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Sustainable Cycles and Management of Plastics:

A Brief Review of RCR Publications in 2019 and early 2020

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Abstract:

Plastics have been playing a vital role in the industrialized economy, resulting in the growing amount of plastic waste and the surging attentions to plastics sustainability challenge. This is well reflected in the growing amount of submissions to and publications in *Resources, Conservation, and Recycling* on plastics, which made the editorial board decide to edit a Virtual Special Issue (VSI) on the "sustainable cycles and management of plastics" in 2018. The call for the VSI has attracted many submissions and twelve were accepted for publication. Together with several other relevant studies, we collected and summarized a total of 26 papers published in RCR mainly during 2019-2020 in this editorial. These papers mostly apply system approach and cover very wide topics such as material flows analysis and circular economy, life cycle assessment and eco-design, regional and global plastic emissions, and human consumption behavior. The whole collection of them offer a comprehensive view of the plastic waste challenges, as well as insights into achieving sustainability in plastic cycles and management. We believe these papers are helpful for government, industries, and individuals in exploring policy implications for building a more sustainable plastics system.

Keywords:

Plastics; Material flow analysis; Life cycle assessment; Circular economy; Recycling; Waste management

1. Introduction

Plastics are widely used in industrial production throughout the modern society on the global scale (Umer and Abid, 2017). Due to the high dependence of the industrialized economy on plastics, 8.3 billion metric tons of plastic materials have been produced as of 2017 (Geyer et al., 2017). In this case, the production and disposal of plastics have exacerbated environmental pollution and degradation. Specifically, plastic wastes cause damages on both terrestrial and oceanic environments via gaseous emissions and pernicious wastewater discharges (Brooks et al., 2018; Jambeck et al., 2015). NO_x and dioxin are two examples of the harmful substances associated with plastic wastes (Hall and Williams, 2007).

When the use of plastics has rapidly expanded in recent years, many studies have been devoted to the plastic waste quantification and the building of recycling system. Classic research methods such as the material flow analysis (Ciacci et al., 2017; Geyer et al., 2007; Zhou et al., 2013), input-output analysis (Liu et al., 2018), and life cycle assessment (Gironi and Piemonte, 2011; Gu et al., 2017) have been used to determine plastic stocks, flows, and trades in the socioeconomic system, and to evaluate the environmental impacts of plastics production and cycles. During the last few years, there were also more and more publications in and submissions to this journal *Resources, Conservation, and Recycling* on plastics, which made us decide to edit a Virtual Special Issue (VSI) on the "sustainable cycles and management of plastics" in 2018 (W. Chen et al., 2019).

The call for the VSI has attracted many submissions and twelve were accepted for publication. Together with several other relevant studies that were not submitted in response to the VSI call, we collected and summarized a total of 26 papers published in RCR mainly during 2019–2020 in this editorial. These papers were categorized into 4 topics including 1) Material flow analysis (MFA) and plastic circularity, 2) Emissions and pollution, 3) Life cycle assessment (LCA) and eco-design, and 4) Public attitude, human behavior, and policymaking. A brief summary of each paper is listed in Table 1 and more detailed introduction are provided in Section 2. A short discussion is used to conclude this editorial in the end.

2. Brief overview of contributions to this VSI

2.1. Material flow analysis (MFA) and plastic circularity

We collected 11 articles related to MFA and plastic circularity and divide them into three categories: (1) Material flow analysis (MFA) cases, (2) Circular economy, and (3) Global trade.

2.1.1. Material flow analysis (MFA) cases

MFA is an effective approach to quantify the stocks and flows of plastics during their life cycle. MFA can be used at various scopes to offer a more direct and comprehensive understanding of the production, consumption, and waste management stages of plastics, therefore identifying disadvantages in the system that should be addressed. Five contributions in this VSI employed MFA, each with a different focus.

Liu et al. (2020) applied a dynamic MFA to quantify polyvinyl chloride (PVC) stocks and flows in China over 1980–2015. Two scenarios were designed to model the demand for PVC, namely (i) a business as usual scenario (BAU) where PVC consumption increases linearly, and (ii) a limited growth scenario (LG). Another scenario was designed regarding PVC at end-of-life: (iii) a PVC waste disposal rate variation scenario (BAUR). Data comparison and MFA were presented and analyzed. China is the largest producer and consumer of PVC in the world and the scenario trajectories discussed in this article calculated that between 500 and 600 Mt of PVC waste will be generated in China by the end of 2050. Such a dramatic increase requires improving the recycling system, decoupling PVC material use, and enhancing cooperation between multiple stakeholders as helpful ways to achieve PVC waste reduction and recovery.

A considerable fraction of plastic losses enters and accumulates in the oceans and adversely affects marine ecosystems. Another fraction is directly released in water bodies due to marine littering including abandoned, lost or discarded fishing gears (ALDFGs) as discussed by Deshpande et al. (2020). In this study, MFA was applied to track physical flows and stocks of polypropylene (PP), polyethylene (PE) and nylon from FGs (i.e. trawls, seines, longlines, gillnets, and traps) used for commercial fishing in Norway through use and post-use processes. Flows of PP, PE and nylon entering the ocean as ALDFGs and end-of-life FGs are quantified. Interviews to stakeholders were carried out to collect data on pre-use phase, use phase, and end-of-life phase. Uncertainty analysis was also conducted. The MFA, which acts as a holistic decision support tool for industry and policymakers, shows an estimated 300 tons of plastic accumulating annually as ALDFG in the ocean ecosystem from commercial fishing, and around 55% of collected waste FG are sent for further recycling out of Norway due to the absence of industrial recycling. Sustainable management strategies for FGs include gear marking and gear identification systems (e.g., bar coding, coded wire tags) to identify location and ownership of lost FGs as well as economic incentives and penalty schemes to ensure effective collection and treatment of plastic waste from the fishing sector.

Express delivery has developed rapidly in many countries, but this also brings significant environmental problems caused by various packaging materials. Duan et al. (2019) estimated the volume, variety, and end-of-life (EoL) treatments of packaging waste in the express delivery industry in China from 1996 to 2017. Dynamic MFA is used in this study to quantify and predict the post-consumer waste form express delivery. Publicly available data and results from field surveys were used in this study. The composition and amount of express delivery packages and waste were presented, and the flows of corrugated boxes in China's express delivery industry were quantified and characterized. Results show that post-consumer packaging wastes are only partially recycled in China, and that the packaging materials, mostly recycled materials, might have significant health impacts on people related to the express delivery industry. Suggestions include: (i) Government should pay attention to incentivizing express delivery service providers to recycle post-consumer waste, (ii) excess delivery service providers need to go beyond existing standards and take on more social responsibilities, and (iii) public awareness needs to be raised regarding the environmental impact of post-consumer packaging materials.

Van Eygen et al. (2017) employed MFA to analyze and quantify the national plastic flows in Austria from the production stage, consumption stage, to the waste management stage, aiming to achieve a thorough understanding of plastic flows in Austria and identify opportunities to increase overall resource efficiency and reduce negative impacts in different stages. The MFA was used to construct a plastic budget model. The reference year was 2010, and data quality evaluation and uncertainty assessment were provided. Results show that the packaging sector accounted for around half of the post-consumer waste amount, and roughly one third of the consumed plastics contributed to net stock increase in all consumption sectors. The majority of waste was incinerated and the rest was mainly recycled, but it's pointed out that potential exists for increasing the mechanical recycling rate. The increasing amounts of plastic wastes also calls for assessment of which processing capacities and treatment priorities are going to be set to achieve more efficient management of plastic wastes.

Millette et al., (2019) conducted a case study of plastic flows in Trinidad and Tobago (T&T) for 2016, demonstrating how leveraging the combination of detailed trade data and a waste characterization study are sufficient for undertaking a national-level MFA. The study achieved the goals of conducting MFA with limited data and applying MFA for circular economy development. Results show that plastic packaging for imported products accounted for 48% of the landfilled plastic in T&T, an example demonstrating the circular economy challenge of importing materials to island nations that have limited domestic demand at end-of-life. Strategies to promote circular economy for the management of plastic waste in T&T include (i) ban of polystyrene, (ii) recycling of polyethylene terephthalate (PET), high density polyethylene (HDPE), and other plastics, and (iii) use of low-density polyethylene (LDPE) plastics as an alternative fuel in cement production, and (iv) diverting plastic waste as feedstock for a local cement plant.

2.1.2. Circular economy

Circular economy is an excellent instrument in supporting sustainability. Besides the work of Millette and colleagues, the ways to promote plastic circularity is also discussed in other contributions in this VSI, especially in the following four works.

Simon (2019) discussed different aspects of promoting circular economy in the plastic industry. Goodland's method of describing sustainability through three criteria was presented and explained. Simon pointed out that under China's plastic ban, exporters should find a solution to treating plastic waste, and several issues should be tackled to better recycle plastics. Less contamination (including cross-contamination) of polymers should be achieved to ensure good material quality. Obtaining a reliable amount of waste in a longer time horizon is also crucial to avoiding uneconomic recycling, as the operation of a processing technology has a certain volume range. The lack of markets for secondary material poses an economic threat and prioritizing sustainable resource usage and supporting NGOs in the communications of fostering circular economy would be possible solutions. Deposit-refund was also discussed as an alternative. As for the quality questions that makes circular economy difficult to be integrated into a company's business, Simon suggested that better communication of procurers and suppliers can help with this situation. Distinguishing open and closedloop recycling as well as upcycling and downcycling were introduced as opportunities to broaden circular economy.

Since low-income and middle-income countries receive the majority of mismanaged plastic wastes and such wastes are often treated informally, it's important to find models that partner with the informal recycling sector. Gall et al. (2020) conducted a case study of Mr. Green Africa, a for-profit company located in Nairobi, Kenya, that operates on the interface between formal and informal plastic collection and treatment sectors by replacing multiple middlemen with a fair-trade like business model. Three different waste picker recyclate materials were selected and compared to two commercially available benchmark recyclate materials from the formal waste recycling system of a highincome country. The recyclate composition was characterized using Fourier-transform infrared (FTIR) spectroscopy, differential thermal analysis, and thermo-gravimetric analysis. To increase the validity of the research, three complementary data sources were captured: (i) desk research, (ii) physical recyclate characterization, and (iii) semi-structured interviews. Results show that the post-consumer plastic wastes sourced from informal waste pickers can be processed into recyclates that were comparable to benchmark recyclates from formal recycling systems, in terms of both composition and basic engineering properties. If suitable cooperation modes are found, high-quality mechanical recycling of plastics under informal conditions as well as socioeconomic benefits for waste pickers can be achieved.

Razza et al. (2020) proposed an adapted methodological approach of the Material Circularity Indicator (MCI) to calculate the circularity of bio-based and biodegradable (BB) products. This adapted approach is applied to BB mulch films. Two major changes were made in this method: (i) the mass of the bio-based component corresponds to the recycled material in input and (ii) the mass of the bio-based component leaving the system through composting or biodegradation in soil is regarded as recycled. The modified scheme of calculation and description of material flows adaptation to BB products were presented. Results show that the MCI of a BB mulch film, characterized by an average bio-based feedstock content of 30%, is 0.37 ± 0.04 in a 0–1 scale, where the amount of BB feedstock is the most sensitive factor. The study applies the principles of the Ellen MacArthur Foundation (EMF) methodology into BB products and aims at catching the specificities of BB products with EMF MCI methodology. The direct uses of the method are supporting eco-design of BB products and comparing the MCI of BB products with MCI of traditional products.

Maisel et al. (2020) studied the influence of particle size on the recyclability of post-shredding plastic fractions from waste electrical and electronic equipment (WEEE) pre-processing and how the shredding and sorting processes can be optimized. Different shredding technologies, their output particle size, sorting technologies and their required input particle size were studied and compared. Three scenarios, namely (i) large particle size (20–50 mm), (ii) medium particle size (10–20 mm), and (iii) small particle size (6–15 mm), were developed and compared to show combinations of shredding and sorting technologies that seem promising for optimized recycling. A particle size between 10–20 mm is found promising for sorting efficiency and minimizing losses. The study suggests improving the communication between pre-processors and recyclers, sorting brominated fractions before transport to the recycler, finding recyclers that are able to separate plastics from WEEE with suitable sorting technologies and not disposing the fine fraction, standardizing the particle size range, and pre-sorting the WEEE plastics before shredding as much as feasible.

2.1.3. Global trade

Two contributions in this VSI focused on China's plastic waste import ban and plastic waste global trade network, but each contribution has a different emphasis.

Being the largest importer of plastic waste, China's plastic waste import ban has placed the global waste recycling system into a serious situation. To investigate the impact of the ban and achieve a comprehensive understanding of global plastic waste supply-chains, Huang et al. (2020) used four models for analysis: (i) environmentally-extended multiregional input-output model, (ii) structural path analysis, (iii) ecological network analysis, and (iv) hypothetical extraction method. For the year 2015, a breakdown of China's plastic waste imports driven by final demand of world economies, China's plastic waste imports driven by sectoral consumption globally, and the Sankey diagram of plastic waste imports to China for China's top five sectors and one global sector were presented. A global plastic waste trade network is established to identify dominant influencers. Results show that China's domestic consumption of products containing recycled plastic is the main driver of the import of plastic waste, and the ban can cause environmental pollution in other countries. The import ban has also caused a lack of recycled plastic material and minor economic loss in China. It's pointed out that countries need to improve their waste treatment capacity. Recommendations include increasing local plastic waste recycling, fostering global collaboration as a form of environmental responsibility-sharing, increasing product efficiency, and reopening imports for high quality recycled material.

The primary role of China in the global plastic cycle is also reflected by the feature of this country as a net-importer of plastic waste. Plastic management at end-of-life often takes place far from where the waste is generated and, after China's import ban, global plastic waste flows have undergone different trade patterns. A global plastic waste trade networks (GPWTN) is analyzed by Wang et al. (2020). The spatio-temporal evolution of the GPWTN is established for 1988–2017 using the UNeComtrade database. The inter- and intra-continental plastic waste trade is mapped and trade patterns of the global plastic waste trade are discussed. Major hubs of the trade network are identified. Attention and analyses are given to the country ranks as well as major import and export countries. The impact of China's import ban is quantified and analyzed using trade data, and the import or export bans potentially implemented by countries are also simulated and analyzed. China is the colossus of global plastic waste trade. The results show that the GPWTNs have small-world and scale-free properties and a core-periphery structure, and that export countries are more important for the robustness of GPWTNs. The authors discussed the effect of import bans in developing countries as a leverage to increase resource efficiency in plastic cycles by reducing waste losses and disposal.

2.2. Emissions and pollution

We received 4 articles related to emission and pollution, all of which used classification and statistics as a quantification and validation method. The clear classification of plastics or plastic products assisted the effectiveness of quantification and analysis.

The presence of solid waste, especially plastic waste, is a severe environmental problem faced by marine ecosystems. A research aiming to quantify and classify the microplastics on Mexican beaches was conducted by Alvarez-Zeferino et al. (2020). A systematic sampling campaign was utilized to provide information about the presence of microplastics in beaches of five marine regions in Mexico. Microplastics were extracted, classified, counted, and weighed. Concentration of microplastics in Mexican beaches were mapped and analyzed, and the results were compared with similar researches in other countries. Types and colors of the microplastics found in Mexican beaches were also presented and compared with different countries. The chemical composition of microplastics was also discussed. A prevalence of land-based activities was suggested as a primary source for microplastics on Mexican beaches. This research showed clear evidence of the presence of microplastics on Mexican beaches, in similar concentrations to those in other countries. The Gulf of California showed a higher mean concentration. The concentration of microplastics was higher in urban beaches and increased with the occurrence of extreme weather events. This research also calls for attention to balancing tourism with the preservation of natural resources and developing and implementing sound waste management policies.

The drinking water contamination incident in Flint, Michigan lead to the generation of overwhelming waste. Wang et al. (2019) developed a case study focusing on the Flint drinking water contamination incident where they reviewed waste management infrastructure in Flint before the incident, estimated the number and mass of plastic waste bottles, filter cartridges, and related waste containers, evaluated the waste management response, and provided recommendations from various aspects. The estimation results are compared against available records. Waste collection and recycling response was presented and analyzed from various aspects. Case study results showed that water distribution and waste treatment activities are enabled and promoted by public and private partnerships, and points of distribution (PODs) provided emergency supplies. However, procedures for POD establishment and water demand estimation for long-term incidents were not found. Detailed recommendations are given, including pre-identifying the roles of waste management organizations, estimating the amount of daily emergency water supply, determining POD beforehand, drafting public notifications about water management activities, making data publicly available, etc.

The increasing employment of single-use plastics in healthcare and medical settings have attracted attention to related elimination and mitigation measures. Leissner and Ryan-Fogarty (2019) carried out a case study of ready-to-use infant formula bottles to examine single-use food packaging plastic waste in Irish maternity hospitals. Single-use plastics in ready-to-use infant formula milk bottles and teats are categorized, quantified, and analyzed. Results show a high variability in materials used for bottles, teats and packaging, as well as the extent of the plastic waste generated. Breastfeeding was highlighted as a way to mitigate plastic usage. Other options of mitigation include reusable bottles, overall improved waste management and recycling system, and a standardized labeling system for all plastics established through legislation to achieve more effective recycling. Collaborative efforts across sectors were also suggested.

A comprehensive estimate of the issue of global plastic loss to the environment is provided by Ryberg et al. (2019). The authors carried out a global estimation of the losses of plastics (including macroplastics and microplastics) to the environment across the entire plastic value chain in 2015, using existing literature and databases coupled with improved and additional methodological modeling of the losses. The losses are characterized according to region and loss sources. Global plastic waste management for the year 2015 was modeled. Comprehensive sensitivity and uncertainty analyses were conducted to identify key drivers of plastic losses. Approximately 6.2 Mt of macroplastics and 3 Mt of microplastics were lost to the environment in 2015. The major loss source of macroplastics was mismanaged municipal solid waste management, while the major loss source of microplastics was abrasion of tire rubbers, abrasion of road markings, and plastics-based city dust.

2.3. Life cycle assessment (LCA) and eco-design

We collected 7 articles related to LCA and eco-design, and divide them into two categories: (1) Life cycle assessment (LCA) and (2) Ecodesign.

2.3.1. Life cycle assessment (LCA)

LCA is widely applied to evaluate the environmental impacts associated with a product system or waste treatment strategies. In the following contributions, LCA is used for the comparison of different products or waste treatment methods.

Environmental burdens and costs during the life cycle of HDPE could be mitigated by replacing pristine HDPE with post-consumer recycled (PCR) HDPE or bio-based polymer (bio-HDPE) in long-lived goods. Nguyen et al. (2020) studied cradle-to-gate and cradle-to-grave greenhouse gas (GHG) emissions and life cycle costs of four alternative resins (pristine HDPE, pristine/PCR HDPE, bio-HDPE and nanoclaypristine/PCR HDPE composite), as well as the GHG emissions and cost in the production of 100-year drainage pipes. LCA was used to systematically evaluate the energy and GHG emissions of alternative HDPE pipe systems. The stochastic LCA models constructed in this study combined service life prediction from experiments with parametric and scenario uncertainty modeling using Monte Carlo simulation and nonparametric bootstrapping. The results suggest that when crystallinity is assumed to govern pipe material service life, the predicted pipe mass among alternatives that use recycled content is significantly greater than pristine HDPE pipe, which leads to a greater Global Warming Potential. Recycled and nanocomposite blends show great potential as their GHG emissions and cost are relatively low. The bio-HDPE resin has the highest material production cost despite a large GHG reduction compared to pristine HDPE. However, the incremental difference among all alternatives is small over a range of discount rates, rendering the bio-HDPE pipe promising for addressing climate change.

China is the world's largest producer and consumer of plastics, as well as the largest producer and recycler of waste plastics. An LCA study was conducted by Chen et al. (2019) to evaluate the environmental impacts of different end-of-life treatments of waste plastics: mechanical recycling, incineration, and landfilling. The life cycle impact assessment results of waste plastics in different treatment methods as well as process-specific environmental impact analysis of mechanical recycling were presented. Scenario analysis on end-of-life treatment of waste plastics was carried out where EOL treatment pattern improvement, mechanical recycling technology improvement, and banning of waste plastics import policy are taken as variables. Results show that mechanical recycling showed much greater environmental benefits than incineration and landfilling, and energy conservation and emissions reduction in atmospheric pollutants would make mechanical recycling more effective. Environmental impacts can also be reduced by the ban on waste plastics imports, as it decreases the transportation distances of waste plastics.

Abejón et al. (2020) employed LCA methodology to evaluate the environmental impact of reusable plastic crates and single-use cardboard boxes for fruit and vegetable distribution in the Spanish peninsular market. Five different impact categories were considered: global warming potential, acidification potential, eutrophication potential, ozone depletion potential, and photochemical oxidant creation potential. Energy and water consumption were also analyzed. The environmental impacts and energy indicators in conservative scenario and technical scenario were compared and presented. Results indicate that plastic crates show better environmental performance than the cardboard boxes for all the impact categories. The total consumption of primary energy is also lower in the case of plastic crates, and the total freshwater use for cardboard crates is 5~6 times higher than plastic crates. The sensitivity analysis showed a strong preference for plastic crates even in alternative scenarios. The highest environmental impact of card boxes was related to the manufacturing stage, while the highest environmental impact of the plastic crates was in the use stage. This case study justified the use of plastic packaging material in certain applications, with the requisite that correct waste management processes should be guaranteed.

Khoo (2019) utilized LCA to investigate different scenarios of plastic waste management options. The land scarcity in Singapore was taken into account, and waste treatment plant capacity was also included in the investigation. Eight different LCA scenarios were presented, and different environmental impact indicators were calculated and compared with each other. The results showed how different combinations of four plastic valorization technologies and associated capacities affect the environmental impact of the treatment of plastic waste. Normalization and weighting were carried out in the selection of the best scenario. Waste planning policies that support investment in innovative technologies that promote waste minimization and satisfy renewable fuels were recommended. This study demonstrated that selected plastic treatment technologies combined with their associated available capacities play a significant role in the environmental benefits and drawbacks generated. It's also pointed out that a different set of normalization and/or weighting factors may affect the results.

Lu et al. (2019) applied an approach based on ex ante life cycle thinking to developing emerging waste treatment technologies, here focusing on the chlorine recovery process. An LCA model was employed to determine the potential energy consumption and greenhouse gas emissions of PVC waste treatment with chlorine recovery using the dechlorination degree, the kinetic rate constant and the energy consumption per unit of time of the dechlorination process as operating variables. The thresholds of the set variables are compared to benchmark (current treatment) and clarified. The study also points out that the GHG emissions of chlorine recovery would be partially offset by the reduced demand for chlorine treatment in tail gas and recovered sodium chloride, and suggests more efficient waste treatment technologies and further research on current PVC waste treatments and chlorine recovery process.

2.3.2. Eco-design

The route towards sustainability in plastic cycles comes through a quantitative assessment of environmental implications driven by a life cycle perspective. Among the studies in this VSI that use the LCA approach or LCA-related thinking, two contributions discussed eco-design and analyzed the potential environmental impacts to guide the optimal development in plastic cycles and process design.

To meet Europe's ambitious recycling targets, “problematic” streams, including the sink fraction, should be tackled and not be merely sent for incineration. Ragaert et al. (2020) carried out a case study where the sink fraction was characterized in terms of composition and mechanical properties after pretreatment of the removal of nonferrous metals and PVC, and developed a new product called “the Greentile” from the materials in the sink fraction. FTIR and near-infrared (NIR) spectroscopy were used to identify polymer composition in the pre-treated mix. Mechanical properties and density were determined on injection moulded testbars. Polymer mass composition of original sink fraction, sorting ratio of auto sort low throughput sorting system, and polymer mass composition of sorted sink fraction were identified and analyzed. The behavior of the untested blend of pretreated sink fraction material are situated with regard to other commonly used polymers, both virgin and recycled ones. The building & construction sector was determined as most suitable for the application of the sink fraction, and the design of the Greentile with marketed features was presented. Produced Greentiles were used to construct a slanted green roof in a small-scale test setup, and the product is evaluated regarding physical properties, market potential, as well as environmental benefits. The study pointed out that how the potential sink fraction will be handled depends largely on the sorting/recycling systems in place, and that current system should be upgraded to achieve the recovery of higher quality sink fraction.

Civancik-Uslu et al. (2019) analyzed a case study on packaging ecodesign aligned with circular economy strategy along the production chain. LCA of three kinds of cosmetic tubes were evaluated and compared: (1) original (2) with mineral filler (3) with mineral filler and recycled content. Impact assessment regarding 9 different impact categories were estimated, and sensitivity analysis on tube weight and end-of-life allocation was also performed. The study shows that combining LCA and eco-design can help achieve efficient environmental and economic savings, as LCA can identify the most contributing life cycle stages while eco-design solutions can be used where they could be more efficient. The option with better environmental performance was also with lower economic costs.

2.4. Public attitude, human behavior, and policymaking

We collected 4 articles related to public attitude, human behavior, and policymaking, and divide them into two categories: (1) human attitude toward plastics, (2) consumption behavior and adaptive injustice.

2.4.1. Human attitude toward plastics

Public survey is a great approach of gathering public opinion. To learn public attitudes towards plastics and bioplastics, Dilkes–Hoffman and colleagues have conducted two studies where they analyzed the results they gathered from surveys and provided recommendations.

Dilkes-Hoffman et al. (2019b) obtained the much-needed data to examine public attitudes towards plastics in Australia and provided insights on a global level, aiming to identify whether the public views plastics as a serious environmental issue and the factors influencing public opinion. The research used an online survey of a nationally representative sample (2518 respondents), and the data obtained from survey results was analyzed using multiple statistical methods. Factor analysis supported the qualitative findings. Results show that plastics are viewed as a serious environmental issue, and are associated with food packaging, convenience, and environmental concern. While 80% of respondents express a desire to reduce their personal plastic use, many don't translate their belief into action. Australians predominately placed the responsibility for reducing the use of disposable plastics on industry and government.

To understand current knowledge and perceptions regarding bioplastics, Dilkes–Hoffman et al. (2019a) gathered data through an online survey of 2518 nationally representative Australians. The data used in this study was gathered through the same survey as detailed in an earlier publication (presented above) by Dilkes–Hoffman and colleagues and the statistical analyses were the same, although this study drew on a different set of questions. The survey asked about the respondents' knowledge and perception of bioplastics, the environmental impact of bioplastics, and the littering and waste management of bioplastics. Results show that the Australian public's knowledge of bioplastics is low, but their perception of bioplastics is positive (biodegradable plastics are perceived as more environmental-friendly and recyclable). Suggestions include establishing clear standards and labeling to be coupled with the introduction of bioplastic packaging materials, better communication about waste management systems for bioplastics, and research on the lifetime of biodegradable plastics. It's also recommended that stakeholders engaged in the development of bioplastics should encompass the general public, organizations using biodegradable plastics, waste handlers, and government representatives.

2.4.2. Consumption behavior and adaptive injustice

Macintosh et al. (2020) addressed the gap of the studies on the effectiveness and durability of the ban on single-use plastic shopping bags by studying the impacts of the ban introduced in the Australian Capital Territory (ACT) in 2011. The environmental effectiveness of the ban and the durability of community support were analyzed. The environmental effectiveness was analyzed by assessing plastic bag consumption and the presence of plastic bags in the litter stream. A supermarket consumer survey and a retailer survey were taken to estimate plastic bag consumption in the ACT. Two scenarios (one with the ban, one without the ban) were also designed to evaluate the effectiveness of the ban. The impact of ACT plastic bag ban was presented and analyzed by comparing the two scenarios. The findings suggest the ban was only mildly successful in reducing plastic bag consumption. However, these reductions were largely offset by an increase in the consumption of other types of bags. The net effect of the ban on plastic consumption over the studied period was only 275 t, which indicates the apparent environmental ineffectiveness of the ban. However, community support for the ban was remarkable, which points out that improved information systems are needed to keep community and policymakers better informed about plastics.

Adaptive injustice is explained in the context of plastic economy by Conlon (2020). Colon pointed out that the onus of environmental degradation generated by plastics that perpetuate for centuries are not borne by companies but by communities, which exemplifies adaptive injustice. The root of the plastic waste problem — the extraction and production — should be addressed, and the responsibility should not be deflected from the producers to individuals. Also, plastics lubricate trade, and the future trajectory of plastic industry is prosperous: the plastic packaging market accrued $300.86 billion revenue in 2016 and is projected to achieve $480.97 billion by 2025. Producers, who are not slowing down the production, get the profit, while the environment gets the externality. Conlon argues that profits should not be privatized and prioritized before social responsibility and the wellbeing of the environment. Adaptive injustice in the global south was also discussed. Corporations should take responsibility for the full lifecycle of their products, and eco-design of products along with their packaging should also be developed by corporations. Opting for materials and practices that promote circular economy has become a social and environmental urgency.

3. Discussion and conclusions

The selected papers collected in this VSI provided a broad overview on the research needed to achieve sustainability in plastic cycles and management, for which material flow accounting techniques, eco-design and life cycle assessment, and improvement of human behavior were confirmed as key and complementary methodologies to meet the goals. Selected articles also provide important insights into circular economy as well as adaptive injustice, which can be helpful to future research as well as the development of sustainable practices promoted by government, industries, and individuals.

The analyses covered historical, contemporary, and future perspectives on major (by production volume) plastics' flows and stocks as well as other aspects related to plastics' life cycle and waste management, with particular interest in PVC and polyolefins. For example, the PVC may cause the formation of hazardous Cl-containing compounds, and polyolefins account for main production of plastics and have high calorific value and hydrocarbon content, which are favorable for feedstock recycling. The scope investigated is both representative of the global situation and of developed countries. Although several studies in this VSI focused on the situation in developing countries, it's still evident that there exists a lack of quantitative information and data availability for developing and least-developing countries, which remains as one of the big challenges in global plastic cycles.

Overall, the anthropogenic metabolism of modern society in regard with plastic demand and supply patterns, plastic losses, and the related environmental implications pointed out the urgent need to improve the use and end-of-life management of plastics. Current inefficiencies taking place in these phases are responsible for the greatest plastic losses and the associated environmental burdens, constituting a major hindrance to the closure of material cycles.

Although selective, the coverage of topics calls for integrative research including (i) understanding plastic pollution in the world's oceans, rivers, and ecosystems, (ii) developing sustainable innovation in recycling system management, (iii) environmental and economic sustainability of end-of-life treatments for bio-degradable and non-biodegradable plastics; (iv) analysis of additives (e.g., plasticizers, lubricants, pigments, stabilizers) employed in plastic articles; (v) fateexposure models and potential toxicological effects of plastic flows in the environment; (vi) setting policies in reducing and controlling the negative impacts of plastics production, uses, and waste management. We hope that building on evidence from the contributions to this VSI, future academic research will tackle the remaining issues related to pursuing sustainability in anthropogenic cycles and the management of plastics.

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Table

Table 1. Summary of papers collected in this Virtual Special Issue.

Title	Summary
MFA and plastic circularity	
Stocks and flows of polyvinyl chloride (PVC) in China: 1980–2050 (Liu et al., 2020)	An MFA study that quantifies polyvinyl chloride (PVC) stocks and flows in China over 1980–2015
Using Material Flow Analysis (MFA) to generate the evidence on plastic waste management from commercial fishing gears in Norway (Deshpande et al., 2020)	An MFA study that tracks the flows and stocks of polypropylene (PP), polyethylene (PE), and nylon from fishing gears used for commercial fishing in Norway
Post-consumer packaging waste from express delivery in China (Duan et al., 2019)*	An MFA study that estimates and quantifies the volume, variety, and end-of-life (EoL) treatments of packaging waste in the express delivery industry in China over 1996–2017
Comprehensive analysis and quantification of national plastic flows: The case of Austria (Van Eygen et al., 2017)*	An MFA study that analyzes and quantifies the national plastic flows in Austria in 2010 from the production stage, consumption stage, to the waste management stage
Materials flow analysis in support of circular economy development: Plastics in Trinidad and Tobago (Millette et al., 2019) *	An MFA study of plastic flows in Trinidad and Tobago for the year 2016, where the combination of detailed trade data and a waste characterization study is utilized
What are the most significant aspects of supporting the circular economy in the plastic industry? (Simon, 2019)*	An article that discusses different aspects of promoting circular economy in the plastic industry
Building a circular plastics economy with informal waste pickers: Recyclate quality, business model, and societal impacts (Gall et al., 2020)*	A case study of Mr. Green Africa, a for-profit company that operates on the interface between formal and informal plastic collection and treatment
Metrics for quantifying the circularity of bioplastics: the case of bio-based and biodegradable mulch films (Razza et al., 2020)	A study where an adapted methodological approach of the Material Circularity Indicator (MCI) to calculate the circularity of bio-based and biodegradable (BB) products is proposed
Preparing WEEE plastics for recycling — How optimal particle sizes in pre-processing can improve the separation efficiency of high-quality plastics (Maisel et al., 2020)	A study on the influence of particle size on the recyclability of post-shredding plastic fractions from WEEE pre-processing and how the shredding and sorting processes can be optimized
Modeling the global impact of China's ban on plastic waste imports (Huang et al., 2020)*	A study that uses four models to investigate the impact of China's plastic waste import ban and achieve a comprehensive understanding of global plastic waste supply-chains
Structure of the global plastic waste trade network and the impact of China's import Ban (Wang et al., 2020)	A study that analyzes a global plastic waste trade networks (GPWTN) where the spatio–temporal evolution of the GPWTN is established for 1988–2017
Emissions and pollution	
Microplastics in Mexican beaches (Alvarez-Zeferino et al., 2020)	A study that quantifies and classifies the microplastics on Mexican beaches
Management of plastic bottle and filter waste during the large-scale Flint Michigan lead contaminated drinking water incident (Wang et al., 2019)*	A case study focusing on the Flint drinking water contamination incident with review on waste management infrastructure, emergency supplies, and the waste management response

Challenges and opportunities for reduction of single use plastics in healthcare: A case study of single use infant formula bottles in two Irish maternity hospitals (Leissner and RyanFogarty, 2019)*	A case study of ready-to-use infant formula bottles examining single-use food packaging plastic waste in Irish maternity hospitals
Global environmental losses of plastics across their value chains (Ryberg et al., 2019)	A study that provides a comprehensive estimate of the losses of plastics to the environment across the entire plastic value chain in 2015
LCA and eco-design	
Uncertainty in the life cycle greenhouse gas emissions and costs of HDPE pipe alternatives (Nguyen et al., 2020)	An LCA study of the greenhouse gas (GHG) emissions and life cycle costs of four alternative resins as well as the GHG emission and cost in the production of 100-year drainage pipes
Life cycle assessment of end-of-life treatments of waste plastics in China (Y. Chen et al., 2019)*	An LCA study that evaluates the environmental impacts of different end-of-life treatments of waste plastics: mechanical recycling, incineration, and landfilling
When plastic packaging should be preferred: Life cycle analysis of packages for fruit and vegetable distribution in the Spanish peninsular market (Abejón et al., 2020)*	An LCA study that evaluates the environmental impact of reusable plastic crates and single-use cardboard boxes for fruit and vegetable distribution in the Spanish peninsular market
LCA of plastic waste recovery into recycled materials, energy and fuels in Singapore (Khoo, 2019)*	An LCA study in Singapore that investigates different scenarios of plastic waste management options
Deducing targets of emerging technologies based on ex ante life cycle thinking: Case study on a chlorine recovery process for polyvinyl chloride wastes (Lu et al., 2019)	A study that applies an approach based on ex ante life cycle thinking to guide the development of the ichlorination process for the Cl recovery from PVC wastes
Design from recycling: A complex mixed plastic waste case study (Ragaert et al., 2020)	A case study where the sink fraction was characterized in terms of composition and mechanical properties after pretreatment and a new product called “the Greentile” is developed
Improving the production chain with LCA and eco-design: application to cosmetic packaging (Civancik-Uslu et al., 2019)	An LCA study on packaging eco-design aligned with circular economy strategy along the production chain
Public attitude, human behavior, and policymaking	
Public attitudes towards plastics (Dilkes-Hoffman et al., 2019b)*	A study that uses survey to understand public attitudes towards plastics in Australia as well as the factors influencing public opinion
Public attitudes towards bioplastics — knowledge, perception and end-of-life management (Dilkes-Hoffman et al., 2019a)*	A study that uses survey to understand public attitudes towards bioplastics in Australia
Plastic bag bans: Lessons from the Australian Capital Territory (Macintosh et al., 2020)	A study of the impacts of the Australian Capital Territory (ACT) plastic bag ban in 2011, with analysis on the environmental effectiveness of the ban and the durability of community support
Adaptive injustice: Responsibility to act in the plastics economy (Conlon, 2020)*	An article that explains adaptive injustice in the context of plastic economy

* not originally submitted to this VSI.