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ORIGINAL ARTICLE

Plastics in the Indian economy: a comprehensive material flow analysis

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Abstract

Plastic is valued for its flexibility to be utilized in different applications, yet it poses a significant threat to our environment because of mismanaged plastic waste. India's compound annual growth of plastic consumption has been around 7% for a decade. Despite this significant growth, there has not been a comprehensive study of Indian plastic flows since 2000. This work presents a 20-year update, detailing plastic production, consumption by all plastic types and sectors, and the overall material flow for 2018–19 to fill the gap in the data on post-consumer plastic flows. The analysis reveals a total plastic production of 19.3 Mt, 22% of which is Polyethylene as the most wildly used plastic. The total mass of plastic in products distributed in various applications is 23.9 Mt. Key sectors for plastic consumption are Packaging (30%), Textiles (17%), and Buildings and Construction (16%). Plastic waste generation is 15.5 Mt, primarily from packaging and textiles. Only 13% of this plastic gets recycled, 46% is mismanaged, and the rest incinerated or dumped. The study's unique nationwide, mass-balanced, transparent approach offers a rigorous reference point for decision-makers. Yet, the lack of reliable data is the main barrier to design, implement, and monitor of policy interventions.

Keywords Plastics and polymers · Material flow analysis (MFA) · India · Recycling · Circular economy

Introduction

Plastics are an affordable and useful component in many products and processes, leading to ubiquitous application across all sectors of modern economies. The profound environmental problems associated with plastics waste have received renewed attention with United Nation (UN) members States now negotiating a new legally binding global agreement—the Global Plastics Treaty—to end plastic pollution [1, 2].

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The Global Plastics Treaty represents a pivotal milestone in our collective efforts to combat the growing environmental crisis posed by plastic pollution. This international agreement signals a commitment from nations across the globe to tackle the problem at its root by transitioning towards a Circular Economy model. The treaty emphasizes the urgent need to reduce plastic production and consumption, promote sustainable design and materials, and enhance recycling and waste management systems. By adopting a Circular Economy approach, we aim to minimize waste generation, extend the life cycle of products, and foster innovation in eco-friendly alternatives to plastics. This treaty not only underscores the importance of global cooperation in addressing plastic pollution but also provides a blueprint for a more sustainable and resilient future, where the world can enjoy the benefits of modern materials without compromising the health of our planet.

India is no exception. Plastic has emerged as a primary material in several end-use sectors in the economy: packaging, building and construction, consumer and institutional products, textiles, transport, and electrical and electronic products. India's economic growth has been accompanied by

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increased production and consumption of plastic products. Between 1990 and 2019, India's consumption of plastics grew 20-fold [3], while its population increased by 60% over the same period [4].

Problems of ecological impact arise in the disposition of plastic products at end-of-life. Plastic can remain in the environment for centuries [5] and one estimate of mismanaged waste per capita in India in 2019 is approximately 9.5 kg/person/year [6] based on Meijer et al. [5], equivalent to a national total of 13 million metric tonnes annually (Mt/year).

The waste management sector in India faces significant challenges despite some positive efforts from government, corporate, and community initiatives. Even though Producers and Brand Owners (PIBOs) have responsibilities for waste management, compliance registration remains incomplete, and the scarcity of accessible data hampers both innovation and policy monitoring. Furthermore, the government's ban on single-use plastics in mid-2022 only addresses a small portion (10–15%) of plastic consumption.

The Plastic Waste Management (PWM) Rules, 2016, mandate the generators of plastic waste to take steps and manage 25% of the 'Q1[1]' waste in metric tonnes in 2021–22 [7]. The PWM Rules, 2016 cast Extended Producer Responsibility (EPR) on PIBOs which shall be applicable to both pre-consumer and post-consumer plastic packaging waste. The 2022 amendment to the Plastic Waste Management Rules 2016 increased the target to 70% by 2022–23, and 100% by 2023–24. However, no formal guidance is available for actors to be able to achieve these targets [8, 9]. A gap exists in the integration of informal sector recycling activities into formal systems [10].

Dealing with the complicated problem of plastic waste demands a comprehensive solution that incorporates technical, economic, social, and political strategies, while also considering the diversities at both national and regional levels. Yet, any approach aimed at tackling the issue of plastic waste must initially create a starting point for quantifying the quantities of plastics produced, used, and disposed of, to gauge advancements in the reduction of plastic waste, especially that which is not properly managed. Through the utilization of material stock and flow tracking, it becomes possible to recognize trends in material usage, anticipate waste generation, and assess the feasibility of recycling [11]. Particularly, material flow analysis (MFA) stands as the principal approach for conducting stock and flow tracking and has found extensive application in examining stocks and flows of different materials [12, 13]. MFA has been also extensively used to provide a better understanding of the flow of plastic in different sectors [14–17] and Wang et al., [11] provided a critical review of global plastics stock and flow data and recognized four data gaps in these existing data for characterizing plastics stocks and flows, including inconsistent classification, missing data, conflicting data, and inexplicit data for plastics products and waste.

Di et al., [16] tracked seven commonly used plastics from production into fabrication, manufacturing, flow into use, waste management, and recycling in the United States in 2015. Low- and high-density polyethylene and polypropylene were found to be the largest in both production and product manufacture. More than 88% of the plastics went into three end-use sectors: Packaging, Consumer, and Institutional Products, and Building and Construction. The actual end-of-life recycling rate of the plastics as a group was no more than 6.2%, with PET and the polyethylene family the most recycled.

Amadei et al. [15] investigated the plastic value chain for the EU27, with the emphasis on 9 sectors and 10 polymers. They estimate the average recycling rate to be around 19%, while around 4.5 Mt of plastic recyclates were produced and consumed in the EU27 in 2019.

Abbasi et al. [18], focused on plastic pollution in Norway, emphasizing the need for improved policies. They presented the MFA of seven plastic polymers in Norway for 2000–2050. In 2020, 620 ± 23 kt of plastic were introduced to the market, with packaging making the largest contribution at around 40%. The in-use stock was 3400 ± 56 kt, primarily within the building and construction sector. Plastic waste in 2020 amounted to 460 ± 22 kt, with half originating from packaging. However, only 25% was recycled, with 50% being incinerated, 15% exported, and 10% landfilled.

A deep knowledge of India plastic material flows is fundamental to understand the significance of the plastic wastes and how to manage them but unfortunately the information available is incomplete, outdated and often unreliable. The last attempt to create an overall account of India's plastics material flows dates almost two decades back. The study by Mutha et al. [14] developed a material flow framework to investigate the stocks and flows of plastics in India for the year 2000. That framework was directed to inform plastic waste management planning rather than providing a complete material flow account. There have been several structural economic changes over the intervening 20 years, and a more recent strategic emphasis on the circular economy [19].

Interestingly, there has been no comprehensive MFA of Indian plastics since Mutha et al.'s [14] investigation and hence our study provides a much-needed update to inform contemporary strategy and plastic waste management rules in India [20].

Indian plastic waste management is one driver of enquiry in this paper, though we seek a broader systemic understanding by emulating the economy-wide framework of plastics

[1] Q1 is calculated by adding the last two years' average weights of plastic packaging material sold and pre-consumer plastic packaging waste and subtracting the annual quantity of plastic packaging supplied to brand owners.

MFA applied in other studies, for example, for the EU28 countries [17]. Accounting for flows from imports and production, through consumption, end-of-life to waste and recycling, we aim to appreciate the larger picture of all plastic flows in India. We take a systematic data harmonisation approach and use a data pedigree assessment to construct a complete and consistent MFA of all plastics in India for the reporting year 2018–19.

There is a putative Indian plastic recycling rate of 60–70% [19–23]. Although this may be genuine, Shanker et al. [24] noted there is a high level of ambiguity as to what plastics or polymers this rate refers to. Contemporary work (such as [25]) refer to estimates in a Plastindia Foundation report [3] that does not specify what flows of which polymers are included in this recycling rate calculation.

Earlier, Siddiqui and Pandey [26] stated a range of 5–25% for India but that paper did not provide analysis of how that estimate was enumerated. Ambiguity in the definition and quantification of a national plastics recycling rate has existed for several decades. Mutha et al. [14] also noted that '*Information about the actual size of the Indian recycling sector varies greatly'* (p. 234), and they presented a variety of estimations (see their Table 6).

If the total plastics recycling rate is 60–70%, this far exceeds the global average of 9% [27] and India should not have substantial plastic waste issues, though further questions arise: where and how does plastic recycling occur? How can it be monitored and encouraged?

Here we emphasise completeness and consistency in our plastics MFA for India. The notion of 'Completeness' addresses to which extended data has been available and identifies area of missing data and under-reporting. Consistency ensures a clear definition of our final dataset without ambiguity. Consequently, we also aim to resolve national recycling rates using the mass-balance of our material flow account.

Data and methods

Material flow accounting (MFA)

MFA is an established approach to measure flows and stocks of materials within a specified spatial and temporal boundary and following the mass-balance principle [13, 28]. It has been implemented in different studies focusing on plastic flows in the EU [17], and plastic packaging in Italy [29]. The mass-balance approach can identify ways to improve raw material's efficiency, contribute to saving natural resources, minimise environmental impacts, and consequently help to accomplish sustainable development goals [30].

Figure 1 illustrates the system boundary of our study and the four main phases that cover the life cycle of plastics in India: (1) plastics production, (2) consumption, (3) waste generation, and (4) waste treatment. The initial extraction of primary materials (feedstock) and any leakage into the environment are excluded from this study.

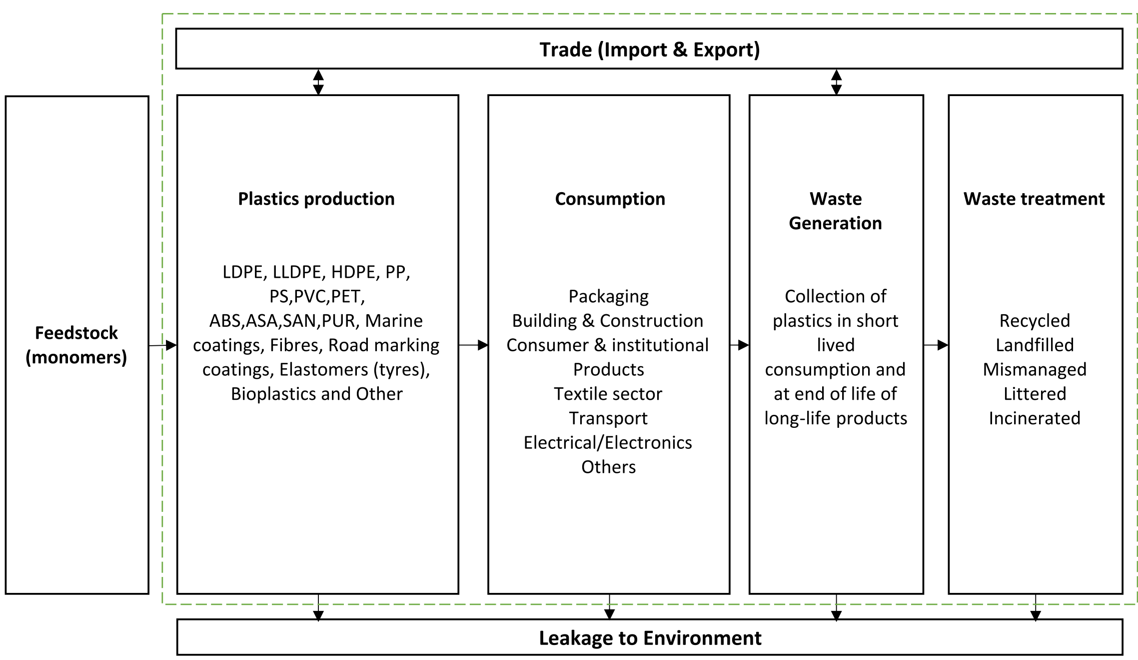

Fig. 1 System boundary, scope, and phases of the MFA. Physical boundary is the nation of India for the reporting year 2018–19

Data collection

The reference year of 2018–19 is defined by the Indian financial and reporting year (1 April 2018 to 31 March 2019) and was chosen because of maximum data availability. Where other data are available by calendar year, this may be referred to as '2019'. Our geographical scope (and limit of spatial resolution) is the national economy of India.

Our scope includes major polymers commonly used in industry and consumer products. We also looked at information on plastic application areas and end-use sectors, as commonly classified by Indian reporting entities and key industry bodies [3, 31].

Data on imports, domestic production and exports of polymer resins were obtained from country reports published by the Chemicals and Petrochemicals Manufacturer's Association of India (CPMA) in the Asia Petrochemical Industry Conference (APIC) series of conferences [32].

The UN Comtrade data [33] indicates that imports of "Waste, parings, and scrap, of plastics" amounted to 0.15 Mt, while exports were 0.003 Mt. Since UN Comtrade does not provide detailed information on the specific polymer types involved in these trades, and because the exported waste is small in comparison with the overall plastic flows, we have attributed this export flow to the "other plastic types" category. Additionally, the trade of plastic products is now included in our assumptions.

Plastindia [3] reported on consumption of plastics, which relied on industry reporting and surveys but does not cover production and imports in as much detail as CPMA [32], nor does Plastindia report on textiles. We also obtained data from the Organisation for Economic Co-operation and Development [34] on plastic polymer's consumption and waste flows. Although this data is based on modelling from the G-TAP project, it presents a complete and self-consistent annual polymer flow account for India. This was used where no data was available or other data sets were incomplete.

The approach involved selecting either a single primary data source, such as CPMA for Imports and Exports, or opting for a combination of data sources specific to individual polymers in a given phase, such as utilizing Plastindia and OECD data for assessing plastics consumption. In terms of data combination, the following protocol was applied; if direct measured data was available, this was preferrable to modelled or estimated data. If only modelled or estimated data was available, extreme values in modelled data were considered less trustworthy than estimates from surveys or industry.

Based on the reported scope, provenance, and metadata from the above sources, we assessed each according to their data pedigree based on the schemas in [35] and [36], refer to Tables SM 1 to 5 in the Supplementary Materials.

Reliability of data

There is a plenitude of studies on Indian plastic waste and management [21, 22, 24–26, 37–44]. Within that literature there are certainly cases of inherited assumptions and unacknowledged incompleteness or age of ultimate data sources. Some examples below illustrate our point though we emphasise that this critique does not fall on author's efforts, rather on the unavoidable estimation that is a feature of studies dominated by informal or unaccounted activity.

The Centre for Science and Environment (CSE) [45] fact sheet, and also Aryan et al. [42], refer to the Indian Central Pollution Control Board (CPCB) [31] and claim that 94% of *total plastic wastes* are thermoplastics that can be recycled and 6% are thermoset plastics that cannot be recycled. In fact, the CPCB [31] report looked exclusively at municipal solid waste (MSW) sites for 60 cities, where waste flows are mostly from households and residential areas. A complete assessment of *total plastic waste* should also include waste from retail, building and construction, and other industry.

Shanker et al. [24] state that 50–80% of Indian plastic waste is 'recycled', referring to an earlier study [43]. In fact, Nandy et al. [43] state that a range of 6.5–8.5 Mt of plastics per year are 'recovered' based on an upper figure that assumes 70% recovery of plastic from mixed household waste. That assumption on plastic content of mixed household waste was derived from municipal waste characteristics in a much earlier study [44] that quoted yet older data from CPCB [38] for 23 Indian states, representing 13% of the Indian population in year 2000. Such an aged lineage needs to be acknowledged as contemporary papers continue to refer to antecedents perhaps without full awareness of the origin of the underlying assumptions or data.

The lower figure used by Nandy et al. [43] re-uses a recycling rate of 47% from Mutha et al. [14], based on Mutha et al.'s own estimates and personal communication with the Indian Petrochemical Corporation Ltd in 1999.

Commendably, Nandy et al. [43] used a separate, bottom-up approach to produce other estimates. Those results were that plastic waste recovered, recycled, or reused, or disposed of through open burning, illicit dumping or as fuel in cooking stoves etc., was at least 6.1–7.4 Mt per year. While this broadly concurs with their first estimate above, no specific number for recycling was given. Though it is possible that recycling genuinely is the fate of ~ 60–70% of plastic waste in India, this collection of citations does not provide a basis in fact.

We re-iterate the difficulty of obtaining primary data in this field of research. We acknowledge the best efforts and empathise greatly with the abovementioned authors, but there is also a need to acknowledge the provenance, limits and age of data sources, or prior estimates, before making a statement about current plastic material flows in India.

We have compiled data based on the systematic approach of Baynes et al. [46] who reconciled incomplete and incongruently disaggregated records to construct a complete and coherent (water) material flow account. This approach involves: collection of primary data sources; comparison of differing data using common categorisation; consolidation of data selections to a final set; and completion, which may involve extrapolation, or other inference to fill any data gaps. Similar approaches have been used to develop economy-wide MFA: West et al. [47] is the latest update of the methodology used to assemble the database underlying the UN's Global Material Flows Database [48].

Data categorisation

Part of the data harmonisation task is to have a common way to translate across different reporting schemes. Table SM 6 in the Supplementary Materials associates international resin codes; product groups used by the Indian Government Ministry of Chemicals and Fertilizers [49]; classes of plastic products used by the OECD; and the CPMA [32, 34]. The range of polymers we include is shown in Table SM 6 where we also align those with different terminology and classifications that can be found in industry and public data sources.

Data comparison and selection

The benefit of data sources like Plastindia and CPCB is that they are derived from primary sources. However, they can be incomplete in their coverage of polymers and plastics applications (See Table SM 7), and not all municipal sites report to CPCB. Whereas Plastindia data sourced directly from industry rates highly in the data pedigree, there is no access to the raw data from those surveys (as in CPMA data), only summaries in graphs. Thus, transparency regarding scope, methodology and data formulation is unknown. For Imports, Exports and Indian production by detailed polymer type, the superior data source is CPMA (see Table 1).

Plastindia reports total *commodity* plastic consumed in India was 16 Mt/year for 2018–19 but this is incomplete as it excludes engineering plastics and textiles. The OECD estimates for all polymers and products in the same year was 29.3 Mt [34]. The data for 2019 were estimated by building on output from the OECD Computable General Equilibrium (CGE) model (ENV-Linkages) using GTAP. The ENV-Linkages model has been expanded to incorporate plastic volumes, for both primary and secondary (recycled) plastics use.

In 2019, OECD.Stat [34] estimated that India generated 18.5 Mt of plastic waste, categorized by various sectors. OECD correlates plastic consumption with sectoral and regional economic projections and calculated waste generation based on the lifespans of different applications. This generated waste is then further categorized by treatment methods: recycling, incinerated, landfilled, mismanaged, and littered waste. The completeness and consistency of this data surpasses the quality of the Indian Central Pollution Control Board (CPCB), a statutory organisation under the Indian Ministry of Environment, Forest and Climate Change [50]. According to CPCB data [20], the "total plastic waste generation" in 2019 was reported as 3.4 Mt, significantly less than the OECD estimation, about a third of the 9.7 Mt/year estimated by TERI [19], and less than the 5.5 Mt/year implicit in the estimations of Padgelwar et al. [39].Consequently, we conclude that while CPCB data is robust, it is fundamentally incomplete for the nation of India. As a result, in the spirit of environmental conservatism, our data selection favours larger estimates of total plastic waste flow, which we see as more complete.

The methodology for estimation of plastic waste by the OECD is the same as that used for plastic consumption, which is explained above. Recycling rates in non-OECD regions were based on estimates of municipal solid waste (MSW) recycling rates from What a Waste 2.0 [51] and consultations with experts. For regions with highly unorganised recycling sectors, projections were adjusted to account for informal recycling that is not reported but typically recovers high value streams such as HDPE and PET bottles.

There is no documentation of the quantity and routes that informal plastic takes. Apart from PET, most other polymers

Table 1 Summary of data pedigree assessment (refer to Supplementary Materials SM1–SM5) and selection of data sources for different phases of the MFA (see Methods)

	Imports and exports	Plastic production	Consumption	Waste generation and treatment
Plastindia Foundation (2019)	N/A	[4,4,1,1,1,2,1,1]	[4,4,1,1,1,2,1,2]	N/A
CPMA (2020)	[1,1,1,1,1,1,1,1]	[1,1,1,1,1,1,1,1]	N/A	N/A
OECD Stat (2020)	N/A	N/A	[3,1,1,1,1,1,1,2]	[3,1,1,1,1,1,1,4]
CPCB	N/A	N/A	N/A	
UN Comtrade	[1,1,1,1,1,1,1,1]	N/A	N/A	N/A

A lower number indicates a higher pedigree over dimensions of: [Reliability; Completeness; Temporal correlation; Geographical correlation; Access; Additional steps; Frequency; Informality and illegality], *N/A* indicates not available are often recycled without segregation to manufacture low quality products. This plastic does not find its way back to formal production, hence a major portion of any recycled flow is unaccounted downcycling [19, 25, 52].

However, OECD.Stat calculates plastic waste based on assumed product lifespan, which does not always translate into reality. In India, consumers often extend plastic product life by multiple utilisations, e.g., secondary uses at household level and even in businesses. Furthermore, the data is not primary in nature, unlike other sources. OECD reasons that the end-of-life fates of plastic waste traded flows differ from domestically treated waste to reflect the fact that a high proportion of traded plastic waste tends to be recyclable (approximately 50%), with the remainder being distributed across other waste streams following the same proportions of end-of-life fates as domestically treated waste, excluding littering.

Results

Flows of plastics in India for 2018–19

Figure 2 illustrates the material processes and flows of the seven primary plastics in India for 2018–19, highlighting stages such as plastics production, consumption, stock, waste generation, waste treatment. The initial phase involves the production of polymers from petrochemical feedstocks for domestic use. Intermediate plastic production employs the foundational polymer and post-consumer resins to generate intermediary plastic materials. These intermediates are subsequently employed in the ultimate production of plastic goods across seven major sectors. The subsequent stage encompasses the integration of these goods into the socio-economic system. Plastics that have reached the conclusion of their functional life constitute the end-of-life waste, which is then subject to management procedures including collection for recycling, incineration, or landfill disposal and mismanaged.

Production, fabrication, and manufacturing

The total plastic production amounted to 19.3 Mt, including LDPE, LLDPE, HDPE, PP, PS, PVC, PET, ABS, ASA, SAN, PUR, Marine coatings, Fibres, Road marking coatings, Elastomers (tyres), Bioplastics and Other. The most consumed plastic is PE (22%), closely followed by PP, fibres, and PVC. The trade in plastic is 14.5% of total production as either imports or exports, with a negative trade balance of 2.7 Mt (7.2 Mt imported, and 4.5 Mt exported).

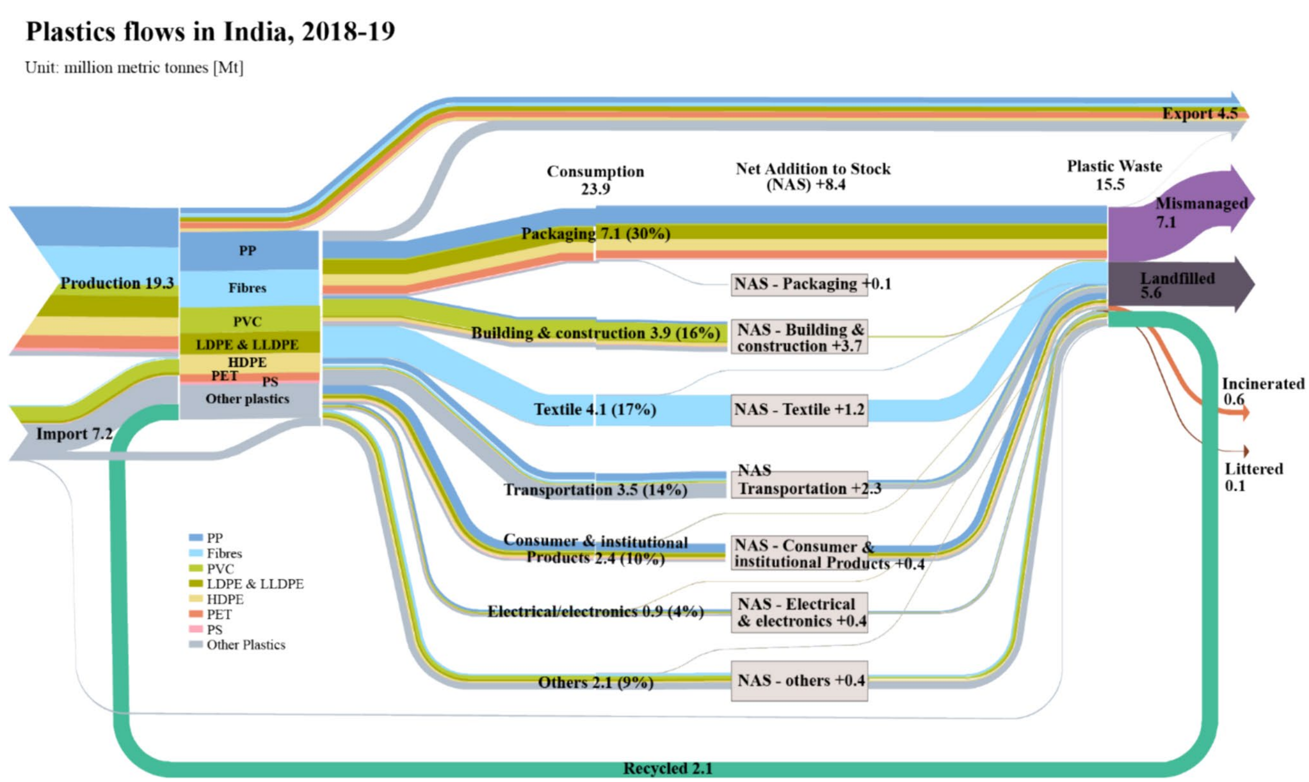

Fig. 2 Summary of total plastic material flows in India for 2018–19. The data used to generate this figure are available in the table labelled SM 9 of the supplementary materials

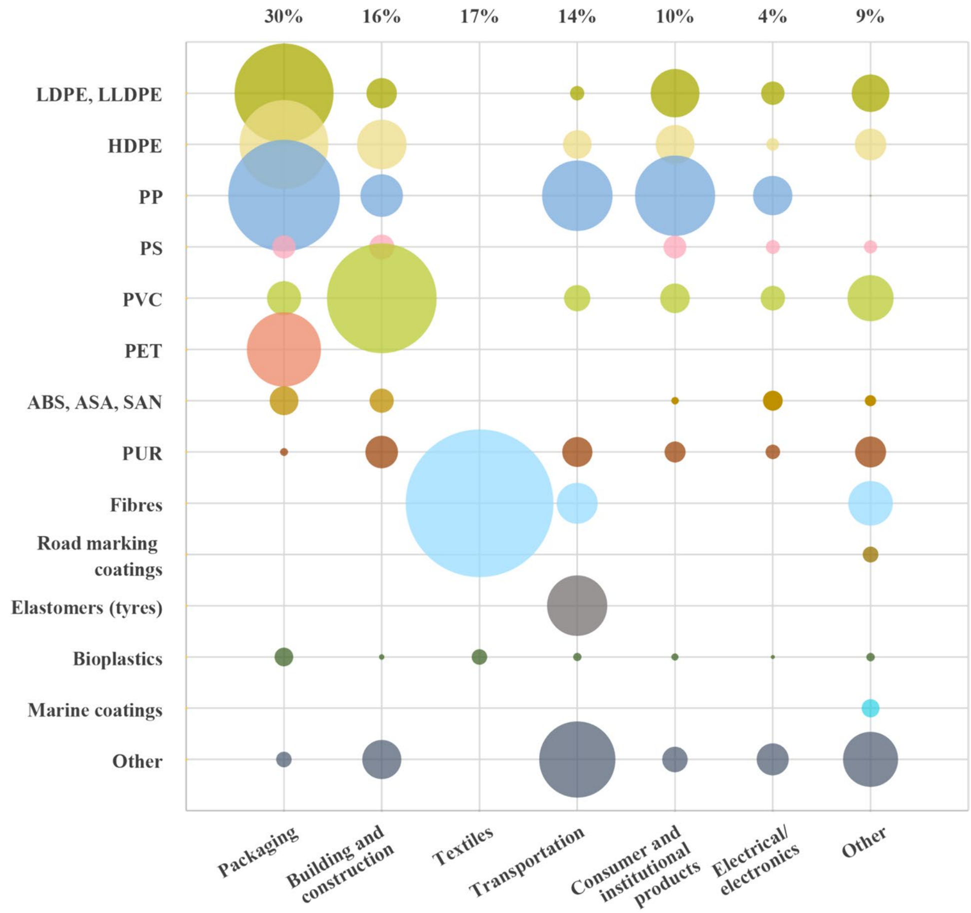

Fig. 3 Distributions of plastics into end-use sectors in the India for 2018–19. The horizontal axis lists the sectors, the vertical axis lists the seven categories of plastics. The area of each bubble represents the percentage of the relevant sector consumption of each specific plastic. All bubbles with the same colour along the horizontal axis aggregate to 100%. The percentage atop each vertical bubble line represents the proportion of all plastics utilized in that end-use sector. The data used to generate this figure are available in the table labelled SM 7 of the supplementary materials

Total mass of plastic in plastic-containing products assembled and distributed into different applications was 23.8 Mt (total apparent consumption = production + imports− exports). Figure 2 also illustrates the consumption of plastic and plastic-containing products by sector.

The selection of a particular type of plastic for a specific purpose is primarily influenced by its physical properties and cost considerations. A comparison of the primary uses of different plastics across various industries is presented in Fig. 3. The data reveal that in the India for 2018–19, Packaging accounted for 30% of plastic applications, followed by textile sector at 17% and, Buildings and Construction at 16%—see detail in Table SM 8 in the Supplementary Materials. Plastic types like PET, LDPE/LLDPE, HDPE, and PP are commonly utilized for producing containers in the Packaging sector as well as for mass-produced items in the Consumer and Institutional Products sector. HDPE, known for its exceptional corrosion resistance, is extensively employed both in Packaging (e.g., bottle caps) and in Buildings and Construction (e.g., water piping). Unlike packages, which are typically discarded within a year, construction components can remain in use for many years. PVC and other plastics find significant applications in the Buildings and Construction, Electrical/Electronic, and Transportation sectors.

Flow into use and end-of-life products

Plastic products by plastic types will be distributed between waste and stock depending on the sector and lifetime of product. A total of 15.3 Mt of plastic waste was generated in 2018–19, a majority of which was packaging products (7.0 Mt) and Textiles (2.9 Mt)—see detail by plastic types in Table SM 9 in the Supplementary Materials. Additions to stock were much higher in Buildings and Construction, and Transport. Accumulation of stocks is important to account for as they will become future waste. Considering the composition of plastic types used in different sectors, OECD. Stat 2019, [34] estimated the distribution of waste between recycling (13%), landfilled (36%), mismanagement[2] (46%), incineration (4%) and littered[3] (1%).

To estimate flows from end-of-life (EOL) for different use sectors, we have used data from OECD.Stat on EOL fate, though we suspect they underestimate the informal sector. This represents a significant data gap, likely linked to the flow of low-value secondary plastic products. These products often contain a high percentage of recycled inputs, processed through mechanical recycling of plastic waste into new moulded products in the informal sector. Approximately 45% of plastic waste comes directly from packaging consumption, which has a lifespan of less than a year, with the rest flowing into stock. We also estimate the fraction of waste coming from the stock using the lifetime data, according to Geyer et al. 2017 [53]

Leakages of plastic waste into the environment and their connection to mismanaged plastic waste, are likely to remain data-scarce topics and may only be understood from the MFA balance, when all other flows are reasonably accounted for.

Discussion

We have presented an MFA for Indian plastics based on national flow data for 2018–19. To the best of the author's knowledge, this represents the first comprehensive analysis of Indian plastic flows since the Mutha et al. [14] using data from the year 2000. According to their projections, total virgin plastics consumption is expected to reach 20 Mt by the year 2030, generating over 18.8 Mt of waste. In contrast, based on our analysis, plastic consumption had already reached 24 million tons in 2018, resulting in the production of 15.3 Mt of plastic waste. Therefore, this trend emphasizes the need for more detailed analysis of plastic flows in particular mismanaged waste, to comprehend how we can reduce waste and transition towards a circular use of plastic. Now is the opportune moment to effect this change—to reduce the environmental impact of plastics and transform them from something harmful into something useful in our world.

Importantly, the MFA approach utilised in this study also provides, for the first time, a national level, mass-balanced snapshot of the stocks and flows of plastic material. This has been informed by primary data sets where possible, using a transparent pedigree framework (see Supplementary Material for data sources and criteria used SM1–SM5). Where primary data sets were not available, estimates have been made to construct a self-consistent model that details the production, consumption and fate of plastics within an Indian context.

This work stands in contrast to several recent studies that provide insights into Indian plastic system subsets, for instance standalone estimates of end-use sectors [41] or end-of-life fate [25] or those that rely predominantly on estimated data [54]. Data available from OECD. Stat has also allowed, for the first time, the examination of a broader range of polymer resin types and the impact of additional consumption sectors, such as Textiles, which accounts for an estimated 17% of all plastic consumption by weight in the country. This national level MFA hence represents the most complete, mass-balanced flow of plastic materials for India to date.

An interesting point of contrast with the newly derived MFA model is the relatively low recycling rate of 13% (2 Mt) established in our assessment. One potential explanation underlying this discrepancy is that our current model utilises economic data that will only represent the formal recycling sector. The Plastindia Foundation estimates that while there are approximately 100 'organized recycling units', this is far outweighed by approximately 10,000 'unorganized units' [3]. While the role of the informal sector on overall recycling rates for India is undeniable, we were unable to source a transparent and verifiable data set quantifying the contribution of the informal sector to overall material flows. Although recycling rates reported in this work are likely to underrepresent reality, the greater scope and completeness of the present work provides a rigorously defined denominator for calculations of a 'total plastics recycling rate'. There is an opportunity for future refinement of this model if such data on the informal sector become available.

The dispersed and unregulated nature of this sector means that it is difficult to accurately measure reliable and transparent flow accounts for the activities of informal waste collectors, aggregators, and recyclers. The difficulty may be worthwhile overcoming as many also argue that India's current policy strategies preclude these groups, ignoring the aggregated (positive) impact these groups could have on waste minimisation and pollution reduction [55–58].

A sensible first step for this integration into the broader plastics policy landscape in India may be to consider processes such as the registration of informal units. This would create better working conditions and more secure livelihoods but may also open avenues for more accurate plastic flow reporting, and hence provide baseline measures for policy makers on the impact of interventions for informal waste collectors. This would also allow more opportunities to

[2] According to the OECD Global Plastics Outlook Database [64] "Mismanaged waste" quantifies plastic waste in areas lacking proper waste facilities, where waste may not be collected or is disposed of improperly.

[3] According to the OECD Global Plastics Outlook Database [64] "Littered waste" includes littering and fly-tipping, regardless of waste facilities, and can be collected or left to leak into the environment.

harness the immense potential of these groups in delivering a more sustainable plastics system in India, as well as the potential to address marked occupational safety and environmental efficiencies of these groups [19].

There has been a recent sharpened focus in India on developing new policy frameworks that ensure plastic products are produced, consumed and disposed of more responsibly. This includes the Plastic Waste Management Rules (2016), and amendment in 2021 [20], which aim to minimise generation of plastic waste, littering, and ensure segregated collection and storage of waste at the source. There are also guidelines to eliminate single-use plastics. The rules were proposed to be implemented in three phases, starting from 30 September 2021 with carry bags. In 2022, six additional major categories of plastics were to be targeted, thus including all major classes of single-use products. This policy package also places a greater emphasis on extended producer responsibility (EPR) for both pre-consumer and post-consumer packaging. There is, however, no current framework or platform to document and track data associated with these mandates. In fact, a lack of accurate and transparent national data has been identified by many as a significant barrier to effective implementation and monitoring of policy interventions [37, 59–61].

The assessment of the success and impact of various policy interventions over time becomes impossible if accurate baseline reporting is not available. A lack of accurate flow accounts also stands in the way of accountability within the supply chain, thus reducing the ability for governments to enforce EPR programmes and the like.

The complete, self-consistent, reproducible, and transparent nature of this approach can allow for longitudinal tracking of the impact of such interventions to India's mismanaged waste flows at a national scale. It will also allow decision makers an opportunity to identify and probe the biggest contributors across the entire system to India's plastic waste issue, and deliver accountability, perhaps one of the most important levers for transitioning the system to more sustainable practices.

The method used in this study also allows policy makers a national, forward-looking perspective. This work serves to include sectors which have previously been overlooked in policy approaches (e.g., the textiles industry) thus helping to identify future intervention opportunities for India. This data also shows that only some 13% of plastics appear to be formally recycled within the supply chain, with the remaining 87% a mix of wasted resources or perhaps a loss of value through informal downcycling. This reflects a missed economic opportunity to redirect these materials into higher value circular approaches, thus serving to grow India's plastic recycling sector.

Still, it is worth noting that the study suffers from a few limitations. As mentioned earlier, the most important constraint is data source quality and reliability. We noticed several cases of relying on old assumptions or incomplete information. We have mainly relied on two key data sources, the Indian national statistics on polymers and the OECD datasets on sectoral use, waste, and recycling. Harmonisation of these two main data sources allowed us to establish a consistent picture of polymer and plastic material flows in the Indian economy but has not supported a complete understanding of all process steps in the polymer-plastics life cycle (such as plastics embodied in imported consumer goods). We are confident that all plastic that has entered the Indian economy in the reporting year and has been managed domestically has been included even if further differentiation to products and consumer goods has not been possible based on the available data.

Conclusion

Our study has shown the extent to which end-of life plastic materials end up in landfill or leak into the environment in India, and how significant the missed opportunity of materials management and resource recovery still is, despite significant policy efforts of the Indian government to clean up India and generate value from waste. One key impediment to the success of policy and of novel business models is the lack of reliable data on plastic material flows and stocks in India.

In this study, we have employed and assessed multiple data sources to produce a single coherent material flow account (MFA) of plastics in India that helps identify key flows and where circular economy policy might be most effectively directed to reduce managed and mismanaged plastic waste flows. The MFA framework has proven to be very useful to improve the notoriously bad data quality of waste statistics by applying a mass-balance framework which ensures that all materials are tracked across the whole supply chain, from cradle to grave. This has also allowed us to produce a more realistic recycling rate for plastic materials in the Indian economy beyond anecdotal knowledge of resource recovery rates for specific plastic materials or specific products. In doing so, the study reveals the significant effort that is needed to divert end-of-life plastics from landfill and avoid environmental leakage and demonstrates the economic potential of an emerging resource recovery industry in India. In short, the updated plastics material flow account, integrating the most recent data, can be a key tool to support the development, monitoring and design of plastic waste management policies in India [62] to deliver sustainable production, consumption, and disposal outcomes and to help stem the plastic waste crisis in the country.

A lack of accurate and reliable data is a known key barrier to plastics policy success, hence the unique national scale, mass-balanced, self-consistent and transparent nature of this approach will supply a key lever for decision makers. This will support India to deliver to the objectives and outcomes of the Global Plastics Treaty, which, once established, will require nations to contribute to ending plastics pollution of waterways and oceans. It will also support India's emergent circular economy policy efforts [63].

The material flow accounting method used in this study can also inform the Indian Office of National Statistics approach to integrate waste accounts in the broader conceptual framework of MFA, which is not just applicable for end-of-life plastics, but can be used across the board, for all waste materials. Metrics, data, and indicators derived from material flow accounts have the advantage of being compatible with economic accounts and with the System of Integrated Environmental and Economic Accounting Framework (SEEA). This is helpful for economic and environmental policy decisions by providing a unified method for longitudinal tracking of policy interventions, and increased accountability within the value chain.

Policy makers and business leaders can use the MFA for plastics, and for materials more generally, for identifying future policy approaches and informing business decisions that are specific to plastic material types or sectors and products that use these materials. In such a way, decision makers in India will be able to identify growth opportunities for a sustainable plastics industry, to redirect currently wasted resources into more circular economic models. This study is hence a timely update to inform contemporary waste management and resource recovery strategy and plastic circular economy rules in India [20].

Finally, the approach presented has validity for other countries and authorities, to raise public awareness of environmental and sustainability issues, to inform policy discussions and policy statements, to set priorities and targets and to judge the efficacy and effectiveness of policies through monitoring and evaluation supported by reliable and up to date data.

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References

1. Bergmann M, Almroth BC, Brander SM et al (2022) A global plastic treaty must cap production. Science 376:469–470. https://doi.org/10.1126/science.abq0082
2. Stokstad E (2022) United Nations to tackle global plastics pollution. Science 375:801–802. https://doi.org/10.1126/science.ada1551
3. Plastindia Foundation (2019) Indian plastics industry Report 2019
4. United Nations 2022 (2022) UN population division data portal. https://population.un.org/dataportal
5. Meijer LJJ, van Emmerik T, van der Ent R et al (2021) More than 1000 rivers account for 80% of global riverine plastic emissions into the ocean. Sci Adv 7:1–14. https://doi.org/10.1126/sciadv.aaz5803
6. Ourworldindata.org (2022) Plastic pollution. https://ourworldindata.org/plastic-pollution. Accessed 11 Nov 2022
7. iPCA (2022) Plastic waste management (Amendment) rules, 2022. New Delhi, India
8. CPCB (2022) Aunnal report PWM Rules
9. Shah D (2022) Why the plastic waste amendment rules 2022 is a paper tiger. In: Science–the wire. https://science.thewire.in/environment/plastic-waste-amendment-rules-2022-epr-certificates-paper-tiger/
10. Talwar S, Thanduparakkal S, Arora K, et al (2021) A review of the policy framework for a circular economy for plastics in India
11. Wang C, Liu Y, Chen WQ et al (2021) Critical review of global plastics stock and flow data. J Ind Ecol 25:1300–1317. https://doi.org/10.1111/jiec.13125
12. Allen FW, Halloran PA, Leith AH, Lindsay MC (2009) Using material flow analysis for sustainable materials management: part of the equation for priority setting. J Ind Ecol 13:662–665. https://doi.org/10.1111/j.1530-9290.2009.00168.x
13. BrunnerRechberger PHH (2016) Handbook of material flow analysis: for environmental, resource, and waste engineers, 2nd edn. CRC Press, Boca Raton
14. Mutha NH, Patel M, Premnath V (2006) Plastics materials flow analysis for India. Resour Conserv Recycl 47:222–244. https://doi.org/10.1016/j.resconrec.2005.09.003
15. Amadei AM, RigamontiSala LS (2022) Exploring the EU plastic value chain: a aterial flow analysis. Lancent Pschch 11:133–143. https://doi.org/10.1016/j.resconrec.2023.107105
16. Di J, Reck BK, Miatto A, Graedel TE (2021) United States plastics: Large flows, short lifetimes, and negligible recycling. Resour Conserv Recycl 167:105440. https://doi.org/10.1016/j.resconrec.2021.105440
17. Hsu W-T, Domenech T, McDowall W (2021) How circular are plastics in the EU?: MFA of plastics in the EU and pathways

to circularity. Clean Environ Syst 2:100004. https://doi.org/10.1016/j.cesys.2020.100004
18. Abbasi G, Hauser M, Baldé CP, Bouman EA (2023) A high-resolution dynamic probabilistic material flow analysis of seven plastic polymers; A case study of Norway. Environ Int 172:107693. https://doi.org/10.1016/j.envint.2022.107693
19. Kapur-Bakshi S, Kaur M, Gautam S (2021) Circular economy for plastics in India: a roadmap
20. CPCB (2020) Annual Report 2019–20 on implementation of plastic waste management rules, 2016
21. Sikka P (2007) Plastic waste management in India. 016: 1–4
22. CSE (2020) Managing plastic waste in India
23. Mohanty S (2017) Recycling of plastics in Indian perspective. UNIDO Office
24. Shanker R, Khan D, Hossain R et al (2022) Plastic waste recycling: existing Indian scenario and future opportunities. Int J Environ Sci Technol. https://doi.org/10.1007/s13762-022-04079-x
25. Neo ERK, Soo GCY, Tan DZL et al (2021) Life cycle assessment of plastic waste end-of-life for India and Indonesia. Resour Conserv Recycl 174:105774. https://doi.org/10.1016/j.resconrec.2021.105774
26. Siddiqui J, Pandey G (2013) A review of plastic waste management strategies
27. OECD (2022) Global plastics outlook. OECD
28. Fischer-Kowalski M, Krausmann F, Giljum S et al (2011) Methodology and indicators of economy-wide material flow accounting: state of the art and reliability across sources. J Ind Ecol 15:855–876. https://doi.org/10.1111/j.1530-9290.2011.00366.x
29. Lombardi M, Rana R, Fellner J (2021) Material flow analysis and sustainability of the Italian plastic packaging management. J Clean Prod 287:125573. https://doi.org/10.1016/j.jclepro.2020.125573
30. Gao C, Gao C, Song K, Fang K (2020) Pathways towards regional circular economy evaluated using material flow analysis and system dynamics. Resour Conserv Recycl 154:104527. https://doi.org/10.1016/j.resconrec.2019.104527
31. CPCB (2016) Annual Report for the year 2015–16 on implementation of plastics waste management rules
32. CPMA (2021) Indian petrochemical industry country paper from India-2021. New Delhi, India
33. United Nations (2023) UN Comtrade database. https://comtradeplus.un.org/. Accessed 31 Jul 2024
34. OECD.Stat (2019) Environment-global plastics outlook. https://stats.oecd.org/
35. Hoekman P, von Blottnitz H (2017) Cape Town's metabolism: insights from a material flow analysis. J Ind Ecol 21:1237–1249. https://doi.org/10.1111/jiec.12508
36. Weidema BP, Wesnæs MS (1996) Data quality management for life cycle inventories-an example of using data quality indicators. J Clean Prod 4:167–174. https://doi.org/10.1016/S0959-6526(96)00043-1
37. Nikam J, Ddiba D, Njoroge G (2022) Analysis of the plastic waste value Chain in India: a scoping study
38. CPCB (2000) Status of solid waste generation, collection, treatment and disposal in metrocities. New Delhi, India
39. Padgelwar S, Nandan A, Mishra AK (2021) Plastic waste management and current scenario in India: a review. Int J Environ Anal Chem 101:1894–1906. https://doi.org/10.1080/03067319.2019.1686496
40. Banerjee T, Srivastava RK, Hung Y-T (2013) Plastics waste management in India: an integrated solid waste management approach, in: Handbook of environment and waste management: Volume 2: Land and groundwater pollution control
41. Hossain R, Islam MT, Shanker R et al (2022) Plastic waste management in India: challenges, opportunities, and roadmap for circular economy. Sustainability (Switzerland) 14:4425. https://doi.org/10.3390/su14084425
42. Aryan Y, Yadav P, Samadder SR (2019) Life cycle assessment of the existing and proposed plastic waste management options in India: a case study. J Clean Prod 211:1268–1283. https://doi.org/10.1016/j.jclepro.2018.11.236
43. Nandy B, Sharma G, Garg S et al (2015) Recovery of consumer waste in India—a mass flow analysis for paper, plastic and glass and the contribution of households and the informal sector. Resour Conserv Recycl 101:167–181. https://doi.org/10.1016/j.resconrec.2015.05.012
44. Sharholy M, Ahmad K, Mahmood G, Trivedi RC (2008) Municipal solid waste management in Indian cities——a review. Waste Manag 28:459–467. https://doi.org/10.1016/j.wasman.2007.02.008
45. CSE (2019) The plastics factsheet 3. https://cdn.cseindia.org/attachments/0.28582200_1570445163_factsheet-2.pdf
46. Baynes TM, Turner GM, West J (2011) Historical calibration of a water account system. J Water Resour Plan Manag 137:41–50. https://doi.org/10.1061/(asce)wr.1943-5452.0000090
47. West J, Lieber M, Wang H (2021) Technical annex for the global material flows database-2021 edition. Global material flows database
48. Schandl H, Fischer-Kowalski M, West J et al (2018) Global material flows and resource productivity: forty years of evidence. J Ind Ecol 22:827–838. https://doi.org/10.1111/jiec.12626
49. MCF (2019) Chemicals and petrochemicals statistics at a glance-2019. New Delhi, India
50. MoEF and CC (2016) Solid waste management rules revised after 16 years; Rules now extend to urban and industrial areas
51. Kaza S, Yao L, Bhada-Tata P, Van WF (2018) What a waste 20: a global snapshot of solid waste management to 2050. World Bank Group, Washington, DC
52. TNN (2020) Officials, residents call to maintain cleanliness at tourist destinations. In: the Times of India. https://timesofindia.indiatimes.com/city/hyderabad/officials-residents-call-to-maintain-cleanliness-at-tourist-destinations/articleshow/78340948.cms
53. Geyer R, Jambeck JR, Law KL (2017) Production, use, and fate of all plastics ever made. Sci Adv 3:25–29. https://doi.org/10.1126/sciadv.1700782
54. Baynes TM, Kapur-bakshi S, Emami N, Bhattacharja S (2021) A material flow analysis of polymers and plastics in India
55. Nagarajan A (2022) The governance of plastic in India: towards a just transition for recycling in the unorganised sector. Local Environ 27:1394–1413. https://doi.org/10.1080/13549839.2022.2084721
56. Nizzetto L, Sinha S (2020) Top priority to curb plastic pollution: empowering those at the bottom. One Earth 2:11–15. https://doi.org/10.1016/j.oneear.2020.01.005
57. Nøklebye E, Adam HN, Roy-Basu A et al (2023) Plastic bans in India—addressing the socio-economic and environmental complexities. Environ Sci Policy 139:219–227. https://doi.org/10.1016/j.envsci.2022.11.005
58. Schlitz N (2020) Environmental change and the informal plastic recycling networks of Kolkata. Singap J Trop Geogr 41:450–467. https://doi.org/10.1111/sjtg.12324
59. Centre for Science and Environment (2020) Managing plastic waste in india: challenges and agenda. New Delhi, India
60. Pandey S, Manuja S (2020) Plastic waste management-turning challenges into opportunities. New Delhi, India
61. Rafey A, Siddiqui FZ (2021) A review of plastic waste management in India—challenges and opportunities. Int J Environ Anal Chem 103:3971–3987. https://doi.org/10.1080/03067319.2021.1917560
62. Moriguchi Y, Hashimoto S (2015) Material flow analysis and waste management. Springer, Cham, pp 247–262

63. Fiksel J, Sanjay P, Raman K (2021) Steps toward a resilient circular economy in India. Clean Technol Environ Policy 23:203–218. https://doi.org/10.1007/s10098-020-01982-0
64. OECD (2022) Global plastics outlook: economic drivers, environmental impacts and policy options. OECD