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Plastics and Environmental Health: The Road Ahead

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Abstract

Plastics continue to benefit society in innumerable ways, even though recent public focus on plastics has centered mostly on human health and environmental concerns, including endocrine-disrupting properties and long-term pollution. The benefits of plastics are particularly apparent in medicine and public health. Plastics are versatile, cost-effective, require less energy to produce than alternative materials – such as metal or glass – and can be manufactured to have many different properties. Due to these characteristics, polymers are used in diverse health applications, such as disposable syringes and intravenous bags, sterile packaging for medical instruments as well as in joint replacements, tissue engineering, etc. However, not all current uses of plastics are prudent and sustainable, as illustrated by widespread, unwanted human exposure to endocrine-disrupting bisphenol-A (BPA) and di-(2-ethylhexyl)phthalate (DEHP), problems arising from the large quantities of plastic being disposed of, and depletion of non-renewable petroleum resources as a result of ever increasing mass-production of plastic consumer articles. By example of the healthcare sector, this review concentrates on benefits and downsides of plastics and identities opportunities to change the composition and disposal practices of these invaluable polymers for a more sustainable future consumption. It highlights ongoing efforts to phase out DEHP and BPA in the healthcare and food industry, and discusses biodegradable options for plastic packaging, opportunities for reducing plastic medical waste, and recycling in medical facilities in the quest to reap a maximum of benefits from polymers without compromising human health or the environment in the process.

Keywords: plastics, health effects, pollution, sustainability, sustainable consumption

Introduction

Most advances of human society over the past century have been facilitated by the use of plastics. Plastics are composed of a network of molecular monomers bound together to form macromolecules of infinite use in human society. Today, there are more than 20 different major types of plastics in use worldwide [1]. Whereas plastics have been in the public eye recently for potentially dangerous human exposure to toxic components such as bisphenol A (BPA) and di-(2-ethylhexyl)phthalate (DEHP) [2], their beneficial impact on society is undeniable and illustrated best by their medical uses and applications in public health. Plastics are cost-effective, require little energy to produce, and are lightweight and biocompatible. This makes them an ideal material for single-use disposable devices, which currently comprise 85% [3] of medical equipment. Plastics can also be soft, transparent, flexible, or biodegradable and many different types of plastics function as innovative materials for use in engineered tissues, absorbable sutures, prosthetics, and other medical applications.

Of course, the reach of plastics goes far beyond medicine and public health, and as such, an enormous quantity of plastics must be accounted for. Over 300 million metric tons of plastics are produced in the world annually [2] and about 50% [3] of this volume is for disposable applications, products that are discarded within a year of their purchase.

There are four major options for disposal of plastics: landfilling, incineration, recycling, and biodegradation. All plastics can be disposed of in landfills or incinerated [4]. But, landfills require space and the chemical constituents and energy contained in plastic articles typically is lost in this disposal route [4]. The second option, incineration, returns some of the energy from plastic production but is known to produce negative environmental and health effects [4]. Many plastics can be recycled, and some of the materials used to make plastics can be recovered. However, this method is not fully utilized, due to difficulties with the collection and sorting of plastic waste [4]. Finally, certain polymers are designed to biodegrade, thereby preventing long-term environmental damage from pollution [5]. However, many biodegradable plastics may not biodegrade rapidly enough under ambient environmental conditions to avoid accumulation from continuous inputs; and biodegradable plastics also can contaminate and disrupt the current recycling stream, due to their similar appearance, yet distinct makeup [4].

It is time to rethink the current management model of the production and disposal of plastics and to move towards a model that considers the entire life-cycle of these abundant, essential materials. Disposal of plastics in landfills ultimately is unsustainable and diminishes land resources fit for other uses of higher societal value. Incineration results in the release of carbon dioxide, a greenhouse gas [7], and of other air pollutants, including carcinogenic polycyclic aromatic hydrocarbons (PAHs) [8] and dioxins [9]. In theory, recycling represents a plausible superior solution. However, numerous practical challenges of plastics recycling exist including: the technical challenge of accurately sorting plastics; the current price of oil and the quality of recycled plastic that results [4]; as well as the knowledge that a significant fraction of one-way articles will bypass programmed disposal and enter the environment, thereby resulting in widespread, long-term pollution. Increasing consumption of biodegradable plastics can reduce the carbon footprint, pollution risks, and greenhouse gas emissions from polymer usage; however, it can do so only if these alternatives are made from non-fossil resources using renewable energy. From a materials management perspective, the blending of biodegradable (compostable) plastics is problematic, however, because separating biodegradable from potentially recyclable polymers is a challenge to both consumers and centralized refuse-sorting operations. Solutions to these problems will be market- and volume-dependent. Plastics of low volume for medical applications may rely more on fossil fuel and be designed for durability, whereas high-volume uses for consumer products will have to be sourced from renewable material stocks and be programmed for rapid environmental decay (i.e., biodegradability). This strategy could prevent irreparable environmental damage from disposable plastic products, while maintaining and maximizing the benefits of plastics in specialized cases, like medicine and public health. The benefits and disadvantages of plastics are discussed hereafter before conclusions are drawn to inform the road ahead.

1. The Good: Medical and Public Health Applications of Plastics

In medicine alone, the diversity of plastics' uses is incredible. Prosthetics, engineered tissues, and microneedle patches for drug delivery are all possible with polymers [10, 11]. In many sectors of society, plastics have replaced glass, wood, fibers, and metal in various products, including dishware, clothing, food packaging, personal care products, and others; these uses have already been explored elsewhere [12]. Disposable products in particular have been a major application for plastics within the last century because plastics are both inexpensive and lightweight [13].

Syringes are a good example of how plastics have benefited public health through single-use applications and later, through reusable products. Healthcare workers have long cited convenience for choosing disposable products [14]. Disposable plastic items such as latex gloves, intravenous (IV) bags and dialysis tubes are inexpensive and allow for patient safety as well as time savings, due to eliminating the need to sterilize used equipment [15]. Disposable syringes in particular were in focus during the early 1980s as a way to reduce the risk of transmitting blood-borne infections such as human immunodeficiency virus (HIV) and hepatitis B through injections from used needles [14]. With reusable syringes, there is a risk of needle-sticks while capping and re-sterilizing the syringe, and improper sterilization techniques can cause transmission of communicable diseases [14]. However, against the explicit recommendations, disposable syringes can and still were being reused; therefore, efforts were made to develop a plastic auto-disable syringe that locks after single use [16]. Although these are more expensive than conventional disposable syringes, they prevent reuse and possible infection [16]. Reusable syringes are experiencing a comeback in developing countries where, single-use syringes still pose a health risk from improper disposal, and sterilizable syringes can always be at hand to administer critically important vaccinations [16]. However, the problems raised by opponents of sterilizable syringes – such as easy breakage and the difficulty of cleaning syringes made of metal and glass – have been solved by designing a sterilizable syringe completely made of plastic [14]. Today plastics are thus facilitating the manufacture of both throwaway and reusable medical syringes.

The development of plastics has led to other disposable items similarly ubiquitous to hospitals, such as intravenous (IV) bags and tubing. These are used for immediate drug-delivery, to treat dehydrated patients through fluid replacement, to transfuse blood, and to correct electrolyte imbalances as quickly as possible. The IV injection of fluids and medicines into the bloodstream is by far the fastest method of delivering remedies into the body. The importance of IV bags and tubing in caring for hospital patients is clear in the fact that they constitute 20–25% of hospital waste [17].

Polymers have also been utilized in the development of innovative materials and methods of healing patients. Absorbable sutures are made of polymers that can be designed to biodegrade over differing time periods depending on patient needs [18]. Since they do not require surgical removal following implantation, they also reduce the number of procedures a patient must undergo. Polymers have demonstrated their value in pharmaceuticals, as controlled drug delivery systems used by tens of millions of people each year, and in orthopedics: the polymer polymethylmethacrylate is used as bone cement in total hip replacements [19]. Tissue engineering has more recently been significantly advanced by polymers, as polymer scaffolds can be designed to biodegrade and can have a variety of different structures [20]. The array of different types of polymers that can be produced has had an enormous effect on the quality of human health through these innovations in medical research.

2. The Bad: Health Effects of Plastics

However, the widespread use of plastics facilitates continuous contact of these materials with the human body and with it daily exposure to ingredients in plastics. Although plastics components do not have significant bioaccumulation potential (except when accidentally ingested and becoming entrapped in the gastrointestinal system), biomonitoring studies [21] have demonstrated the presence of steady-state concentration of plastics' components in the human body, thereby reflecting the ongoing balance of constant exposure, metabolism and excretion of these compounds. This situation implies that in today's plastics-enabled society there are no control groups to be found to analyze the effects on human health from low-level, environmental exposures to plastic constituents. Everybody is being exposed to some degree at any given time from gestation through death. Detectable levels of bisphenol A have been found in the urine of 95% of the adult population of the United States [22]. In recent years there have been several epidemiological studies and controlled animal experiments performed concerning the health effects of plastic components such as BPA and DEHP. Associations were found between exposure to these compounds and destructive effects on health and reproduction, such as early sexual maturation, decreased male fertility, aggressive behavior, and others (reviewed in 2, 23, 24, 25). At present, BPA has been one of the first plastic materials to be recognized for its potential harm. Evidence of potential harm has been deemed sufficient by the U.S. Food and Drug Administration (FDA) to issue a statement that "recent studies provide reason for some concern about the potential effects of BPA" [26]. In response to such concerns, BPA also recently has been banned in the U.S. from use in infant bottles and spill-proof cups for toddlers in an effort to protect a particularly vulnerable population [27]. In Canada and the European Union, polycarbonate plastics made from BPA have also been banned from use in baby bottles [28].

There are similar issues with di-(2-ethylhexyl)phthalate (DEHP). DEHP is the plasticizer most frequent used in polyvinyl chloride (PVC). There are particular concerns with human exposure, as this additive is not chemically bound to the plastics in which it is incorporated, and thus can leach out readily [29]. Several rodent and human studies have found correlations between DEHP exposure and harmful health effects, including changes to the female and male reproductive systems, increased waist circumference and insulin resistance [reviewed in 29, 30, 31]. The 'cocktail effect', i.e., the fact that environmental exposures do not occur in isolation but are cumulative, also is an issue requiring further study. Furthermore, there are additional components of plastics that are being studied for potential harm, including polyhalogenated flame retardants (e.g., polybrominated diphenyl ethers), polyfluorinated compounds (e.g., polyfluoroalkyl compounds such as perfluorooctane sulfonate or PFOS and perfluorooctanoate or PFOA), and antimicrobials (e.g., triclosan and triclocarban) that have been reviewed elsewhere [See reference 2 and sources cited therein].

Although evidence due to research so far has been sufficient for governmental agencies to take action, more is still being done to demonstrate conclusively that the negative health effects listed above and others are due to the compounds such as BPA and DEHP in plastic. For example, a recent study found a significant association between urinary concentration of BPA and obesity among children and adolescents [32]. However, as noted by the authors, "explanations of the association cannot rule out the possibility that obese children ingest food with higher BPA content or have greater adipose stores of BPA" [32]. These and other possible explanations for observed associations of exposure and health outcomes should be tested, as research proceeds regarding the role of plastic components as potential obesogens.

3. The Ugly: Persistence of Plastics in the Environment

Although the spectrum and extent of health effects stemming from the pervasive and ubiquitous human exposure to plastics constituents are as of yet uncertain, the issue of plastic waste has been obvious and problematic for some time and demands action (Figure 1). When mass production of plastics began in the 1940s, it quickly permeated into all facets of modern daily life [2]. However, there was never a cognizant consideration of the effects plastics will exert on the environment when produced at today's enormous and still expanding scale. Although healthcare facilities in the United States contribute 3.4 billion pounds of waste annually, they are not a major contributor to the overall production of plastic refuse [33]. Plastics represent between 15 to 25% of all hospital waste in the U.S. [33, 18], which amounts to a maximum annual loading of 850 million pounds of plastic waste per year. This implies that human medicine accounts for less than 0.2% of the plastic waste produced and being disposed of in the U.S. each year (Figure 2). Fifty percent of the annual plastic production goes toward disposable applications such as packaging [3]. So, although there have been great benefits from using plastics, especially in the healthcare sector, there needs to be a second revolution of plastics in which life-cycle considerations are integrated production and consumption decisions to handle the voluminous present-day flow of plastics, most of which being destined for disposal after single use.

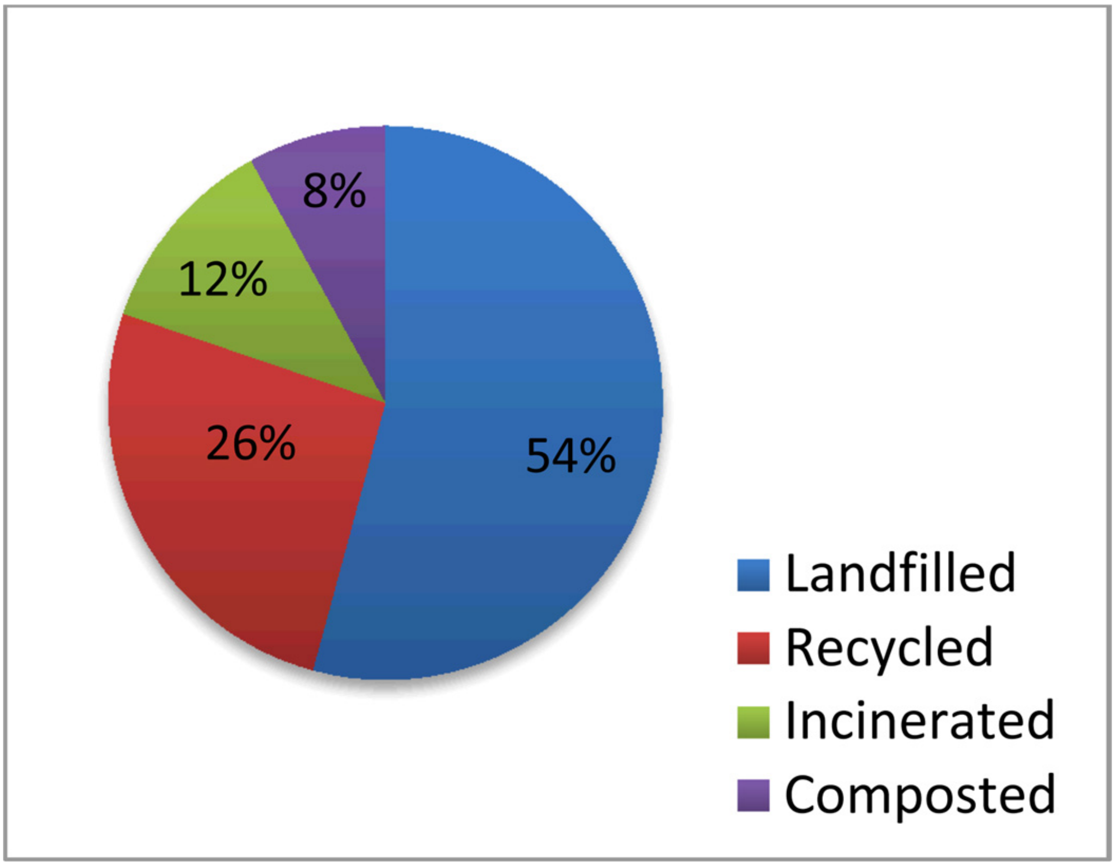

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Figure 1

Disposal by percentage of the approximately 250 million tons of municipal waste generated in the United States in 2010 (Figure was created from data contained in reference [52]).

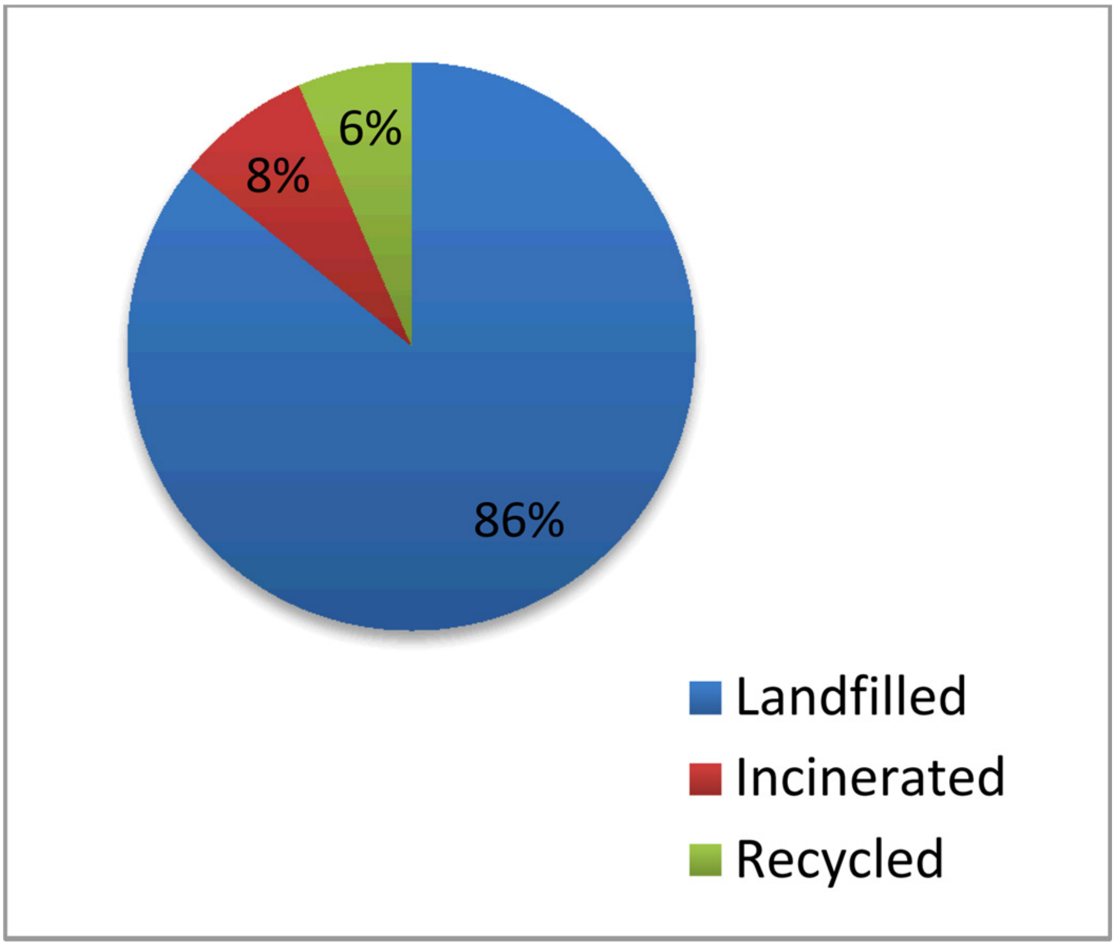

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Figure 2

Disposal by percentage of the approximately 34 million tons of plastic disposed of in the United States in 2008 (Figure was created from data contained in reference [53]; compostable bioplastics were not called out separately in this data source).

A look at medical waste handling illustrates current options for disposal of plastics. Today, 60% of regulated and potentially infectious waste, including sharps and pharmaceuticals, is incinerated [53] (Figure 3). Whereas the term 'incineration' is not readily associated with sustainability, this disposal route does have a number of benefits, including the prevention of disease transmission, a significant reduction in the volume and mass of the waste, and recovery of at least some of the energy used to produce these materials. Improper incineration poses significant human health risks, however, particularly from the massive release of carcinogenic air toxins such as dioxins [35]. In rural America and many parts of the developing world, open burning of waste in barrels is common instead of or in addition to landfilling. Depending on the quantity and composition of household waste processed, backyard burning from 2 to 40 households can rival the emissions of polychlorinated dibenzo-*p*-dioxins/polychlorinated dibenzofurans (PCDD/PCDF) from an industrial-sized municipal waste combustor handling orders of magnitude larger volumes of waste [34]. And, incineration produces ashes containing toxic metals that can pose risks to groundwater resources underlying landfills employed for ash disposal [35].

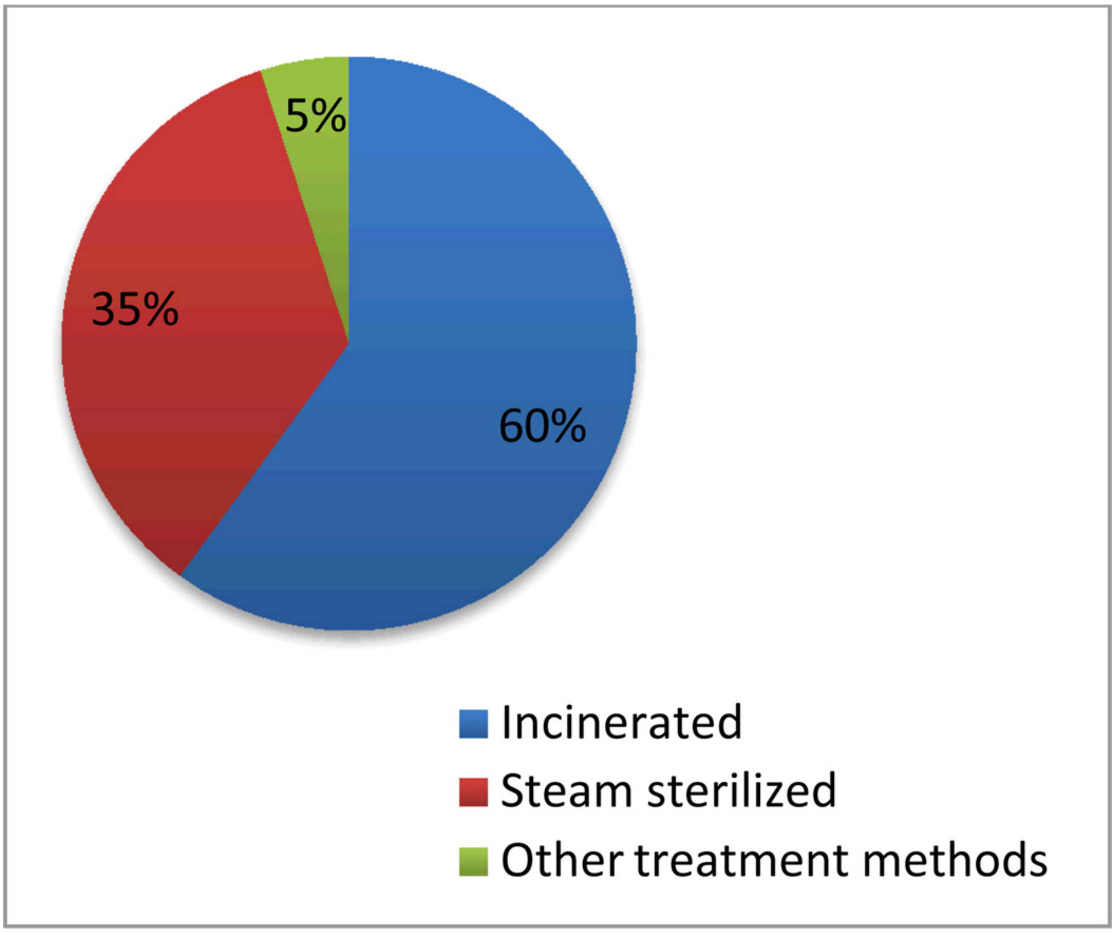

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Figure 3

Treatment of regulated medical wastes (RMW) by treatment method. (Figure 3 was created from data contained in reference [54].)

Discarding plastics in landfills is also not the ideal solution. Whereas the disposal of plastics in landfills does sequester almost 100% of the carbon from the atmosphere [36], this also implies that both the material and the energy stored in plastics are lost (i.e., sequestered for the long term) in the process. Plastics manufacture comprises 4.6% of the annual petroleum consumption in the U.S., 329 million barrels as feedstock and 2 million barrels for use as fuel [38]. Although the use of plastics can reduce the need for fossil fuels by replacing denser materials such as glass and metal in different applications, none of the energy or material used can be recovered when plastics are disposed of in landfills [4]. Space constraints are also becoming an issue. Although land in the United States is abundant, smaller countries such as Denmark and Japan already are relying more heavily on incineration to conserve land resources [4]. As its population increases, the United States likely will experience similar land scarcity and will have to adjust its disposal practices accordingly. Finally, the protective liners separating landfills from the soil and from underlying drinking water resources may rupture or leak over time. This constitutes a long-term risk of contamination of soil and groundwater with plastics' components [4] as well as with other contaminants contained in landfill leachate.

If plastics must be disposed of, recycling may be perceived intuitively as the best option (although only a full life-cycle assessment can answer this question conclusively) because it allows for partial recovery of both the material and energy used to produce them. However, not all plastics can be recycled. Thus, they must be effectively sorted, which increases the cost. Contamination of different plastics streams is obviously one of the major challenges with regards to recycling and causes yet another issue: lower quality of the resultant post-consumer plastics. It is difficult if not impossible to produce recycled plastics of the same quality as virgin polymer because sorting systems are imperfect and the raw materials used to produce recycled product are expected to be impure. Thus, although recycled polymers are cheaper to produce, their quality decreases due to contamination with each recycling cycle, which hinders or prevents their use in high-value applications, such as the healthcare sector. As of yet, the prices of oil and landfill disposal are not high enough to significantly incentivize the use of recycled materials. However, as petroleum and land resources grow scarcer, and as the public becomes more aware of the environmental consequences of plastics consumption, it is likely that consumer products made from recycled plastics and other materials will become more mainstream.

Biodegradable plastics are also an option that should be considered. At this point, it is necessary to clarify the differences among many terms that are often used interchangeably, specifically ‘biodegradable’ and ‘compostable.’ From ASTM International (formerly known as the American Society for Testing and Materials), a biodegradable plastic is one in which the “degradation results from the action of naturally occurring microorganisms such as bacteria, fungi, and algae,” whereas a compostable plastic “undergoes degradation by biological processes during composting to yield carbon dioxide, water, inorganic compounds, and biomass at a rate consistent with other known compostable materials and leaves no visible, distinguishable, or toxic residue” [38]. This means that a plastic material technically could be biodegradable if it disintegrates into smaller and smaller polymer fragments, but this can lead to unwanted consequences for the environment [39]. Plastics labeled as being compostable must be certified under the ASTM D6400 compostability standards using the test method ASTM D 5338-11 to ensure that it can be commercially composted. The certification requires a polymer to biodegrade at a rate similar to those of other naturally occurring, compostable materials [40]. Whereas ASTM compostability standards are unique to the United States, national and international standards from other countries are also used, including those made by the European Standardization Committee (CEN), the International Standards Organization (ISO), and the German Institute for Standardization (DIN).

Although conventional plastics are not biodegradable, plastics are being manufactured and developed today that are, including polyhydroxylalkanoate (PHA) and polylactic acid (PLA) based plastics. However, they are not yet the perfect solution to disposable plastics. Most bioplastics today are derived from plant sources such as corn and molasses, thereby representing a competition for the food supply of humans and farm animals [41]. Not figuring in the various externalities from environmental pollution and human health effects, biodegradable plastics currently are more expensive than conventional plastics. However, as oil prices rise and technologies to produce biodegradable plastics advance, this may change in the near future.

There are also issues that must be resolved concerning the disposal of biodegradable plastics. Biodegradable plastics are being tested under conditions at commercial composting facilities of ~58°C and ~60% relative humidity. Typical home composting may deviate from the above conditions [42], thereby resulting in delayed or incompletely biodegradation. Asking consumers to be educated about this and to demand disposal in commercial composting facility appears to be unrealistic. However, pilot programs in Boulder, CO found that curbside composting program increased waste diversion from landfills up from 40% to 55–69%, thereby indicating that consumers are willing to adopt better disposal modes if presented with suitable options [43]. In the United States, cities other than Boulder that have implemented curbside composting services include, for example, San Francisco, Portland, and Seattle [44]. Finally, as biodegradable plastics are fairly new and are designed to look like traditional plastics, conventional plastics may contaminate composting feedstock and biodegradable plastics may enter into recycling streams, thereby decreasing the quality of both compost and recycled plastics [4]. As with recycling, the product of composting must be of sufficiently high quality, so that running a composting facility becomes practical. Although some biodegradable plastics can be recycled a limited number of times, they would need to be recycled with other biodegradable plastics and have not reached a critical volumetric mass warranting a revamping of current recycling systems.

4. The Road Ahead: Research into Biodegradable Plastics and What Can Be Done Now to Restrict Plastic Usage to Sustainable Levels

Current research seeks to address some of the challenges and limitations of biodegradable plastics. For example, a method was discovered recently enabling the synthesis of biodegradable polymers from the abundant compounds carbon dioxide and carbon monoxide using metal complexes as catalysts [45]. This development represents a potential solution to at least one of the problems concerning bioplastics in that this new process utilizes a resource that is widely available and can bind unwanted greenhouse gases, as opposed to competing with feed stocks for animals and the human food supply. This method is now being commercialized as a potential replacement for the epoxy resins that line metal cans and contain BPA. If this coating were to be fully adopted, aside from reducing human exposure to BPA, 180 million metric tons of carbon dioxide emissions annually would be sequestered and avoided [46]. Recent innovations in bioplastics, such as this example, demonstrate the benefits of continuing the development of plastic alternatives.

The healthcare sector may serve as a model for illustrating how steps can be taken immediately to move toward a more sustainable consumption of plastic materials. Some hospitals have begun reprocessing medical equipment for multiple uses, switching to alternative plastics from those that have been associated with harmful health effects, and reducing their use of plastics altogether. More vulnerable patient groups, such as infants in the neonatal intensive care units, at present are exposed to high and presumably harmful amounts of DEHP from blood bags, IV tubing etc. made from PVC [2]. In response, organizations such as the American Medical Association have recommended that hospitals and physicians find alternatives to products made from PVC and containing the harmful additive, DEHP [47]. Also, although expense has been identified in the past as a reason for using disposable products, it is now becoming more cost-effective to switch to reusable alternatives. This has been estimated to potentially result in a 50% reduction of medical equipment costs [48]. One hospital switched from using blue polypropylene wrap for keeping surgical tools in the operating room sterile to using surgical hard cases for protection, thereby realizing $51,000 of annual savings in the process [49]. Twenty-four percent of U.S. hospitals have begun using reprocessing like this to decrease disposable waste [50]. As medical facilities take steps towards use of safer plastics and reductions in overall consumption of polymers, plastics manufacturers and stakeholders will listen, since the healthcare industry corresponds to 15.2% of the gross domestic product (GDP) of the United States and continues to grow [51].

However, problematic issues extend far beyond simply avoiding plastics that have already been linked with health hazards and substituting alternatives. Instead, it will require an entire rethinking of the way in which we use plastics today. The damaging and lasting effects of plastics in the environment stem primarily from applications whose long-term harm clearly outweigh any short-term benefits realized – often merely as a matter of convenience. This can be seen most readily in the differences between using polymers in applications that are produced in limited quantities and provide significant benefits – such as prosthetic limbs, medical gloves, etc. – and in those that are simply convenience items, such as plastic bags and bottled water. Although waste can and should be reduced in the healthcare industry, the high volume of plastics disposed of in the United States is derived by uses other than those in medicine. In other words, the societal conundrum stemming from the reliance on plastics cannot be solved by focusing on the healthcare sector alone.

The environmental and health issues human society faces today in the ‘age of plastics’ mostly stem from the fact that the impact of the scales of plastic consumption and disposal were not considered until after mass-production was well on its way. As alternatives to conventional, petroleum-based plastics are developed, it will be important to perform life-cycle assessments on each. This will be necessary to ensure that these new choices and alternatives truly serve to reduce the sum of adverse effects, ranging from unwanted human exposure in plastics manufacturing and clinical uses, to environment pollution from inappropriate disposal. Again, using large volumes of otherwise noxious greenhouse gases to drive the sustainable production and consumption of biodegradable plastics may represent an important initial step in the right direction; it also would avoid unwanted competition of the plastics industry with the world’s food supply.

After taking steps to eliminate the uses of plastics that have been associated with harmful health effects and to move towards reusable products, the long-term solution may lie in determining which applications are truly necessary, which ones offer short-term benefits only, and in developing biodegradable plastics for production of disposable items with a programmed, short lifespan. This could help to realize the full potential of plastics in medicine, public health and human society without compromising the quality of life of current and future generations.

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