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A Review of Recycling and Waste Management Systems Through the Lens of the COVID-19 Pandemic

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ABSTRACT

Recycling and waste management have garnered immense popularity in recent years, but few studies have been carried out regarding these systems. Therefore, an in-depth literature review was done in order to highlight the different sectors of the recycling system that need to be re-formed. Hence this study examined recycling and waste management systems within three categories–medical, municipal, and plastic–that were carried out pre and post COVID by reviewing previous studies, technical reports, and annual reports. This was done by visiting numerous academic search engines alongside online resources that were utilized to assemble literature related to waste and recycling systems. Continuing a recurring idea was that no matter the type of waste, further research regarding all waste should be carried out. Additionally, since recycling and waste management are a vital part of our society, and seeing how unpredictable events such as the pandemic may be, it is paramount that that research is done not only on how the pandemic has affected systems now, but also how we can learn from current issues to utilize them for future "waste shocks".

Introduction

Recycling and waste management have garnered immense popularity in recent years due to the increase in production costs, namely, resource depletion and environ-mental concerns (Tilton, 1999). In addition, in British Columbia, Canada, the net annual recycling collected was upwards of 200,000 tonnes in 2020 (RecycleBC, 2020). Just five years ago this number was much smaller: 178,000 tonnes. This suggests there was a substantial increase in recycled materials. Additionally, in 2018, awareness of Recycle BC, the government-sponsored company in charge of recycling, rose from 38% to 51% over the previous year (RecycleBC, 2018). However, with the global average temperature having already increased by more than 1°C (1.8°F) above the pre industrial level (Levine & Steele, 2021), it is becoming imperative that the world begins to shift towards more sustainable systems: a key component being recycling and waste management systems. Adding onto this, of the almost 4.7 million tonnes of plastic that Canada produces each year, only 9% is recycled, which leaves a staggering amount to be disposed of in landfills or incinerated (Jérôme Petigny et al., 2019). More developed countries, such as Australia, Canada, and the United States, normally relied on countries like China, Myanmar and Cambodia to handle plastic waste. However, this posed considerable threats to those countries' citizens and environment. By 2050, researchers at World Wildlife Fund (WWF), reported that greenhouse emissions due to the production and incineration of plastic could rise to as much as 2.8 billion tonnes: tripling that of this year's 850 million tonnes. What's more is that as the planet gets warmer due to greenhouse emissions, recycled plastics further breakdown leading to an increase in methane and ethylene which heats up the earth resulting in a positive feedback mechanism (Major Kerri, 2022).

General waste can also contribute to climate change through a multitude of processes. For example, organic waste–consisting of items such as kitchen waste, garden waste, and paper–accounts for over half of all waste (Kharola et al., 2022). When organic waste de-composes, much of which is done in dumpsites and landfills, carbon dioxide and methane gas are released into the atmosphere, contributing to global climate change (Secretariat of the Pacific Regional Environment Programme [SPREP], 2009; United States Environ-mental Protection Agency [EPA], 2022a). Currently, most recycling management systems have reduced greenhouse gas emissions in their processes in two ways.

This was done by saving energy in the processing of materials for industrial and consumer use, and by reducing the flow of materials into landfills, where decomposition releases greenhouse gasses (North Carolina Department of Environmental Quality [NCDEQ], 2022). This, however, has not resulted in a net reduction in greenhouse gas emissions globally from waste management (Stoddard et al., 2021). Furthermore, in some cases, recycling can be detrimental. For example, it has been reported in the UK that millions of tonnes of carefully sorted recycled items are being burned after collection and that over 11 percent of all garbage collected for recycling in the UK is incinerated (Siegle, 2021). Another example is in Canada, where the amount of waste disposed in landfills or incinerated increased by 1.7 million tonnes (or 7%), reaching 25.7 million tonnes in 2022 (Envi-ronment and Climate Change Canada, 2022). Since the incineration of waste leads to the release of dust hydrocarbons, gaseous compounds, metallic compounds, and metalloid compounds (including carbon dioxide, nitrous oxide, hydrogen chloride, and sulfur dioxide) an increase in incineration has a harmful impact not only the environment but also our health (R. Sharma et al., 2013). Equally important to note is the fact that although incinerators, alongside the use of advanced air pollution technologies (Environment and Climate Change Canada, 2022) can be beneficial in the short term, these methods aren't a long-term solution as, on average, incinerators only last around 30 years (Baptista, 2019).

In addition, more recently, the coronavirus–more commonly known as COVID-19– has impacted many sectors of the economy, including but not limited to transportation, tourism, and other business sectors (Chaudhary et al., 2020). As of July 4, 2022, it is re-ported that there have been over 6.34 million deaths and 545 million cases due to COVID-19 (World Health Organization, 2022): a tell-tale sign of grave and globally in-fluential changes. Furthermore, since protective measures such as mask wearing, traffic restrictions, social distancing, and home isolation have been globally implemented to reduce the spread of the COVID-19 (Xu et al., 2021), it has been found that waste has increased in numerous countries due to the intensification of said measures (Sarkodie & Owusu, 2021). Moreover, several studies have also shown that medical waste has in-creased significantly due to the COVID-19 pandemic (Andeobu et al., 2022; Etim et al., 2022). This is mainly to sustain the enormous demand for personal protective equipment which includes face masks, gloves, gowns, etc. (Peng et al., 2021). According to the World Health Organization, there has been a dramatic influx of medical waste due to the pandemic, with over 30% of healthcare facilities (and over 60% in developing countries) not being able to handle the medical waste produced (Wise, 2022). Additionally, medical waste is a type of waste to which incineration is applied extensively (National Academies Press (US), 2000). In 2020, the United States EPA reported that incineration accounted for 13.1 million metric tons (MMT) of carbon dioxide emitted (United States Environmental Protection Agency [EPA], 2022b), and since U.S. healthcare spendings encompass 19.7% of the entire country's GDP, it is clear that medical waste is also a major carbon emitter (Hartmann et al., 2022).

Additionally, throughout the world, there has been an increase in total municipal waste (Tiseo, 2022), which includes all items from homes and businesses. An instance of this was in the United States. In early 2020, the US government put in place restrictions and lockdown measures in order to slow the spread of the COVID-19 virus; however, due to the novelty of the virus alongside the many restrictions, many consumers engaged in panic buying, leading to an increase in consumption. This also meant an increase in municipal waste (Pappalardo et al., 2020). In the context of the European Union (EU), many countries between 2015 and 2020, including Slovakia, Belgium, France, and Finland to name a few, also saw an increase in total municipal waste. The EU itself also saw a general increase in municipal waste; in 2015 the EU produced 480 kg per capita of municipal waste, but in 2020, with the start of the pandemic, the production of said municipal waste increased to 505 kg per capita (Statistics | Eurostat, 2022). From 2002 to 2018, the total solid waste generated in Canada also increased by 4.8 million tonnes (Yunis & Aliakbari, 2002) and it is likely that, looking at the patterns in other countries, the pandemic has exacerbated this increase.

Few studies, however, have been carried out on the sudden and rapid shock on an already exacerbated waste management and recycling system, mainly due to effects of the COVID-19 virus as aforementioned. This means it is especially pertinent, as our current plastic and recycling system is already plagued with inefficiencies that have been in-tensified and exposed by the COVID-19 pandemic (Ebner & Iacovidou, 2021). A fact that is equally important to

note is that any adjustments to current waste and recycling systems in order to manage the waste shocks require adequate information (Sarkodie & Owusu, 2021).

Therefore, an in-depth literature review is needed to highlight the different sectors of the recycling system that need to be reformed. Hence this study aims to examine recycling and waste management systems and processes that were carried out pre and post COVID by reviewing previous studies, technical reports, and annual reports. Through this, it is hoped that the following questions will be answered: a) How have the current recycling and waste management systems performed during the pandemic? and b) What specific areas need to be modified to withstand future waste shocks, and what sustainable approaches to put in place?

Methodology

Numerous academic search engines (Google Scholar, SpringerLink, MDPI, etc.) alongside online information sources (Google, news platforms, annual reports, etc.) were utilized to assemble literature related to waste and recycling systems before and during the COVID-19 pandemic. To do this, key words such as “waste shock,” “COVID-19,” “sustainability,” “waste management,” and “recycling” were used.

The following criteria were used for the initial selection of articles for this review:

1. English-language publications
2. Published in peer-reviewed scientific journals and official annual reports
3. A publication range between 2015 to present

Articles selected were then refined by recycling status. These were then further categorized into types of waste: medical, municipal, plastic, and a combination of them (see Fig 1). Selection process was further refined by looking at articles that discussed two or more of the following:

- Recycling
- Waste management
- COVID-19
- Sustainability
- Waste shock

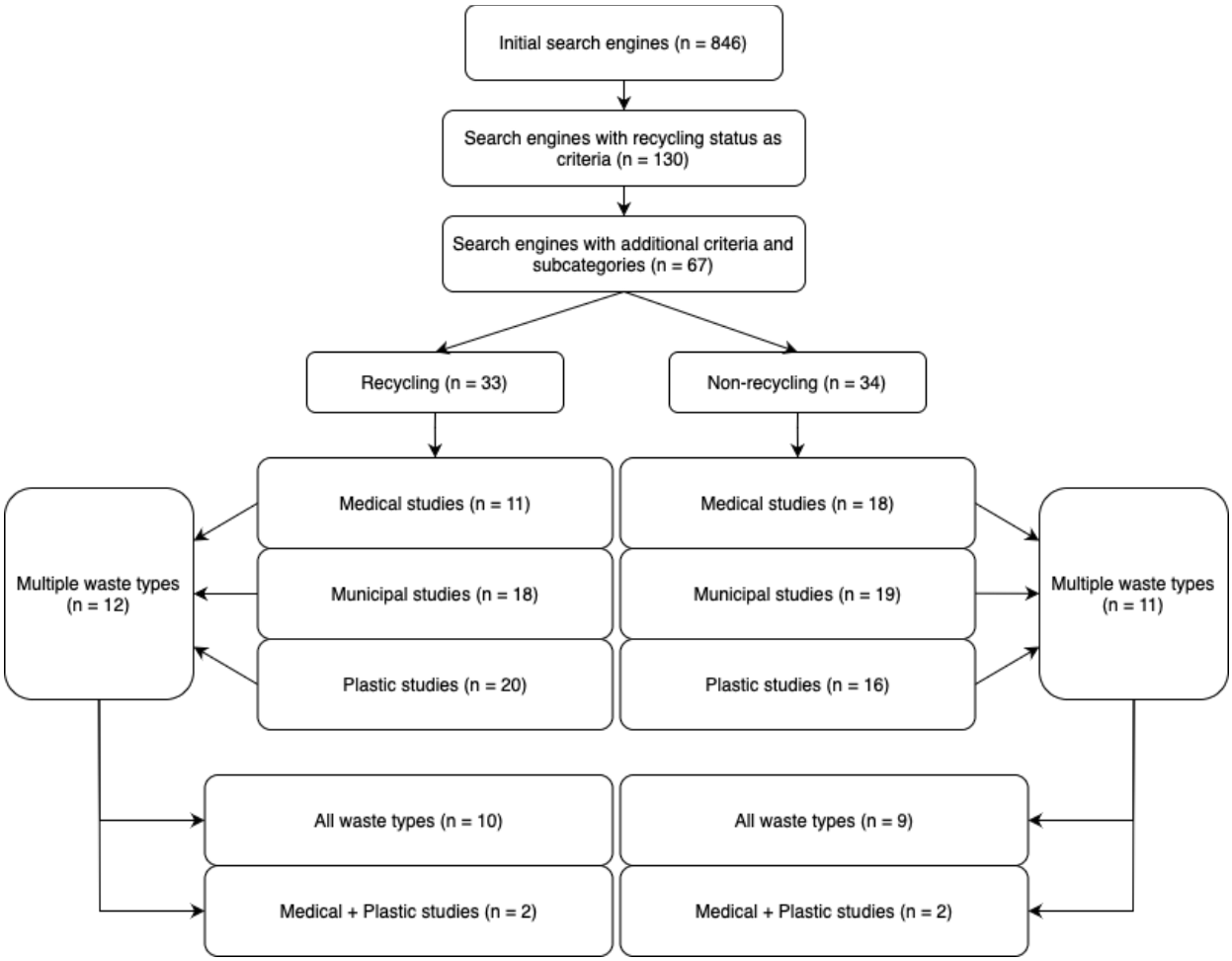

Fig. 1. Schematic diagram of literature search and article selection process.

Results and Discussion

Based on the initial findings, 130 articles were selected. From the 130 articles, 67 were chosen based on further criteria and categorization. See fig. 1. for more details. All of the articles utilized were sorted into two categories: recycling and non-recycling. They were then split into more sub-categories: medical, municipal, plastic, and the combination of the three. They were split into these three categories as all articles reviewed fell under those categories; for instance, if an article focused on food waste, then it could fit under municipal, and an article focused on personal protective equipment (PPE) could be categorized within medical.

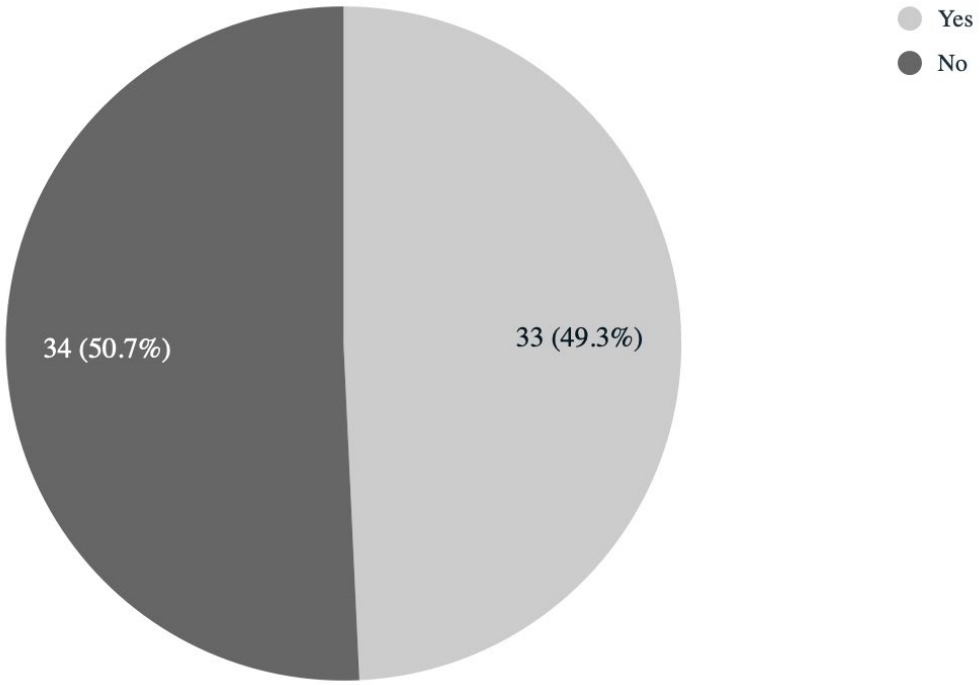

Fig. 2. Recycling status of articles collected for this review.

Of the 67 selected articles, 33 were recycling and 34 were non-recycling (see figure 2), with 29 focused on medical, 37 on municipal, and 36 on plastic. Additionally, over 34% of studies were focused on multiple types of waste, suggesting there is a need for more studies on specific waste management sections given that waste management is a complex multidisciplinary problem (Bani et al., n.d.). Furthermore, those that focused on all three types of waste developed solutions that only dealt with one or two types of waste. This suggests that there is also a need for clearer, more accurate research/data and possible solutions on waste management systems (Naughton, 2020; Peng et al., 2021). In order to clearly report the results and address the research questions mentioned in the introduction, the following information is split into two sections: "performance of recycling and waste management systems" and "policies, waste shocks, and sustainability approaches." Within the "performance of recycling and waste management systems," the performance of three different types of waste were explored. Additionally, results showed that throughout the span of the pandemic and as of now, the amount of non-recyclables being produced has significantly increased. A similar finding was reported by Argentiero et al. (Argentiero et al., 2022). This is an overarching finding that is further explored through the rest of the discussion.

Performance of recycling and waste management systems

Medical

The general consensus around waste and recycling management systems during and after the peak of the pandemic is that they have been negatively impacted (Argentiero et al., 2022; Bhar et al., 2022; Etim et al., 2022; Hantoko et al., 2021; Mohamed et al., 2022; Roy et al., 2021; Zhou et al., 2021). From a broad perspective, the amount of household (municipal) waste generated in the EU was 181.4 million tonnes in 2016, 186.1 million tonnes in 2018 (the start of the pandemic), and 195.9 million tonnes in 2020 (largely considered the peak of the pandemic) (Statistics | Eurostat, 2022).

As of 2022, there is no data regarding the amount of waste generated within the United States, Canada, and many countries around the world. This makes it especially difficult to assess the true impacts and damage that was done by the pandemic. Addi-tionally, the data for the amount of household waste generated in the EU was extracted just a month ago in September of 2022. Thus, using pure numbers and statistics to assess the performance of recycling and waste management systems is difficult; this makes reviews such as this much more important and relevant.

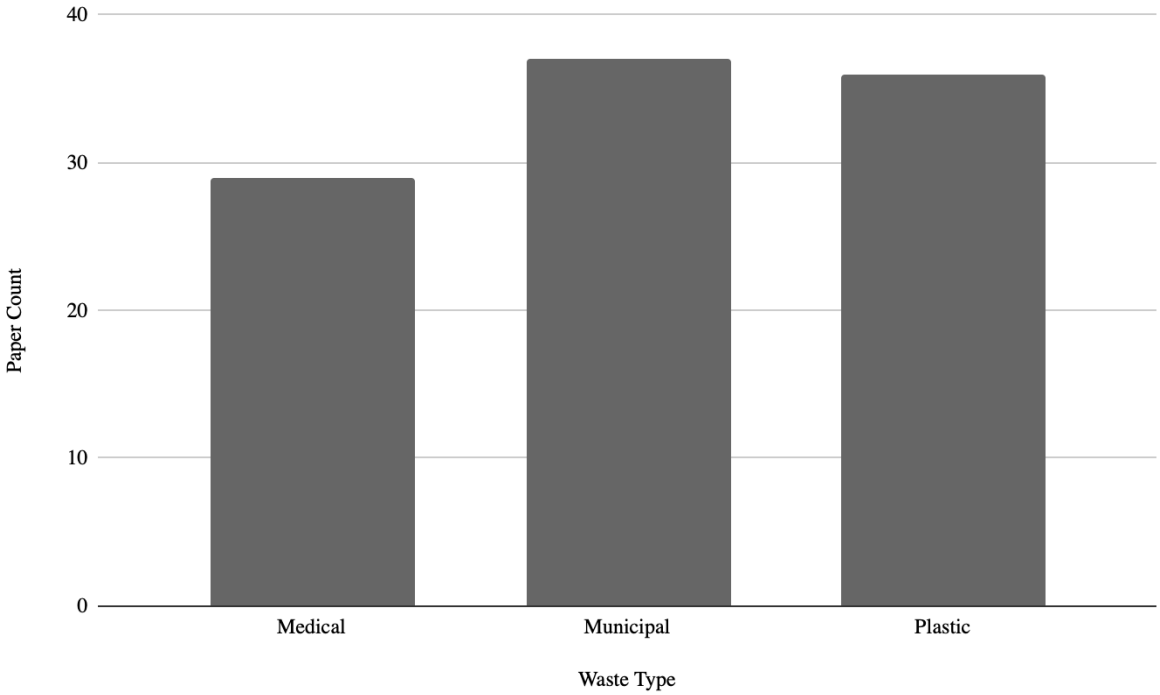

Fig. 3. Number of papers that focused on different types of waste.

Out of the 29 articles discussing medical waste, every study found that medical waste has increased due to the COVID-19 pandemic and that further actions need to be taken (Bhar et al., 2022; Etim et al., 2022; Peng et al., 2021; Sarkodie & Owusu, 2021). Addi-tionally, out of the three sub-categories, there was more information about municipal waste (37 articles) compared to medical waste (29 articles) (refer to figure 3). Despite the fact that at the peak of the COVID-19 crisis, waste generation, in relation to output, by the medical sector increased 65% as reported by Wuyts et al. (Wuyts et al., 2020), fewer ar-ticles, relative to the other categories, have researched the impacts of the pandemic on medical waste management as clearly shown in article counts (see fig. 1). This is consistent with previous studies by Dharmaraj et al. (Dharmaraj et al., 2021) and Su et al. (Su et al., 2021) that have shown the need for more research on medical waste management.

This review revealed a few possible reasons, centered around the environment and public health, why medical waste needs to be further explored and addressed. In terms of the environment, many studies have confirmed the short-term effect of an increasing amount of waste. This has created an enormous strain on current waste collection and management systems, leading to an increase in tonnes of medical waste in the form of PPE being released into landfills as well as to the marine environment, which can have grave adverse effects on not only marine life but humans as well (Dharmaraj et al., 2021; Peng et al., 2021). This review also revealed that there may be long-term impacts, which are still widely unknown. These long-term impacts may even outweigh and have a greater consequence than the short-term impacts (Artacho-Ramírez et al., 2022; Ikiz et al., 2021; Peng et al., 2021; Ranjbari et al., 2022). Even though long-term changes are unknown as of now, observing the initial short-term changes will provide insights for research-ers and policy-makers when attempting to reverse the impacts we're seeing. This is an area we can further explore in

order to combat and minimize "waste shocks" that may occur in the future (Ikiz et al., 2021). Another reason why medical waste needs to be further explored is the fact that it has and will continue to impact public health (Upadhyay & Bajpai, 2022). A considerable amount of hazardous medical waste has been generated from hospitals and other healthcare facilities during the pandemic (Su et al., 2021). Not only does this increase in medical waste affect the environment as mentioned above, but it also impacts the public's health and safety; this is a real concern as COVID-19 can survive on many recyclable medical wastes related to households, healthcare facilities, and even trans-portation (Suthar et al., 2021). To combat the spread of COVID-19 within medical waste, a possible solution could be to label waste from medical facilities as "hazardous waste," and allow trucks picking up this type of waste to be regularly disinfected.

In addition, within this review, a larger percentage of articles in the non-recycling category (see figure 1) focused on medical waste (47.4%) compared to a lesser focus on articles within recycling focused on medical waste (37.9%). This goes to show how current research on the recycling of medical wastes is insufficient, especially relating to sustainability.

Municipal

Municipal waste is defined as general waste from both households and businesses. It was another major section analyzed for this review. Compared to the two other sectors of waste, studies on municipal waste were most prominent (37 articles) as shown in figure 2. This was expected as the pandemic impacted households and businesses more. Municipal waste can be split into two different categories: residual waste (regular recyclables and garbage) and bio-wastes (any material that could contain bio-hazards which includes PPE). It was recommended that residual waste should be maintained as it was before and during COVID-19 as the impacts on it seem to have been negligible (Hantoko et al., 2021). Bio-wastes on the other hand are more dangerous than residual waste given that COVID-19 is able to spread through them (Selvan Christyraj et al., 2021). Therefore, a possible short-term solution would be to increase the number of trucks picking up bio-wastes (Hantoko et al., 2021). Additionally, not only are more trucks required but the frequency in which waste trucks are collecting should be increased as well so that places where waste is generated are not overwhelmed (Hantoko et al., 2021).

Plastic

Plastic was also a major sector within the studies utilized for this review. Similar to the municipal waste studies, plastic waste generated a total number of 36 articles (see figure 3). As with medical waste, environmental and health impacts are reasons why it is im-portant to continue advancing research on plastic waste.

Plastic usage has and will continue to increase as the pandemic continues, and there is little that can be done to avoid that fact (H. B. Sharma et al., 2020a). As of now, much of the medical waste discussed involves some sort of plastic. For example, the typical blue surgical masks we commonly see and use involve polypropylene, a thermoplastic polymer (Sherman & Desk, 2021). Additionally, providing information through awareness campaigns is unlikely to affect human behavior towards the plastic issue (H. B. Sharma et al., 2020b). Therefore, given that it is difficult to decrease the amount of plastic usage and because it is unlikely to be solved through awareness campaigns, this review suggests that it is important to develop non-plastic PPE, and reduce the amount of single use plastic. This idea of developing sustainable alternatives to plastic waste is further corroborated by Wen-Tien Tsai (Tsai, 2021).

Ignoring the issue of increasing plastic waste could cause serious issues not only to our landfills but also the environment. A lot of the plastic waste (usually in the form of mi-cro-plastic) produced during the pandemic has not only made its way to landfills but also to aquatic ecosystems that affect human and marine life alike (Mohamed et al., 2022; Yusoff et al., 2021). Therefore, it is important to continue research on not only ways to reduce plastic consumption but also in creating new sustainable alternatives to plastics.

It is also necessary to focus on some of the ways the existing excessive plastic waste produced during the pandemic can be safely dealt with. Once such solution is pyrolysis. It works similarly to incineration, but the key difference is it uses thermal conversation in the absence of oxygen. This has other additional benefits as well; for example, it can be used as a substitute for natural gases in energy production (Demirbaş & Arin, 2010; Skrzyniarz et al., 2022; Su et al., 2021). The use of pyrolysis is further discussed in a later section regarding sustainability (Waste shocks and sustainability approaches).

Multiple Types

There were also many papers that focused their studies on multiple sections of waste; more specifically, 19 papers talked about all three sections and 4 talked about a combination of just medical and plastic waste. The reason for these numbers is clear: all types of waste have been detrimentally affected due to the pandemic (Argentiero et al., 2022; Bhar et al., 2022; Etim et al., 2022; Hantoko et al., 2021; Mohamed et al., 2022; Roy et al., 2021; Zhou et al., 2021) meaning the demand for studies regarding these types of waste have increased. The fact that many studies also focused on numerous types of waste also highlights the importance of dealing with all sections of waste management. Therefore, whether it has to do with medical, plastic, or municipal, further research regarding all waste should be carried out (Naughton, 2020; Peng et al., 2021; Selvan Christyraj et al., 2021).

Policies, waste shocks, and sustainability approaches

Policies

A major component of this review was also aimed around policies and sustainability approaches. Overall, out of the 67 papers reviewed, 22 (32.8%) of them mentioned possible policy implementation and changes as seen in fig. 4 below. Policies are vital for protecting the solid waste industry (Zhou et al., 2021). However, few studies discussed the policy changes that could be put into place around the solid waste industry, suggesting that there is more that needs to be done regarding policy analysis around waste management.

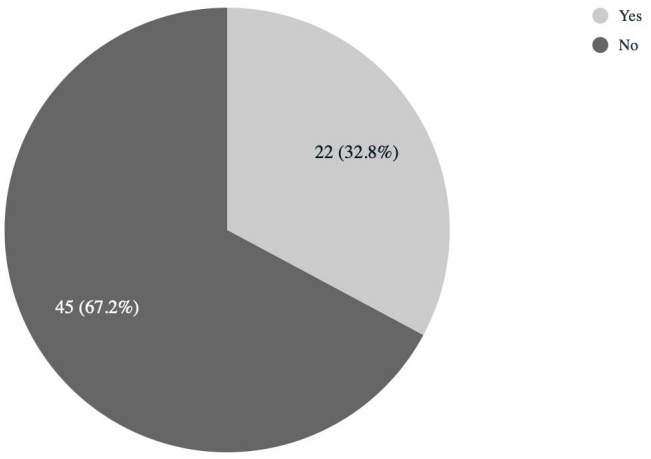

Fig. 4. Policy status of articles collected for this review.

On the other hand, papers that did discuss policies offered innovative changes to existing policies or suggested entirely new policies. For example, in a study done about waste management systems in China by Zhou et al. (Zhou et al., 2021), it was suggested that enhancing information collection, establishing mechanisms for temporary and short-term storing of recyclable materials, and increasing government financial input were all viable policy

changes that could positively impact overall waste management systems during a "waste shock". Another study done by de Blasio & Fallon (de Blasio & Fallon, 2022) offered more valuable insight reporting that policymakers need to create incentives to rationalize plastic waste chains that are currently highly fragmented. Ar-gentiero et al. (Argentiero et al., 2022) corroborates this idea, reporting the positive effects of both incentive based and behavioral policy changes such as information/educational campaigns. All of these are practical policies that can create small steps in reducing the damage to the environment and public health caused by the pandemic. Therefore, as suggested by Roy et al. (Roy et al., 2021), these policies must be implemented at a national level by governments around the world. A good example of successful policy changes is with the government of South Korea, who introduced increased measures to bridge the gap between existing waste management systems and the influx of waste due to the pandemic (Ilyas et al., 2020). This included communications from the government such as same-day incineration of COVID-19 infected waste and labeling of closed garbage bins based on whether households were quarantined within their homes (Yadav et al., 2022). Based on this, it is clear that more research regarding policy changes and implementation on national levels needs to be done.

Waste shocks and sustainability approaches

Current traditional disposal methods such as incineration and landfills are unable to reduce environmental burdens, especially in the face of a "waste shock" like COVID-19. This is due to the fact that methods such as those release toxic gas, occupy large amounts of land, and are simply unsustainable in the long-term (Su et al., 2021).
Although incineration is popular in developed countries and can be an effective method in the removal of waste as well as in the generation of energy (Tsai, 2021), it is only a short-term solution that would lead to a further contribution to waste as incineration plants only last an average of 30 years (Baptista, 2019). A viable system found throughout the review that can replace incineration is called pyrolysis.

Pyrolysis, essentially, is the degradation of biomass by heat in the absence of oxygen. The process has a net positive environmental impact by avoiding the burden of direct incineration and dealing with it in landfills, where virtually all value of the waste is lost. There is also an economic aspect to pyrolysis. Pyrolysis of medical waste is an ideal source of raw material as they possess high hydrogen and carbon concentrations meaning there are other benefits aside from reducing the amount of waste (Su et al., 2021). Additionally, as of now, the incineration industry is simply dying, and since incinerators only last an average of 30 years, many are beginning to deteriorate and are in need of replacement (Baptista, 2019): pyrolysis is an opportunity to replace them. Thus, this system presents an environmentally and cost-effective alternative to incineration that can effectively deal with the influx of waste that's currently creating a "waste shock".

Although handling the issue of waste is one aspect of waste management, another commonly proposed idea throughout this review to deal with the issue of "waste shock" is to reduce waste generation in the first place. In order to do this, it is suggested that a circular economy should be integrated into our waste management system. A circular economy works as a holistic approach to recycling and waste management systems where production and consumption of goods involves the sharing, reusing, and repurposing of existing materials for as long as possible (de Blasio & Fallon, 2022; Giudice et al., 2020; Kharola et al., 2022; Kurniawan et al., 2022; Wuyts et al., 2020). For example, within a circular economy, rather than incinerating or throwing plastic in landfills, it can be re-purposed as plastic pellets. This allows for two things: a decrease in the amount of waste in landfills and incineration plants, and a reduction in plastic generation in general. This works because when waste is repurposed, less waste is generated; essentially it makes it so that the source of waste generation is relied upon less. In the context of the pandemic, PPE such as masks and gloves could have been repurposed in areas such as clothing which would ultimately reduce the amount of waste generated from them. Therefore, the pandemic has created a perfect opportunity for governments, researchers, and scientists to re-evaluate waste management systems, and the circular economy model to be a viable answer that satisfies the need for more sustainable solutions (Hartmann et al., 2022). Consequently, this review strongly suggests the need for more research on sustainability approaches within the setting of a "waste shock".

Conclusion

The pandemic has detrimentally affected all parts of our country, including recycling and waste management systems. These systems are vital for countries to continue running without creating risks and dangers for both the environment and the public.

Based on this review and given the recency and novelty of COVID-19, there is a clear need for further research on all types of waste. Within the medical sector, it is suggested that there should be more research on how the influx of medical waste can be dealt with in a sustainable manner; for example, questions could ask what other purpose used masks may have or what ways garbage transportation can be altered so that the spread of COVID-19 is reduced. These concerns and questions surrounding medical waste need to be answered as the influx of medical waste we're seeing is impacting both the environment and the public's health and safety. Within the municipal setting, there needs to be more research on the methods in which waste can be dealt with without harming the environment, workers, and the public. This could include studies that deal with how garbage truck frequency affects the spread of COVID-19, if there even is any. Within plastic, it has been found that there needs to be continued work on ways waste can be sustainably reused and be dealt with, such as a shift towards a circular economy. It's also important to continue improving research on new methods of waste disposal such as pyrolysis.

This review also suggests not only the need for waste to be handled, but also the need for ways in which waste can be reused in the first place. Policy changes are an effective means by which the government can create large changes in short periods of time. Since less than half of articles mentioned policies, and because they are vital for protecting the solid waste industry, it is clear that further research regarding policy implementation and changes on national levels needs to be conducted in order to accelerate the agenda in reaching effective, efficient, and sustainable waste management systems. Continuing to work towards a more circular approach, where waste can be reused rather than disposed of, will allow for the source of waste generation, human consumption, to decrease.

Additionally, since recycling and waste management are a vital part of our society, and seeing how unpredictable events such as the pandemic may be, it is paramount that further research is done not only on how the pandemic has affected systems now, but also how we can learn from our current issues and mistakes to utilize them for future "waste shocks".

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