposal of food containers as waste.	Provide a simple washing facility to remove food contamination.
Improve range of plastic types which are recyclable.	Soft or crinkly plastics are now collected on a voluntary basis at some supermarkets in Sydney for processing into new and durable products (Redcycle—https://www.redcycle.net.au/ (accessed on 12 February 2021)). A company in the UK is also taking hard-to-recycle plastics and returning them to feedstock for new, similar products [83].
Improve bio-degradable alternatives to petro-plastic.	Compostable versions of plastic will still need to be handled responsibly through education and behavioural change.
Recognise leaders in their quest to cut plastic waste, e.g., circularity philosophy.	Promote their goals and actions, especially design for multiple re-uses.
Support extended producer responsibility (EPR) laws at the state level.	EPR legislation will decrease source pollution, e.g., by: (i) Requiring manufacturers to use recyclable and recycled materials; (ii) Developing recycling programs. EPR laws are proposed for plastic packaging in California and Washington states;
Require profit-making businesses to take responsibility for their customers' waste.	(i) Food retailers to stop issuing free plastic bags; (ii) Fast food operations to have waste bins at the exit of the drive-through lanes for responsible disposal of fast food packaging; (iii) Similarly, retailers and petrol filling stations need to operate bins for recyclables.

Source: compiled by the authors from [79,81,83,84]. Note: [1]. Plastic bag, straw and EPR ordinances have been passed in over 300 US cities and a few states, but some 16 US states have passed ordinances prohibiting local jurisdictions from banning plastic waste and pollution in their communities.

There are other encouraging technologies developing as governments struggle with mountains of plastic garbage. Indeed, a shift may be taking place in moving from mechanically recycling plastic to chemical processing. Mechanical recycling is technically down-cycling since it can only take place a finite number of times. On the other hand, breaking the plastic into its original monomers or chemical components, in theory, allows it to be recycled infinitely since it is virtually identical to the original feedstock from oil [81]. If either form of recycling could achieve the scale of glass or metal can recycling, it would represent an enormous advance on current plastic recycling levels. However, there would still be the toxicity issue to deal with in continuing to use plastic intensively, notwithstanding the much-vaunted technology 'improvements' being achieved.

Researchers established some years ago [87] that plastic could be converted into a low-emission alternative to motor fuel using catalytic depolymerisation, and [88] have developed a successful large-scale pilot plant on the New South Wales' (NSW) Central Coast of Australia. The first commercial plant is being built next year in the UK for full-scale processing. The technology has now matured to the extent that in May 2019, the Government of Timor Leste signed a memorandum of understanding at the University of Sydney, Australia, with Mura Technology. Mura Technology is a joint venture between

Licella Holdings and UK renewables investor Armstrong Energy which will develop a USD40 million chemical recycling plant, which will shortly make Timor-Leste the first plastic neutral economy in the world. It is a breakthrough technology that turns plastics back into oil, with the potential for 80 plants throughout Australia and similar potential in the UK and Canada [89].

While this technology looks promising, there are organisations in Europe that see chemical recycling as bringing considerable environmental impacts such as high carbon emissions. Zero Waste Europe, for example, considers that it will hinder innovation in recycling generally and is promoting a more robust system of mechanical recycling, emphasising initiatives such as better collection and sorting, thoughtful product design, extended producer responsibility and digital labels for tracking (as reported by Zero Waste Europe (2021) at https://zerowasteeurope.eu/2021/07/design-for-chemical-recycling-kills-innovation-upstream/ (accessed on 25 June 2021)).

4.4. Reducing Food Waste

One of the impacts of climate change is likely to revolve around the inextricable relationship between food waste and food security which has received attention from many governments around the world. Landfills have been the most popular destination for food waste, and because they are relatively cheap to use in Australia compared to other parts of the world, it can be difficult to make alternative food waste treatment technologies cost-effective [90]. In Australia, some 3.2 million tonnes of food is sent to landfills each year, enough to fill 5400 Olympic-sized swimming pools, with 75% of the waste originating from our households [91]. It comprises 12.6% of total solid waste going to landfills, and better management of food waste is critical for improving food security [92] (p. 283). Moreover, it has been estimated that food waste costs the Australian economy AUD20 billion each year. However, the Australian Government has worked with state and territory governments to develop a National Food Waste Strategy and introduce levies for disposing of organic waste to landfills. This makes alternative treatment methods such as bio-digestion and composting more cost-effective options for businesses. The strategy was released in 2017 and is aimed at achieving a 50% reduction in food waste by 2030 [93].

There are also food organisations in most major cities of Australia which rescue food that is still suitable for human consumption. For example, [91] re-directs or re-purposes some 37 million kg of food and groceries that would otherwise end up in landfills, thus performing a valuable social function as well as avoiding more than 81 million kilograms of CO_2 emissions every year. One of Australia's states—Victoria—has also published a report on food waste which recommends strategies such as 'use it up' recipes, household and small business composting and worm farms and promoting programs for the hospitality industry to reduce waste and at the same time, improve profits [94].

In the US, approaches to reducing food waste include cajoling businesses by providing funding assistance as well as introducing regulations [95]. As noted earlier, placing organic materials in landfills generates GHGs, but solutions to this problem seem more readily available than for the disposal of plastics. The authors of [96] recommend composting all organic waste—including food scraps and yard trimmings—which could eliminate nearly one-third of all materials sent to landfills and trash incinerators across the United States. Composting is technically straight forward, although Australian research has perfected a low management but high-performance system [97] (FABCOM 2019). Turning organic wastes into valuable compost helps pull carbon out of the atmosphere, returns nutrients to the soil and replaces petrochemical fertilisers and as the World Resources Institute says [98] (Flanagan et al. 2019), it will help farmers, companies and households save money, combat hunger and alleviate pressure on climate, water and land.

There are, indeed, 148 kerbside food waste collections and 67 drop-off programs in the US as of November 2017, servicing 348 communities or 5.2 million households [99]. This is a minuscule proportion of the nation—only 1.7% of the total number of towns and cities in the US, but kerbside programs alone represent an 87 per cent increase since

2014. Programs are taking root in large, and some midsized, fast-growing cities in the US, such as Austin, Texas, that provides composting to almost half of its kerbside customers and expects to provide it to all of them by 2020 [95]. California offers state-wide funding to set up composting [99] and New York City, with 8.5 million residents, launched an organics collection pilot several years ago (see Figure 3). Domestic composting has been mandatory in San Francisco since 2009 [35,100]. New York City's waste management efforts have now evolved into a full program offered to half of the city's schools and more than 3.5 million residents. The program is being rolled out in parallel with food scrap drop-offs (see Figure 4), which allow people to participate even before collections roll out to their buildings [95,101].

Figure 3. Bins for food scraps and other organics in New York [95].

Figure 4. One of 150 drop-off locations in Manhattan, US. [95].

Large cities such as New York have the resources to back food waste programs, but despite notable successes, there are barriers. Larger cities usually have many multifamily dwellings where it can be hard to measure success and incentivise participation in food waste programs. Most New York City residents, for example, live in multi-unit buildings, and brown bins and starter kits are automatically delivered to residents of one to nine-unit buildings. Residents in 10-plus unit dwellings must enrol to receive bins, and a challenge has been in recruiting both residents and building staff, with buy-in from building managers and training staff crucial, but the program has evolved greatly from a pilot several years ago [99].

There are currently bans on food waste in five states in the US, introduced to encourage the development of the infrastructure that will be required to support the mandate and supported by state funding created for processing facilities. These efforts require substantial investment and planning with much effort from multiple players, but the new regulations are driving business activity, and some programs are now reporting spikes in food diversion and food donations. It seems that the key to obtaining high rates of composting rests on a mix of incentives and mandates, including convenience for residents; affordability, that is making composting programs less expensive than conventional waste disposal; requiring large commercial producers of organic waste, such as grocery stores, to divert waste from landfills and incinerators to composting facilities and ensuring locally produced compost is used in public projects or distributed to residents, community gardens or other local projects, so there is a steady market for it [99].

4.5. Ensuring Metals and Glass Are Recycled

In the waste hierarchy, recycling is good, but reuse is better. In a circular economy, there is no such thing as single-use products; resources circulate, and nothing goes to landfills [82,102,103]. Designing products to be used multiple times and ensuring there is no contamination are keys to avoiding the landfill. Contamination has been a serious obstacle to good recycling rates, so that a kerbside recycling bin containing obvious recyclable materials such as glass bottles, metal cans and plastic bottles can become destined for the landfill if soft plastic or food and green waste are carelessly thrown into the bin. It becomes simply too costly to spend time re-sorting the bin to remove contamination. North Sydney Council in Sydney, Australia, has started to refuse collection in such circumstances (see Figure 5) in an effort to advertise a policy that expects consumers to take responsibility for correct sorting. In the USA, artificial intelligence technology is starting to use in-bin cameras to identify the most problematic contaminants such as garbage bags, styrofoam and bulky items and alert haulers remotely [104].

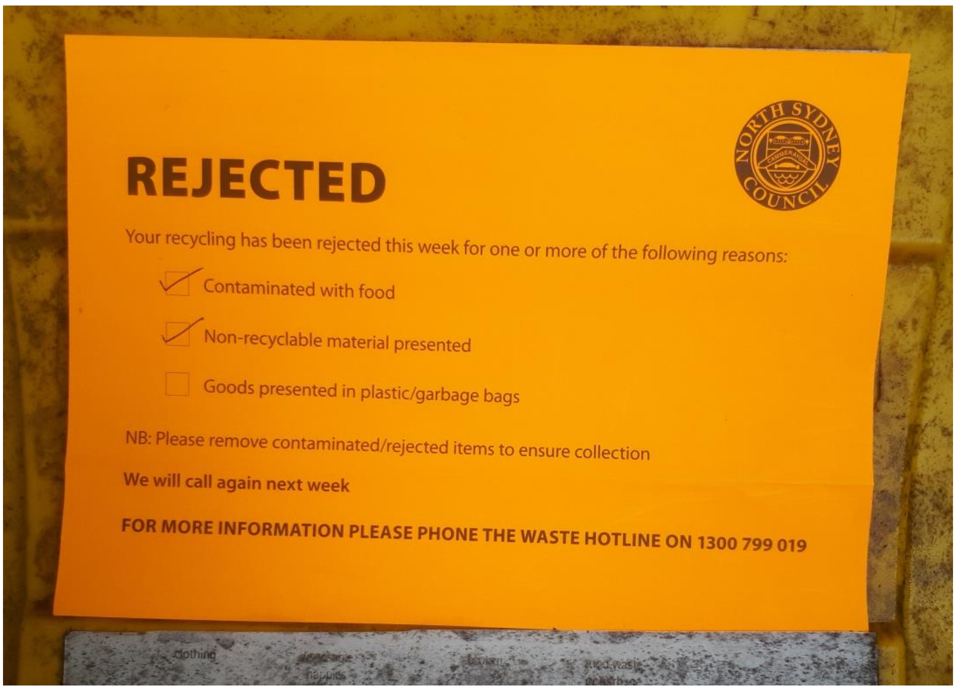

Figure 5. Co-mingled recycling bin in North Sydney, Australia, rejected due to contamination with soft plastics and food (Source: authors).

However, giving this class of recyclables monetary value, as in a deposit scheme, will also help greatly, although collection costs are rather similar to conventional kerbside programs [105]. The German deposit system already uses the principle that if a bottle has monetary value and we have 20 of them, they are likely to be returned. Moreover, plastic bottles are designed to be used up to 25 times and glass bottles up to 50 times. They are returned to colour-coded collection points (Figure 6) for a deposit, cleaned, sterilised and circulated back into use, although in the case of plastic bottles, this would require a change to hygiene regulations in some countries. In San Francisco, where officials claim to be 80 per cent of the way to achieving zero waste, the city's Department of Environment says it can reach 90% by focusing on product design and extended producer responsibility [35].

Figure 6. Colour-sorting public glass collection in Germany and throughout Europe. From the left, the first two bins are for green glass, the third is for brown- and darker-coloured glass and the white bin is for clear glass. Sorting by colour permits much higher recycled content in glass bottles [105].

In comparison with many recycling programs in the US and Australia, the two examples above are stellar indeed. Expanding the recycling rate elsewhere when the commodity aspect is crucial and existing program costs are high would certainly benefit from consumer sensitivity to recycling. Audits of kerbside collections in NSW, Australia have shown that around 10% by volume, ranging from 7% to about 20% of the material placed in kerbside recycling bins should not be there (As reported in the Sydney Morning Herald December 16, 2019: https://www.smh.com.au/national/nsw/not-sure-what-can-and-can-t-be-recycled-here-s-how-it-works-20191204-p53grj.html (accessed on 12 July 2021)). The most common contamination items include plastic bags (both full and empty), textiles, green waste, polystyrene (styrofoam) and general rubbish. The problem exists in reverse, too: around a third of landfill waste bins routinely contain recyclables or green waste. It is important to have clear information from our municipalities about which items can and cannot be recycled. One example is plastic shopping bags, which many supermarkets urge their customers to recycle by placing unwanted plastic shopping bags in dedicated bins on the shop premises. Possibly this prompts shoppers to assume that plastic bags can also be recycled in their kerbside collection, which then brings a 'rejection' notice as illustrated in Figure 5, which suggests that education could play a stronger role.

The reality in many jurisdictions is that the costs of recycling programs will not necessarily be covered by the value of the materials being recycled. In the US, for example [105], aluminium will pay for itself in kerbside programs, but PET and glass do not, and aluminium's profitability does not necessarily compensate. PET is of low inherent value, and the glass is costly to recycle because of its sheer weight and the contaminated nature of much of the glass. A result is that some city recycling programs are no longer offering glass collection in the US, while Germany has gained a modicum of 'crowd support' by providing for colour-sorting in public areas.

4.6. Dealing with Carpets and Textiles

Carpet waste has long been known to pose environmental and public health concerns. It contains some 40 toxic chemicals, according to [106], even in synthetic carpets claiming to be eco-friendly. Carpeting which contains natural fibres and which is deposited in landfills also adds to GHGs. In the US, carpets contribute 3.5% of all waste material that ends up in landfills [107] and in Australia, used carpet is in the top 10 of waste items going to landfill [108]. It is estimated that more than 90% of the 1.1 billion m^3 of carpet sold in the US each year eventually ends up in landfills. This is despite the existence of a carpet industry organisation since 2002, tasked with diverting and recycling such materials [109]. Indeed, the general failure of the organisation to achieve recycling goals recently led the Californian legislature to introduce new measures to purposefully increase the recycling rate to 24% by 2020 [110].

Carpet and rug recycling are a largely untapped opportunity in Australia according to [111], and keeping these products out of the landfill has the potential to reduce GHGs and resource use. Carpets and rugs are not universally destined for the landfill, with major cities in Australia and all states offering at least a few drop-off locations, although civic-minded consumers may have to pay fees to use the facility [111].

Similarly, the end-of-life of textiles still tends to be the landfill. The authors of [112] indicate that there were 14.5 million metric tonnes of textiles generated in 2015 with an overall recycling rate that year of 15.3% and 13% going to combustion with energy. It is not clear from the data whether the recycling figure includes the significant amounts of textiles that enter the re-use market through charitable shops, or more recently, Yerdle Recommerce [113,114]. The company deals in branded used clothing and is the commercial version of the Australian charity shops, Salvation Army and St. Vincent de Paul. There are no data for the proportion of natural materials used in the textiles that are destined for landfill, so that the burden of GHGs is unknown.

5. Discussion

Material presented in the preceding sections explained the importance of eradicating landfills from our society. Yet, this will require highly coordinated and determined action by the state sector together with the key stakeholders of business, commerce and industry and homeowners with supporting policy, guidelines, consumer education, regulations and strict accountability processes. At a more strategic level, it will also require consideration of resource utilisation and consumption behaviour, as well as the more concrete aspects of reuse and recycling of all products based on ‘closed-loop’ principles [115]. However, establishing this is only the start; if history is something to go by, a zero-waste system will need to be watched very strictly for transparency and accountability and be subject to continuous improvement as well.

Australia’s overall recycling rate is estimated to be 55% [116], and since incineration is infrequently used in this country, most of the balance goes to landfills. Sweden, on the other hand, has extremely little garbage going to landfills, with 98% being reused, incinerated or recycled [3]. While the average Australian sends more than one tonne of waste to landfill each year, the average Swedish household sends around three kilograms, although, as noted earlier, approximately 50% of Swedish MSW is incinerated, raising concerns over its ability to achieve sustainable outcomes. Even if toxic emissions are fully controlled, it is the polar opposite of circularity, bringing irrevocable destruction of resources. Indeed, it is more destructive than landfilling, although energy benefits are exploited from the waste. The Zero Waste International Alliance (ZWIA) specifically excludes burning from its current definition of zero waste [36,117].

Several factors are hindering intelligent management of waste and GHG reduction in Australia, although society can exert some degree of control over most of them. The only factor it is impossible to influence is the second law of thermodynamics, which suggests that all matter experiences entropy or disorder, although a few materials can be reprocessed several times without deterioration of quality [118]. From a strategic point of view, the effort for reduction and/or re-use should come before recycling, and that entails modifying our preoccupation with relentless growth and consumption to become more mindful of non-renewable resources, and therefore waste, in the first place. Such an approach will not be popular with many consumers and in particular, business and politicians [54], but eventually, society's demands on virgin materials such as glass, metal and timber need to be reduced to a level that meets equilibrium in resource availability and utilisation. However, this is not relevant to GHG emissions from landfills except in a very indirect sense in that, if these recyclables are redirected from the waste dump, it will also reduce the significant additional quantities of GHGs that are involved in extracting, manufacturing and distributing further virgin natural resources.

One of the five core business models to enable circularity is the product as a service (PaaS) umbrella, which includes the rental, leasing, pay-per-use and pay-per-service approach to providing items that have traditionally been purchased outright—and then usually landfilled by consumers when no longer needed [119]. When a manufacturing entity retains ownership of a product, it becomes accountable for its end-of-life management, whether it is a sofa, sweater or a shipping container, and the company is incentivised to extend product life cycles through repair, retrofit or upgrade. An example is the carpet company [120] which popularised PaaS with its carpet tile policy, allowing worn areas of floor coverings to be replaced without removing the entire carpet installation.

As noted earlier, circularity and carpets are far from being synonymous, with the US only being able to reuse or recycle 10% of carpet material [121]. Comparative statistics for the Australian carpet lifecycle are hard to find because there is no carpet recycling industry in Australia. However, it is reasonable to surmise that the percentages would be around the same or lower than in the US. The reasons are primarily associated with the economy of scale that is required for a carpet recycling industry to function as a viable commercial enterprise. Consequently, the issue of carpet waste has been ignored in the Australian National Waste Policy. It is a sign that carpet recycling is in the 'too hard basket' and will continue to be so for the foreseeable future [77] (Commonwealth of Australia, 2018).

The application of or product stewardship or extended producer responsibility (EPR) to carpets [122] (Lindhqvist, 1992) seems limited in practice. In the US, opposition from carpet manufacturers to having EPR laws for carpets is well known, though a few manufacturers have formed a nationwide Voluntary Product Stewardship Program [123]. However, the robustness of such initiatives has constantly been questioned [107]. In Australia, a few carpet manufacturers, including Godfrey Herts and Feltex Carpets, as well as Nolan Carpets, offer a voluntary product stewardship initiative which is called the 3-Rs (reduce, reuse and recycle) program for commercial carpet products [124–126]. In Australia, Planet Ark supports commercial carpet recycling for reuse but confirms the absence of a carpet recycling industry, though noting the commercial opportunity that exists [111,127].

The level of recycling achieved in a society is dependent on factors controlled by that society. Re-use is more energy conserving than recycling and minimises GHG emissions, but the potential for reusing existing products beyond the first use reflects consumer behaviour, the logistics for processing stockpiles, as well as handling costs. While sanitary cleansing is essential for hygiene reasons, direct re-use of plastic milk bottles, as opposed to melting and re-forming them, should also apply to durable glass containers. Indeed, TerraCycle, an innovative recycling company based in Trenton, New Jersey and a global leader in handling hard to recycle material, is trialling a program whereby customers order products online, from ice cream to juice and shampoo, with a small container deposit. These items are delivered to their house and collected again with the next delivery. The containers are washed and taken back to the manufacturers for a refill. The major participating brands such as Mars, Pepsi and Procter and Gamble have redesigned their packaging to participate in the program [128]. This is the kind of initiative needed on a very large scale if the goal of forsaking the landfill is to become realistic.

The cost of recycling raises a principle about the degree to which MSW is considered a commodity as opposed to an essential service for a circular economy. A commodity mindset appears to have a significant influence on the level of MSW recycling achieved since contamination in recycling bins may not be further sorted at a materials recycling facility (MRF) into genuinely recyclable materials and waste. The fate of the contents of recycling bins with 'contaminants' varies across municipalities in the major Australian cities. However, the risk of the entire contents of a 'contaminated' recycling bin finding its way to the landfill cannot be overemphasised, defeating the very purpose of having a waste service with a recycling component [129]. Society must become more serious about fulfilling their collective responsibility towards each other for correct sorting. Simply mixing soft plastic into comingled recyclables can contaminate entire loads of otherwise valuable and materials, thus ending up as waste [54]. While self-regulation may be less onerous for the consumer, a rejection notice on a recycling bin (Figure 5, above) goes very little further, and a penalty system is probably needed to ensure that violations are minimised and the practice of clean separation becomes habitual. Indeed, for the eminently recyclable materials involving metals and glass, a participation rate which is as purposeful and intense as possessing a driving licence should be enforced, though that position in many non-European western countries such as Australia and the USA may not be reached until material scarcity begins to be felt [23–25].

At the same time, business and commerce have much to contribute, perhaps through EPR, which would help elevate compliance rates comparable to the strict attention we give to driving licence regulations or social distancing requirements under the SARS-COV-2 pandemic. While it is relatively easy for the householder to differentiate between soft or crinkly plastic and hard plastic containers, the latter are a problem in themselves. The codes used on firm plastic differentiate between polymers and are not a guide to recyclability. Indeed, of the seven codes, only two are regularly recycled; Code 1 (PET or polyethene terephthalate) and Code 2 (HDPE or high-density polyethene) with a third, Code 5 (PP or polypropylene) occasionally so. Municipal recycling guidance does not refer to the resin codes but uses images of physical objects such as plastic bottles and food containers which are not restricted to a particular resin [130]. Occasionally, these key physical items use non-recyclable resins. Moreover, the codes on the plastic are sometimes barely visible, so if a resident wishes to check for recyclability, it may not be possible. Even worse, many hard plastic containers used by Australia's main supermarkets to hold cakes, prepared meals and other foodstuffs have no codes whatsoever. Little wonder contamination occurs: surely we can improve on this chaotic and cavalier behaviour by business and regulators.

We have considerable difficulty managing much more than plastic, however. Almost any container or packaging that consists of mixed materials will be destined for landfill because the MRF is highly unlikely to separate the recyclables from the remaining material on time and cost grounds. Take the innocent tube of 'Original Flavour Stacked Chips' available from national supermarkets in Australia. It consists of five different materials: a cardboard tube, an interior lining to maintain freshness, a plastic seal at one end with a plastic cap over the top for use after the seal is broken (no plastic code) and an aluminium base. At least three of these materials are potentially recyclable. Although a dedicated householder may disassemble all five components, the average homeowner will either dispatch the whole tube into recycling, viewing the cardboard tube mistakenly as the guide to disposal or, of course, direct it into the garbage bin. Our homes have multiple examples of products like this, but prescriptive measures connected with EPR and the design of products to recognise end-of-life issues would dramatically enhance our potential to take care of problems such as mixed materials and non-recyclable plastics. Otherwise, we are simply abandoning rather difficult issues to the individual resident.

There is another group of waste materials that poses particular management problems, such as mattresses, e-waste, appliances, batteries, gas bottles, fire extinguishers or household goods including furniture, collected in the free two-weekly pickup by many municipalities in the Sydney metropolitan area. There are small-scale recycling projects such as producing acoustic and thermal insulation panels from waste textile and mattresses by the Smart Centre at UNSW in partnership with the Soft Landing Mattress Product Stewardship Scheme [131]. However, such materials do not exist in bulk, and even though some elements of most of the items could be recycled, there are too many obstacles hindering recyclability. There is the highly mixed nature of many of the goods, the commodified nature of recycling and its frequent unprofitability, as well as the ease with which the goods can be thrown 'away', which prevent most of the goods from being turned back into new or refurbished products.

From a behavioural point of view, even conventional recyclables seem to cause problems for householders. It is the responsibility of the residents to familiarise themselves with what can and cannot be recycled, although this is not standard across municipalities, and there is limited education undertaken for residents. Audits of kerbside collections show that around 10% of the material in recycling bins should not be there, contamination consisting of plastic, food and green waste, textiles and general garbage. The problem also occurs in waste bins destined for landfills, where about 30% of the contents consist of recyclable products. Clean recycling streams would improve labour efficiency, and markets for recyclables would improve and, in the long term, could avoid the likely necessity of landfill mining [54] (Thornton 2019).

6. Conclusions

Two Canadians, in an effort to live completely waste-free, embarked on a year-long competition to see who could forsake consumerism and produce the least amount of waste. Filmed as the Clean Bin Project, the ethical duel is rather light-hearted, but the background is the bleak problem of the vast amount of waste humankind produces and how the two struggle to find meaning in their infinitesimal influence on the overall problem [132]. However, the pair is to be congratulated for their leadership in encouraging us to think of the unthinkable since what we achieve is little better than tokenism at present. Gaining even a modest degree of circularity with recyclable cans, glass and certain plastic resins and diverting all decomposable waste from food and green clippings from landfills is a long way from realisation at present. Moreover, gaining full waste circularity for some of our difficult materials such as textiles and carpets or mattresses is likely to be even further away so that the solution with such waste is either landfill or incineration which will maintain at least some degree of GHG emissions. However, lessons can be learned from the examples given in this paper, and the potential for them to be mainstreamed cannot be overestimated.

As noted above, waste is an environmental issue, a resource issue and an ethical matter. When Australia approaches 2050 with a population of 40 million, resources will be more valuable than ever. If we persist in having landfills, we could mine them since the immediately recyclable materials such as aluminium and steel cans, glass bottles and various plastics do not decompose, though it would be much better to avoid the journey. Ideally, and perhaps critically necessary given the medium- to long-term non-renewability of many of our resources and the issue of GHGs in landfills, society needs to be moving towards zero-waste. While the ZWIA definition of zero waste is admirable, it should also embrace the chemicals that are used in PFAS. Recently, it has been shown that conventional plastics can produce GHGs, albeit slowly, and perhaps the long-term implications of complex human-made compounds such as PFAS cannot be predicted, so the precautionary principle would be an appropriate addition to ZWIA. However, at this point, society will need to regard it as a long-term goal since it is not likely to be reached until several crucial steps are taken and coordinated. Three strategic ones are, first, to restrain the intensity of consumption; second, to build a degree of consumer waste behaviour change that is genuinely proactive and third, to underpin this with pro-EPR policy and regulation. Additional concrete steps including designing products both for multiple re-uses as well as for disassembly, followed by recycling the component parts. Waste is a 'low hanging fruit' compared to most other sources of GHG. While developing an uncompromising system to achieve 'zero' waste to remove 'landfills' from the equation rests with the state and its regulatory apparatus, incorporating community education, accountability, transparency and participatory governance in that system cannot be underestimated. In the meantime, eliminating contamination, improving recovery rates of materials and prohibiting certain substances such as organic waste from landfills would be useful steps on the journey towards 'zero'.

Author Contributions: J.B. conducted 50% of the research and compilation of this paper and S.M. also conducted 50% of the research and compilation of the paper. Both authors have read and agreed to the published version of the manuscript.

Funding: The authors received no funding for this paper.

Institutional Review Board Statement: Not applicable since the studies did not involve humans or animals.

Informed Consent Statement: Not applicable since the studies did not involve humans or animals.

Data Availability Statement: Not applicable since this was not a data-oriented study.

Conflicts of Interest: The authors have no conflict of interest in preparing this paper and there are no ethical reservations to be declared.

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