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# COVID-19 PPE plastic material flows and waste management: Quantification and implications for South Africa

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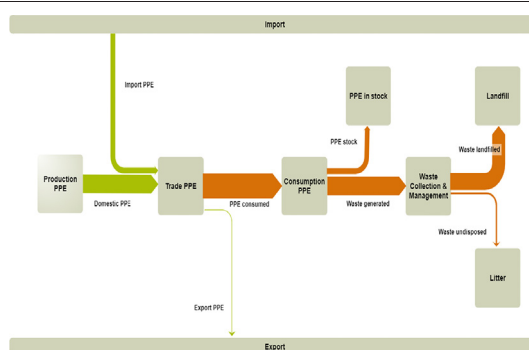
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## HIGHLIGHTS

- Sankey diagrams developed to capture uncertainty in the plastic PPE material flow.
- Mass flow of PPE was relatively smaller to the total national plastic.
- Number of separate PPE items is a growing problem for waste management systems.
- Known estimate of Covid-19 plastic material resources and waste legacy presented.

## GRAPHICAL ABSTRACT



## ARTICLE INFO

### Article history:

Received 11 March 2021

Received in revised form 26 May 2021

Accepted 28 May 2021

Available online 1 June 2021

Editor: Damia Barcelo

### Keywords:

COVID-19

Material flow

Personal protective equipment (PPE)

Plastics

Waste management

## ABSTRACT

The COVID-19 pandemic has exposed the vulnerability of countries to resource constraints while highlighting the indispensability of plastic. Personal protective equipment (PPE), comprising plastic materials, is experiencing an unusual increase in demand globally due to unprecedented consumption for the protection of healthcare workers and the general population. There is a need to model and better understand the material implications of the pandemic. In this research, material flow analysis was used to model the flow of plastic material pre-COVID-19 in South Africa and the additional contribution of the COVID-19 PPE to the plastic footprint. Sankey diagrams were developed to capture the material flow analysis. The mass flow of PPE through the supply chain during the ongoing pandemic is relatively smaller compared to the total national plastic. However, the number of separate PPE items presents a major and growing problem for waste management systems. This paper puts the COVID-19 resource requirements into perspective in relation to South Africa's total national plastic and provides the first known estimate of COVID-19 plastic material resources and waste legacy.

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## 1. Introduction

In 2020, the COVID-19 pandemic had an unprecedented devastating impact globally. South Africa was declared the epicentre of the crisis in Africa by the World Health Organisation (WHO), with the highest number of confirmed cases at 775,502 as of 25 November 2020

(SACoronavirus, 2020). While the COVID-19 pandemic is directly a health problem, it has greatly impacted the global community economically, socially and environmentally. Several studies have been conducted on COVID-19 and its impacts on social life and the economy. Besides the startling socio-economic impacts, the impact on the natural environment has to be considered.

The social isolation and lockdown imposed by governments globally positively impacted the environment in terms of cleaner beaches and streets (Ryan et al., 2020), noise reduction (Zambrano-Monserrate

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et al., 2020), improved air quality (Wang and Su, 2020; Tobias et al., 2020) and surface water quality (Braga et al., 2020). However, there are reported negative impacts related to increased solid waste generation and reduced recycling programmes (Zambrano-Monserrate et al., 2020).

Undoubtedly, a critical component of this COVID-19 pandemic is personal protective equipment (PPE). During this crisis, PPE is playing a primary role in the protection of people, with special focus on health workers and other frontline personnel. Specifically, PPE, including masks, respirators, gloves, goggles, gowns, etc. has been recommended for health personnel in handling patients and for protection. Also, several countries are making it mandatory for their populace to wear face masks in public places for protection. Globally, millions of PPE are being produced and consumed daily for protection against the deadly COVID-19 virus.

Consequently, the unusual massive use of PPE to combat the pandemic has created an unusual demand increase, resulting in enormous supply chain disruptions. According to the WHO (2020a), the estimated monthly needs of PPE for healthcare professionals are 89 million medical masks, 76 million gloves and 1.6 million goggles. Plastic, a vital component of medical equipment, has continued to be a crucial material in PPE production and in the multi-disciplinary collaboration to end the pandemic (Prata et al., 2020).

The increased use of plastic PPE has inadvertently produced a corresponding increase in the waste generated. The increased demand for plastic packaged products through food delivery services and groceries has also increased plastic waste immensely (Vanapalli et al., 2020). Plastics have revolutionised the world, contributing greatly to the health sector through food safety and disposable medical equipment, but the indiscriminate use and waste mismanagement of the material have resulted in prevalent environmental contamination. The sheer mismanagement of non-biodegradable plastic makes the resource harmful to the environment (Borg, 2020).

More than ever before, the increased reliance on plastics for safety and hygienic purposes due to the COVID-19 pandemic has further exposed the vulnerability of the global system to resource constraints and proper waste management. Therefore, this study aimed to apply material flow analysis (MFA) to quantify the mass flow of COVID-19 plastic PPE in South Africa. The scope was to assess the plastic supply chain pre-COVID-19, estimate the mass flow of plastic PPE during the pandemic and explore the management of COVID-19 waste. Modelling the material flow will help develop a research database and an

understanding of the contribution of the PPE generated during the pandemic to the plastic footprint of the country and its impact on the environment.

## 2. Research stream on COVID-19, plastic PPE and waste management

A review of studies on the nexus between COVID-19 and plastic PPE management was conducted for an understanding of the existing body of knowledge and confirm the research direction for this study. The literature review was performed between 10 and 17 November 2020.

Firstly, research articles related to the research topic of interest on COVID-19 and the environment were retrieved from the Scopus database by typing in a combination of words in the database search engine. The search keywords were: "COVID-19 AND/OR PPE", "COVID-19 AND/OR plastics", "COVID-19 AND/OR waste", "COVID-19 AND/OR waste management" and "COVID-19 AND/OR material flow analysis". The resulting papers were further narrowed by excluding those relating to medical and nursing research.

The search exercise produced 702 articles. In order to further refine the selection of articles for the research focus, the retrieved articles were screened by reading the title, keywords, combination of words and abstract, and also by assessing the full text when in doubt, an approach similar to that described by Shakil et al. (2020). This further screening produced 21 research articles specifically relevant to this study. Furthermore, by applying thematic network analysis (Attride-Stirling, 2001) for further assessment, these selected articles were classified into five research themes using the keyword codes: resource, policies, material flow, waste management and environmental footprint. Lastly, the selected articles under the different research themes were analysed in detail. The classification and analyses of these studies, under different themes, are presented in Table 1.

Methodologically, almost all the articles analysed were based on descriptive study and perspectives, except those by Nzediegwu and Chang (2020) and Sangkham (2020), which involved mathematical calculations of the estimated daily face mask usage in some selected countries (with confirmed cases of COVID-19) in Africa and daily face mask use and medical waste disposal in Asian countries, as part of their descriptive narrative. The study by Urban and Nakada (2020) was on quantitative analysis of the disposable masks in state capital cities in Brazil.

Considering the recommendations for further research, in order to establish more knowledge and substantive results on COVID-19 related PPE and waste management, a number of future research works were

**Table 1**  
Thematic analysis of COVID-19 related studies on plastics, PPE and waste management.

Research themes	Resource	Policies	Material flow	Waste management	Environmental footprint
References	Rowan and Laffey (2020a, 2020b)	Patrício-Silva et al. (2020); Prata et al. (2020); Singh et al. (2020)	Dente and Hashimoto (2020)	Rowan and Laffey (2020b); Urban and Nakada (2020); Vanapalli et al. (2020); Klemes et al. (2020a); Di Maria et al. (2020); Rhee (2020); Prata et al. (2020); Shammi and Tareq (2020); Singh et al. (2020); Fan et al. (2020); Zand and Heir (2020a, 2020b); Sharma et al. (2020); Nzediegwu and Chang (2020); Fadare and Okoffor (2020); Ryan et al. (2020); Sangkham (2020)	Klemes et al. (2020a, 2020b)
Research findings	Shortage of PPE; countries are reprocessing and reusing PPE; improved stock management required	Policies targeted at reducing or banning single-use plastics in some countries were withdrawn or suspended	Uncertainty about the total impact of COVID-19 on resource and waste management, and the dynamics of material flow	Increase in plastic PPE waste generated impacted the waste management system; more waste is landfilled as recycling has been suspended	The increase in PPE use and waste treatment has brought about corresponding increase in environmental impact (plastic footprint and plastic waste footprint)
Further research (gaps)	Use of real-time data analytics to overcome the problems of critical shortage of PPE in the supply chain	Improved policies and regulations to manage plastic uses and reduce waste, efficient technologies and sustainable product	Better modelling of material flows; use of MFA, life cycle assessment, network analysis to analyse the impacts of the pandemic	Analysis of long-term impact and techno-economic assessment of waste and waste management planning and tools	Environmental sustainability of plastic PPE; microplastic environmental pollution post-COVID-19; development of reusable PPE

suggested by the reviewed studies as outlined in Table 1. Generally, they all queried the unusual flow and corresponding consequence of the on-going and increasing consumption of PPE during this period. To further examine the relationship between COVID-19 and the environment, this study considered the research gaps/further research particularly suggested by Dente and Hashimoto (2020), i.e. MFA, the theme with the least percentage of studies. Specifically, they recommend the application of analytical tools such as MFA, life cycle assessment, network analysis, etc. to wholly understand the outcomes of the COVID-19 pandemic. However, they caution that the development of such analyses could depend on the capacity to collect unconventional data. Consequently, the knowledge contributed by the selected COVID-19 studies with respect to the different life cycle phases of an MFA was analysed and is set out in Table 2.

**Table 2**  
Contributions of COVID-19 related studies to life cycle phases of MFA of a country.

Life cycle phase	Reference	Contribution
Production	Patrício-Silva et al. (2020); Rowan and Laffey (2020a, 2020b); Fadare and Okoffor (2020); Dente and Hashimoto (2020); Sharma et al. (2020)	<ul style="list-style-type: none"> <li>The pandemic caused challenges for plastic PPE production due to increased demand.</li> <li>A resilient localised supply chain is required to combat future PPE shortage crisis.</li> <li>Changes in medical practice will result in high demand and production of PPE post-COVID-19.</li> </ul>
Consumption	Klemes et al. (2020a, 2020b); Fan et al. (2020); Patrício-Silva et al. (2020); Zand and Heir (2020a); Nzediegwu and Chang (2020); Rowan and Laffey (2020a, 2020b); Sangkham (2020)	<ul style="list-style-type: none"> <li>Plastic use for medical purposes has massively increased, especially PPE consumption.</li> <li>PPE is made for single use, making reprocessing challenging.</li> <li>The number of usages and washing/disinfection could greatly affect the total environmental footprint.</li> <li>Monthly estimated 129 billion face masks and 65 billion gloves are being consumed globally.</li> </ul>
Waste management	Patrício-Silva et al. (2020); Rowan and Laffey (2020b); Urban and Nakada (2020); Vanapalli et al. (2020); Klemes et al. (2020a, 2020b); Di Maria et al. (2020); Rhee (2020); Prata et al. (2020); Shammi and Tareq (2020); Singh et al. (2020); Fan et al. (2020); Zand and Heir (2020a, 2020b); Sharma et al. (2020); Nzediegwu and Chang (2020); Fadare and Okoffor (2020); Ryan et al. (2020); Sangkham (2020); Dente and Hashimoto (2020)	<ul style="list-style-type: none"> <li>COVID-19 pandemic is expected to cause changes in waste composition, amount, disposal frequency and timing, distribution and risk of infection.</li> <li>Developing countries are engaging in poor waste disposal and management activities, including direct landfilling or open burning, whereas developed countries have better waste management system.</li> <li>The crisis has impacted the plastic recycling industry regarding lack of operations and less recycling collection, thus increasing landfilling and pollution.</li> <li>Proper healthcare waste management includes effective identification, collection, separation, storage, transportation, treatment and disposal.</li> <li>Treatment includes incineration, sterilisation, autoclaving, microwave, chemical disinfection, thermal inactivation and irradiation.</li> </ul>

Table 2 shows that there are a number of challenges, current and legacy, arising from the use of PPE. Therefore, based on the research gaps highlighted by Dente and Hashimoto (2020), it is important to understand the amount of plastic flow in a country in order to be able to support more informed decisions about product availability and waste management.

### 3. Methodology

The motivation for this study was to quantify plastic material flows to help inform material supply risks within the South African economy pre- and during the COVID-19 pandemic. The focus was not on cradle-to-grave life cycle impacts of products. MFA was selected as the most common method to map resource flows and optimise resource management (Montangero, 2007). It allows wastes to be monitored, the efficiency of the use of material resources and material flow management within a defined system and boundary to be evaluated and material supply risks to be assessed. MFA can contribute into life cycle assessment by providing an in-depth snapshot in time of the material inventory. In this study the mass flows of COVID-19 related PPE were evaluated during the 2020 pandemic, and also plastics for the reference year of 2019 within the system boundaries of production, procurement, consumption, imports, exports and waste management in South Africa, using the MFA approach. The reference year 2019 for the plastic flow was selected for analysis on the basis that it had the most recent reported material flow data before the advent of the COVID-19 pandemic.

#### 3.1. Method description

MFA is a modelling approach used in quantifying the flows of elements, substances, materials and products within a system or value chain (Brunner and Rechberger, 2004). The system comprises the material flows, stocks and the processes (Baccini and Brunner, 1991). The balance of the system is governed by the law of mass conservation. The mass balance principle assesses the total mass of the inputs and outputs associated with the system, and also the remaining mass (material) stocks in the system for the reference year under analysis, as shown in Eq. (1):

$$\sum M_{input} = \sum (M_{output} + M_{stock}) \quad (1)$$

where  $M_{input}$  is the total mass of material inputs,  $M_{output}$  is the total mass of material outputs and  $M_{stock}$  is the total mass of material stocks in the system.

In relation to the study's assessment of the mass flows of COVID-19 PPE during the pandemic and plastic flow for 2019, the production and imports in the system describe the inputs; the consumption and exports depict the output, and stocks describe the storage, as shown in Eq. (2):

$$\sum M_{stock} = \sum M_{production} + \sum M_{import} - \sum M_{consumption} - \sum M_{export} \quad (2)$$

where  $M_{production}$  is the total mass of PPE/plastic produced,  $M_{import}$  is total mass of PPE/plastic imported,  $M_{consumption}$  is the total mass of PPE/plastic consumed,  $M_{export}$  is the total mass of PPE/plastic exported and  $M_{stock}$  is the total mass of PPE/plastic stocks in the system.

In modelling the plastic material flow using the Sankey diagram for 2019, the following assumptions were made:

- Production waste: About 1.12 kg resin produces 1 kg plastic product (Horowitz et al., 2018), and plastic production has a material efficiency of over 80% (BKV, 2010).
- Waste to landfill: About 90% of plastic waste in South Africa ends up in landfills (SAPRO, 2020b)
- Other unavailable data was estimated using the mass balance principle.

**Table 3**  
Model and criteria for qualitative estimation of data uncertainty, adapted from DEPA (2019).

Data source	Direct availability	Indirect availability	Estimation	Mass balance
Qualitative degree of uncertainty Description	Small Data collected directly from statistic	Medium Data collected from a proxy statistic (such as monetary equivalency)	Large Projection estimates based on concrete data	Extra large Flow computed by balancing corresponding inputs and outputs

### 3.2. Data sources and reliability

Multiple sources were used for the collection and collation of the data to assess the plastics flow for 2019 and COVID-19 material flow. Following the process illustrated by Babayemi et al. (2019), the plastic trade (import and export) data for 2019 was estimated by synthesising trade data from the Comtrade database of the United Nations (UNComtrade, 2020) using harmonised system (HS) codes. The primary plastics (imports/exports) were calculated as the summation of all plastics in primary form, from the category HS 3901 to HS 3914. The plastic products (imports/exports) are a summation of all plastics in product form, from HS 3915 to HS 3926.

Therefore, assessing the reliability of the flow data used for this study was critical in considering that the data sources had different degrees of quality and varied origins. The qualitative estimation of uncertainty approach, adopted from DEPA (2019) and modified with respect to Galafassi et al. (2019), was applied to the flow data to determine its reliability and assess the uncertainty of the flow model. The qualitative estimates were based on the data source used, which could be either direct availability, proxy availability, estimation, mass balance or

unknown. The model and criteria for the qualitative estimation of the degree of uncertainty in the data sources are presented in Table 3.

Accordingly, the data source and reliability for the respective flows in the different phases of the value chain for plastics (in 2019) and the COVID-19 related PPE (masks) (as of May 2020) were analysed and are presented in Tables 4 and 5, respectively.

The robustness of any analysis on material flows is directly related to the availability and quality of the data used. This study was limited by data availability, similar to a substantial number of COVID-19 studies published. As shown in the reviewed studies above, many COVID-19 related articles are descriptive study, published within a short period, and can be interpreted subjectively due to data constraints. In addition, considering that the pandemic is still ongoing, accessing and assessing the limited data and the numerous data sources in order to conduct different analyses relating to the unprecedented COVID-19 pandemic is still quite challenging. As a result, Rowan and Moral (2021) posit that while systematic reviews of available data and information can be allowed for now to guide short-term policies, the effective solution to these challenges will involve collective, organised, controlled and randomised trials to enable predictive modelling and produce data with high reliability.

**Table 4**  
Flows, data sources and reliability for plastics in 2019.

Flow	Data source			Reliability
	Data source 1	Data source 2	Data source 3	
Production				
Domestic primary plastic	1,380,000 (EUROMAP, 2016)			Medium reliability (M). Data was an estimation, based on concrete data of previous annual plastic production and assumptions. Medium reliability (M). Data was an estimation from monetary equivalent.
Domestic plastic product	2,195,162 (StatsSA, 2020a)			
Consumption				
Primary plastic consumed (virgin)	1,504,000 (Plastics SA, 2020)	1,504,000 (SAPRO, 2020a)	1,504,000 (Bizcommunity, 2020)	Plastics SA (2020) – High reliability (H). Both flow values from this data source were based on empirical data and surveys. Also, Plastics SA is a credible data source for the South African plastics industry.
Primary plastic consumed (recycled)	337,745 (Plastics SA, 2020)	337,745 (SAPRO, 2020a)	337,745 (Bizcommunity, 2020)	
Trade				
Import primary plastic	813,274 (UNComtrade, 2020)			High reliability (H). Mass flow values were from empirical data and survey.
Import plastic product	436,831 (UNComtrade, 2020)			
Export primary plastic	357,789 (UNComtrade, 2020)			
Export plastic product	190,630 (UNComtrade, 2020)			
Waste management				
Plastic waste generated		1,855,436 (Mass balance)		Low reliability (L). Flow computed by balancing corresponding inputs and outputs using Sankey diagram software.
Plastic waste landfilled		1,669,892 (Mass balance)		
Plastic waste for recycling	352,500 (Plastics SA, 2020)			High reliability (H). Mass flow estimates were based on empirical data and surveys. Plastics SA is credible as a data source and an acknowledged representative of all sectors of the South African plastics industry.
Plastic waste import	17,000 (Plastics SA, 2020)			
Plastic waste export	14,755 (Plastics SA, 2020)			



**Table 5**  
Flows, data sources and reliability estimation for COVID-19 related PPE (masks).

Flows	Data source	Reliability
Production	DTIC (2020a, 2020b)	High reliability (H). Flow value was based on empirical data and surveys.
Consumption	Mass balance	Low reliability (L). Flow computed by balancing corresponding inputs and outputs using Sankey diagram software.
Import	Van Rensburg (2020)	Medium reliability (M). Data reported by different media organisations (GroundUP and News 24) and not scientific, although credible organisations.
Export	AmaBhungane (2020)	Medium reliability (M). Data reported by a media investigative organisation and not scientific, although a credible organisation.
Waste generated	Mass balance	Low reliability (L). Flow computed by balancing corresponding inputs and outputs using Sankey diagram software.

#### 4. Results: material flow of plastics pre-COVID-19 pandemic

The relationship and breakdown of all the flows and processes in the life cycle phases within the system boundaries in the flow model are shown in Table 6.

The mass flow of plastic in the supply chain of South Africa in 2019 was modelled based on mass flow balance and is presented in the Sankey diagram in Fig. 1, with flows and processes. The volume of each flow corresponds to the width of the flow arrows in the figure. In addition, the flows are colour-coded to represent data uncertainty.

In South Africa in 2019 the domestic production of primary plastic was estimated at 1,380,000 tons (EUROMAP, 2016). Similarly, the domestic production of plastic products amounted to 2,195,162 tons (StatsSA, 2020a), with the mass flow comprising primary plastics of both virgin and recycled resins. For a population estimate of about 58,775,022 (StatsSA, 2019), the annual per capita production for primary plastic and plastic products in 2019 was 24 kg/capita and 37 kg/capita, respectively.

At the consumption phase, the cumulative use of primary plastic reached an estimated 1,841,745 tons in 2019, amounting to 31 kg/capita annually. This flow consisted of both virgin primary plastic at 1,504,000 tons (Plastics SA, 2020) and recycled primary plastic at 337,745 tons (Plastics SA, 2020). The apparent consumption of plastic products in 2019 was estimated at 2,441,363 tons (42 kg/capita), using the mass balance principle.

Plastic imports contributed a sizable share to plastic consumption in South Africa in 2019, with about 813,274 tons and 436,831 tons (UNComtrade, 2020) imported in primary plastic and plastic product form, respectively, totalling 1,250,105 tons. Equally, the cumulative plastic exports amounted to 548,419 tons, with primary plastic and

**Table 6**  
Processes and mass flow of plastic in 2019 (tons).

	Primary plastic	Plastic product	Total
Production	1,380,000 (EUROMAP, 2016)	2,195,162 (StatsSA, 2020a)	3,575,162
Consumption (Virgin)	1,504,000 (Plastics SA, 2020)		1,504,000
Consumption (Recycled)	337,745 (Plastics SA, 2020)		337,745
Consumption		2,441,363 (Mass balance)	2,441,363
Imports	813,274 (UNComtrade, 2020)	436,831 (UNComtrade, 2020)	1,250,105
Exports	357,789 (UNComtrade, 2020)	190,630 (UNComtrade, 2020)	548,419
Stock-in	331,485 (Mass balance)	585,927 (Mass balance)	917,412
Stock-out	616,836 (Mass balance)		616,836
Waste generated			1,855,436 (Mass balance)
Waste landfilled			1,669,892 (Mass balance)
Waste for recycling			352,500 (Plastics SA, 2020)
Waste imports			17,000 (Plastics SA, 2020)
Waste exports			14,755 (Plastics SA, 2020)
Production waste			263,419 (Computation)

plastic products having shares of 357,789 tons and 190,630 tons, respectively (UNComtrade, 2020). This puts the country at an overall trade deficit of 701,686 tons, with primary plastic and plastic products contributing 455,485 tons and 246,201 tons, respectively.

An apparent 1,855,436 tons of plastic waste were generated in the country in 2019, amounting to 32 kg/capita annually. Further assessment of this waste flow shows that about 1,669,892 tons were landfilled, 352,500 tons (Plastics SA, 2020) were recovered for recycling and an apparent 113,463 tons were undisposed (litter). The mass flows for both the landfilled and undisposed plastic waste were estimated using the principle of mass balance, in accordance with the assumptions outlined above. The statistical reports for this flow data estimated were not available for South Africa for the reference year. Similarly, the mass flow for the production waste was estimated at 263,419 tons, using the principle of material efficiency for plastic production as stated in the assumptions.

Furthermore, the MFA modelling led to a computed plastic recycling rate of 19% for South Africa for the reference year of 2019, as against the reported input recycling rate of 45.7% (Plastics SA, 2020). The Plastics SA report computed the recycling rate based on the assumption that about 60% of the total plastic (polymer) consumed yearly becomes waste. However, in the study reported on in this paper, the calculation was based on the comprehensive analysis of waste materials in the system as depicted by the MFA and Sankey flow diagram, i.e. the actual flow estimates for the total plastic waste generated (1,464,818 tons) and the plastic waste recovered for recycling (local recycling and waste exports for recycling) (352,500 tons). According to this calculation, approximately 76% of the total plastics consumed annually ends up as plastic waste, which is higher than the assumed value of the Plastics SA statistical report. Therefore, re-evaluating the 60% plastic waste assumption is important in order to prevent the under-estimation of the total plastic waste generated in the country and to accurately evaluate the positive impact of the recycling sector on the circular economy of South Africa.

#### 5. PPE material flows and inventory during COVID-19 pandemic

The volume of COVID-19 PPE masks flowing through the value chain during the pandemic was quantified using the MFA approach. In modelling the mass flow of PPE in 2020 for South Africa, the COVID-19 PPE was analysed and estimated from January to December 2020. While the pandemic intensified in March 2020, the estimation was computed from January 2020 to ensure enough representation of data (as there is limited data availability), and also for easy comparative analysis of the PPE flow results with those for plastic. The average weight of a PPE (mask) is 0.002 kg (actual measurement).

The following assumptions and estimations were made from different statistical reports:

Production:

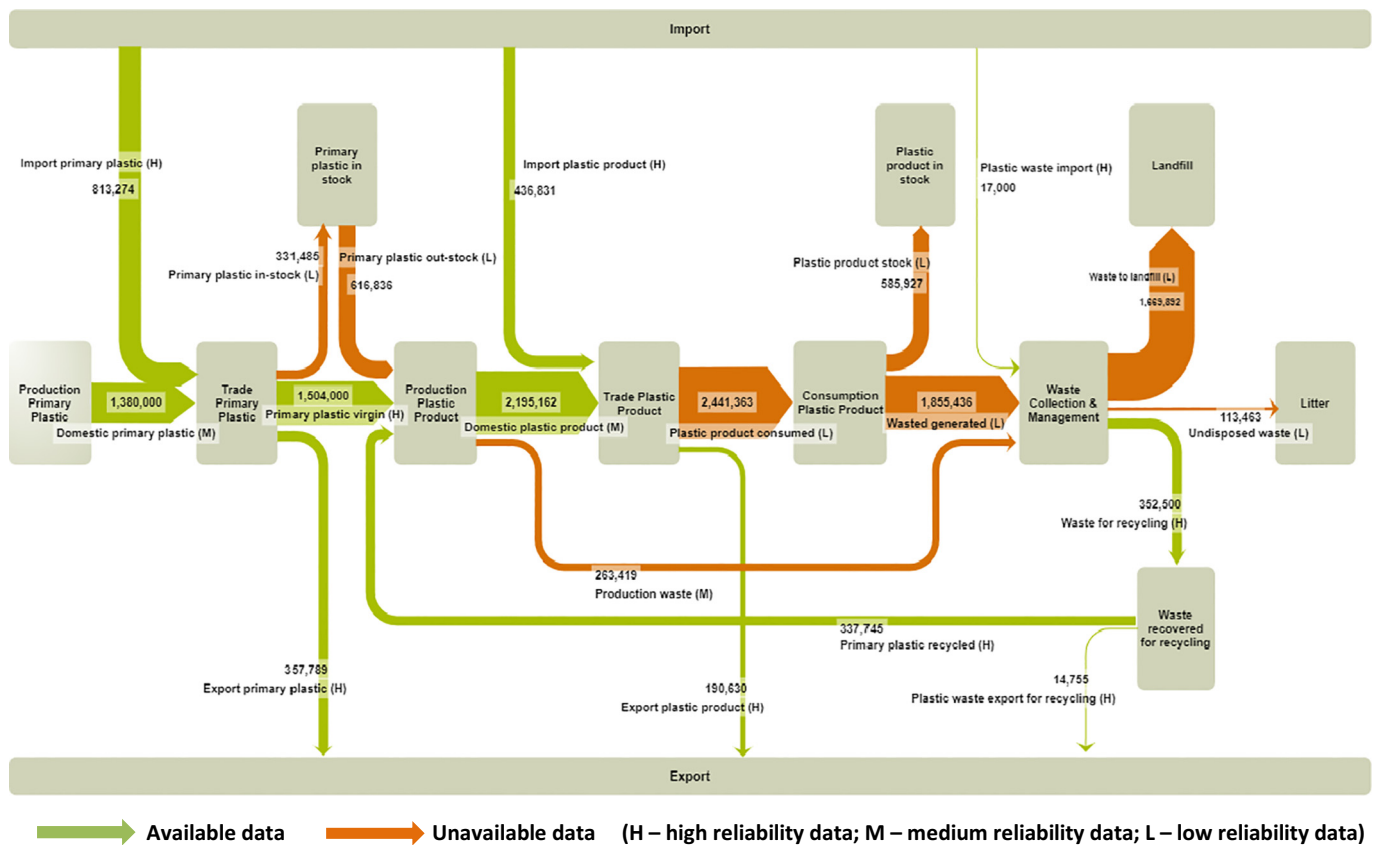


Fig. 1. Sankey diagram of plastic flows and stocks in South Africa in 2019 (tons).

- According to the Department of Trade, Industry and Competition, estimated monthly production capacity of 18,352,225 face masks commenced in May 2020 (DTIC, 2020a). This monthly mass flow supposedly continued up to December 2020.
- Considering that the monthly face mask production capacity increased by 17 million in May 2020 (DTIC, 2020b) in response to the intensity of the COVID-19 pandemic, the estimated monthly production capacity of face masks before May 2020 (i.e. January, February, March, April) was assumed to be 1,352,225.

Imports:

- As at May 2020, South Africa initiated PPE imports of 50,200,000 masks (Van Rensburg, 2020).
- The massive ramp-up of local production (DTIC, 2020a) was expected to have an effect on PPE imports after May 2020. As a result, PPE imports were not considered for the rest of the year.

Exports:

- The monthly volume of PPE (mask) exports for 2020 released by AmaBhungane (2020) shows that the units of 90,720, 540,590 and 314,968 masks were exported for January, February and March 2020, respectively.
- Masks were apparently not exported from April to December, considering the ban on exportation of the product on 27 March 2020 by the government when the state of disaster and lockdown were declared (Van Rensburg, 2020).

Furthermore, similar assumptions made for plastics were applied to estimate the volume of PPE waste generated (i.e. 76% of PPE consumed becomes waste) and PPE waste landfilled (i.e. approximately 90% of PPE waste ends up in the landfill (SAPRO, 2020b)). The principle of mass

balance was applied to estimate the unavailable mass flow of PPE consumed. The mass flow for waste recycled was not quantified considering that recycling operations were suspended during the lockdown in the country, as also reported in many countries (Prata et al., 2020; Urban and Nakada, 2020).

The estimated monthly production and export of PPE (masks) from January to December 2020 are illustrated in Fig. 2.

The breakdown of the units and mass flows of the PPE through the supply chain of the country is presented in Table 7.

The schematic representation for the MFA of the COVID-19 PPE (masks) in South Africa from production to waste management during the pandemic is shown in Fig. 3.

In analysing the material flow for COVID-19 related PPE (masks) for South Africa's population estimates of 59,620,000 (StatsSA, 2020b) in 2020, the domestic production of PPE masks at the production phase was calculated at 304,453 kg, amounting to 0.005 kg/capita. The consumption phase indicates that the apparent mass of masks is about 402,960 kg. This mass flow, estimated using the principle of mass balance, amounted to 0.007 kg/capita of masks consumed.

Regarding COVID-19 PPE (mask) trade, the cumulative mass flow of PPE imports was approximately 100,400 kg (Van Rensburg, 2020), whereas that of PPE exports was estimated at 1893 kg (AmaBhungane, 2020). Interestingly, the PPE imports contributed substantially to the consumption pattern in South Africa. Due to the enormous trade imbalance, the country recorded a trade deficit of 98,507 kg. This substantial trade deficit represents about 98% of the total PPE imported for the period analysed. Approximately 306,250 kg of COVID-19 PPE (mask) waste was generated, amounting to 0.005 kg/capita. The waste mass flow was derived using the mass balance principle, in line with the assumptions outlined earlier.

The results of both the plastic flows in 2019 and PPE (mask) flows were assessed in terms of the annual capita flow, to understand the

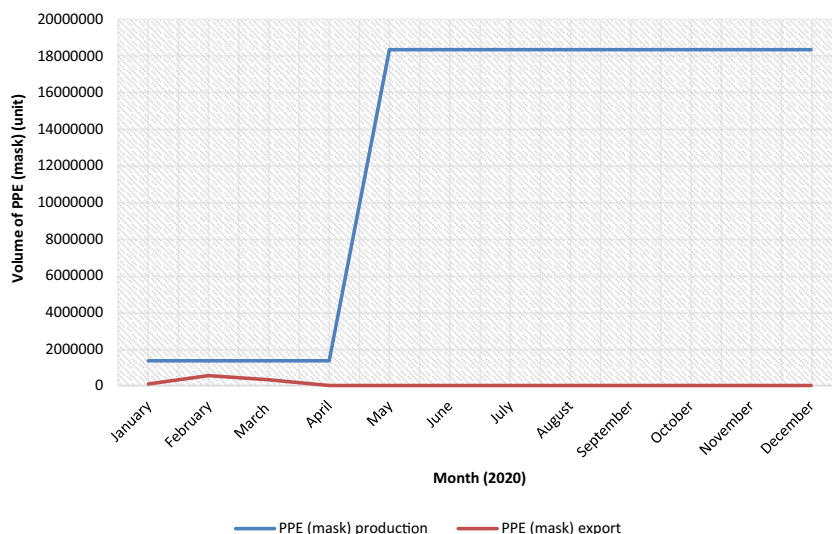


Fig. 2. Estimated monthly production and export of PPE (masks) in 2020.

mass weight impact of the PPE on the existing plastics system, especially the addition of the unusual PPE waste generated to the existing plastic waste management system in South Africa during this pandemic. The comparative analysis is presented in Table 8.

The assessment of the two material flow results above indicates that the PPE (mask) waste generated during the COVID-19 pandemic is apparently low when analysed in terms of the mass compared to the national plastic. However, the number of pieces (153,125,123 units) is high. This suggests the mass of the COVID-19 PPE waste is not the bigger challenge, but rather the quantity in loose units or form, which are already being disposed of indiscriminately in South Africa (Beangstrom, 2020). This may further spread the infection of the coronavirus in communities, thereby increasing the number of cases in the country. The possible solution to this challenge is the packing or compacting of the PPE waste to reduce the number of contaminations.

6. Sensitivity analysis

Due to the use of a large amount of data with uncertainty in the MFA conducted, sensitivity analysis was carried out for the plastics and PPE (mask) material flow results. For both materials, the sensitivities of their consumptions to variations in production, imports and exports were conducted. Successive variance in input values of ± 10%, ± 20% and ± 30% were applied. The sensitivities for plastic material consumption in 2019 and PPE masks in 2020 are presented in Figs. 4 and 5, respectively.

From Figs. 4 and 5, the estimation of plastics consumed is most sensitive to the estimation of plastics produced. The sensitivity ratios of plastics consumption to the input variables of plastics production, imports and exports are 0.84, 0.29 and 0.13, respectively. The sensitivity ratios of PPE consumption to the input variables of PPE production, imports and exports are 0.76, 0.25 and 0.01, respectively. The plastics and PPE consumption is most sensitive to the value of production and least sensitive to the quantity of exports. This is reassuring since the quantity

Table 7 Unit and mass flow of PPE (masks) in 2020.

Flows	PPE (unit)	PPE (kg)
Production	152,226,700 (DTIC, 2020a, 2020b)	304,453
Consumption	201,480,425 (Mass balance)	402,960
Imports	50,200,000 (Van Rensburg, 2020)	100,400
Exports	946,275 (AmaBhungane, 2020)	1893
Waste generated	153,125,123 (Estimated)	306,250
Waste landfilled	137,812,611 (Estimated)	275,625

of plastic produced is a flow parameter which had relative low uncertainty as reported earlier in Figs. 1 and 3 based on the scheme shown in Table 3.

7. Regulated PPE waste management

The start of the COVID-19 pandemic added to the complexities of plastic waste management globally. The unusual consumption of PPE during this unanticipated pandemic has created corresponding waste challenges. As shown by the WWF (2020) report, there is a possibility of the introduction of over 10 million masks in the environment on a monthly basis with an improper disposal of only 1%. The unexpected shift in waste volume and composition underscores the necessity for a waste management system that is dynamically responsive.

As expected, used PPE and other related COVID-19 waste that has been dumped randomly into the ecosystems in South Africa is already being discovered. COVID-19 related used PPE is regarded as medical waste (UNEP, 2020), which is frequently pathogen-contaminated and must be handled as hazardous waste in order to destroy any residual pathogens (Windfeld and Brooks, 2015). Therefore, these used PPE and other wastes from medical facilities must follow regulated disposal and management guidelines (Rhee, 2020). They should be appropriately identified, collected, disposed of, transported and treated to ensure effective management (UNEP, 2020). Most countries have introduced new guidelines to manage wastes related to COVID-19. The guidelines were compiled from the present knowledge and understanding of the COVID-19 pandemic and existing practices in the management of healthcare waste.

For South Africa, dynamic and responsive measures are being taken by the government and related stakeholders to manage used PPE and other healthcare wastes effectively and efficiently, considering that infectious waste masks, gloves, etc. without proper management and treatment can result in viral transmission (Shah et al., 2020). The guidelines for the waste management of healthcare waste in South Africa are governed by the COVID-19 National Public Hygiene Strategy and Implementation Plan developed by the Department of Health (DOH, 2020).

While the situation of the pandemic still continues to develop and is far from over, this study analysed and benchmarked the healthcare/ COVID-19 related waste management guidelines (under different circumstances) for countries against the WHO guidelines, as presented in Table 9. These circumstances include guidelines introduced for waste generated in healthcare facilities and home quarantine. The assessment covered the used material life cycle of waste storage, transportation and treatment/disposal.



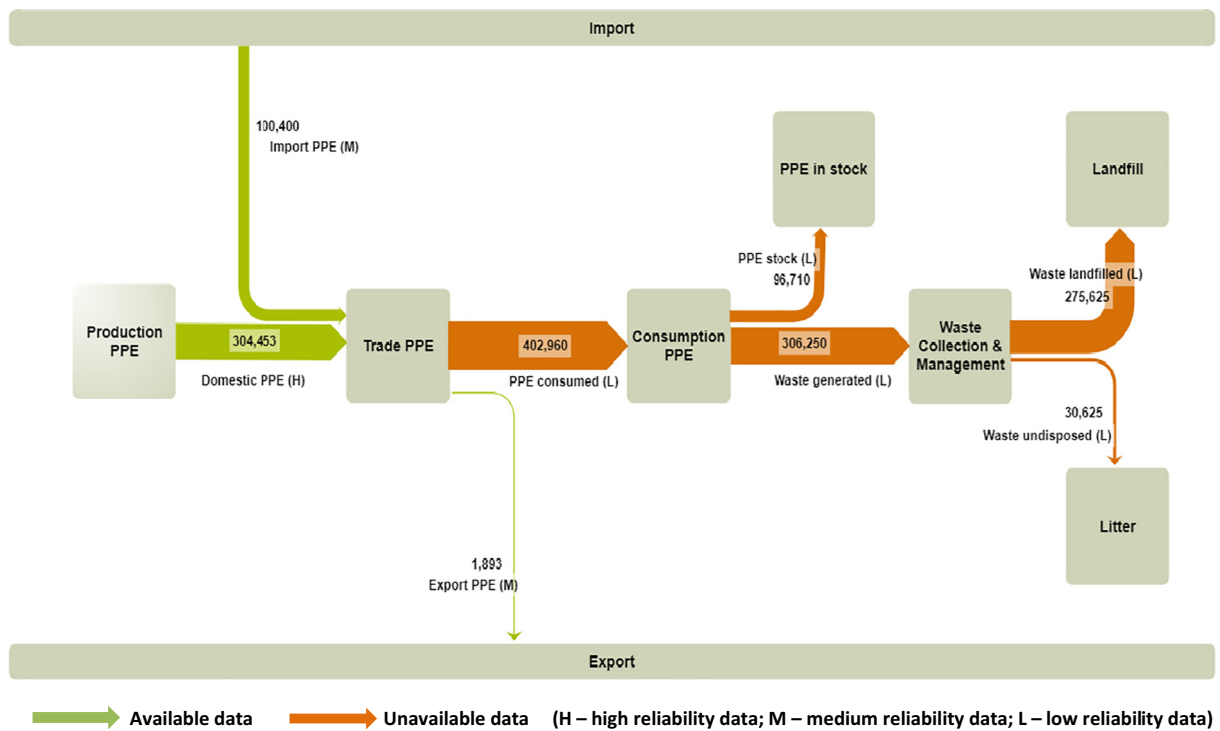


Fig. 3. Sankey diagram of PPE (mask) flows and stocks in South Africa in 2020 (kg).

As shown by the table above, the guidelines released by the WHO were an interim general guidance for countries to formulate their respective related national policy framework. The guidelines are largely generic and not detailed. For South Africa, the guidelines were built on existing provisions for healthcare waste management in the country. Largely, they contain adequate information, properly categorised for different settings or circumstances, and the guidelines on separation at source and storage are documented. The guideline document for the United States is brief and refers mostly to the existing provisions for healthcare and municipal waste in the country. The specific document lacks information on storage, transportation and treatment of the waste.

China issued waste management guidelines that generally provide for segregation and storage of the waste. Guidelines for transportation and treatment are not provided in the document. For India, the guidelines are very detailed and properly categorised for different circumstances. Colour codes for guidance are much more in use. Information regarding source separation and storage are well detailed, while transportation information is partly provided. The disinfection of bins is included in the document, unlike other countries. The document for the EU is brief and refers primarily to existing waste laws and provisions issued for the respective countries by the commission. The guidelines are expected to be practised in conjunction with the additional guidelines from member countries.

The national, provincial and local level of healthcare waste management will involve special managerial, operational and precautionary practices regarding the present pandemic, in addition to the usual measures for general healthcare and household waste management.

### 8. Policy implications and recommendations

Highlighting the spatial variation of the COVID-19 crisis across countries in Africa, with respect to the volume of PPE masks consumed and disposed of, the total daily consumption of face masks in Africa (some selected countries with COVID-19 cases) was estimated at 586,833,053 units as of May 2020 (Nzediegwu and Chang, 2020). This early research study applied a mathematical calculation (containing an arbitrary and subjective assumption data of average daily face masks per capita of 2 and face

mask acceptance rate of 80% for all the countries analysed) to estimate the number of face masks consumed by some selected countries with COVID-19 cases in Africa. It estimated that the largest volume of daily face mask use would be by Nigeria at 171,508,138 units, possibly since this is the most populated African country.

For South Africa, analysing the early study's estimated daily PPE mask consumption of 63,578,916 units (accounting for approximately 11% of the total daily consumption in the continent) along with the estimated annual PPE mask consumption of 201,480,425 units for 2020 computed by this present study, possibly confirmed the presumed apparent fact that the total daily PPE masks consumed in South Africa will continue to increase unusually as the current COVID-19 crisis lingers and the possibility of future waves exists.

Therefore, the surge in the supply of PPE in response to the unusual additional demand will necessitate a substantial increase in PPE manufacturing and distribution through the supply chain, thus necessitating localised and cost-effective production in the country. Investments in the research and development of circular products also need to be promoted, as innovations are required to improve on existing product designs. The current crisis is still mounting and the possibility of future waves should not be readily dismissed.

Furthermore, the waste management of used PPE and other COVID-19 related wastes is experiencing challenges in South Africa, as these wastes are found dumped randomly in the environment (Beangstrom, 2020). Incineration, landfilling and mechanical recycling are the most used applications in plastic waste management globally (Vanapalli

Table 8 Comparative assessment of mass flow of plastics in 2019 and PPE (masks) during COVID-19 (kg/capita).

Flows	Plastics	PPE (masks)
Production	61	0.005
Consumption	73	0.007
Imports	21	0.002
Exports	9	3.18E-5
Waste generated	32	0.005

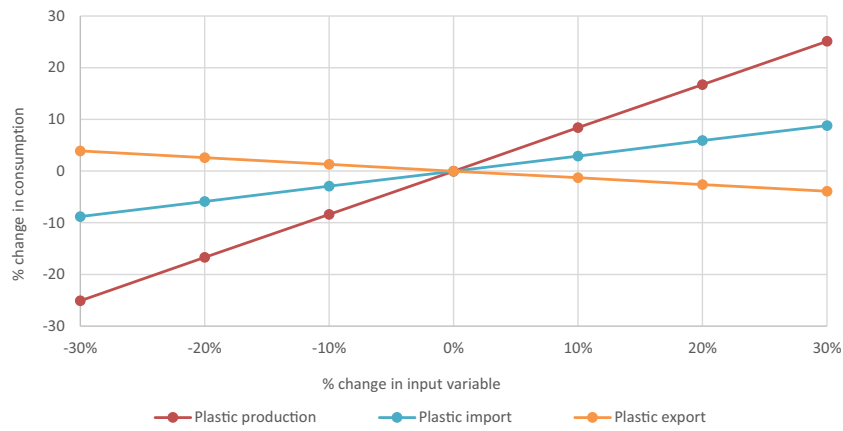


Fig. 4. Sensitivity of plastics consumption to variation in production, imports and exports in 2019.

et al., 2020), but these methods have their shortcomings in managing the challenges of plastic waste. With the increase in the waste volume being generated during this crisis, the situation has worsened.

The current crisis has negatively impacted the plastics recycling industry in the country with respect to lack of operations and reduced recycling collection. This has led to an increase in landfilling and pollution. Landfilling is the primary waste management solution in South Africa (WWF-SA, 2020). Most plastic PPE waste being collected through municipal waste management (formal) is expected to end up in landfills. However, the majority of these landfills are suspected to be operating outside of licensing conditions and do not meet compliance standards (WWF-SA, 2020), while about 69 landfills are unlicensed and are operating illegally (DEA, 2016). The only municipalities with substantial landfill airspace remaining include eThekweni Metropolitan Municipality in KwaZulu-Natal and the City of Ekurhuleni Metropolitan Municipality in Gauteng (DEA, 2018). The practice of open or uncontrolled waste dumping in landfills by most developing and underdeveloped countries leads to huge space constraints, open fires and leaching of harmful substances and chemicals, thereby contaminating the natural environment (Azoulay et al., 2019).

There should be special collection provision for waste that is infectious from home quarantined or specially designated places. Landfill facilities should be well controlled and secured. Personnel must be well trained in handling healthcare waste. The rapid and ongoing changes of the dynamics of the pandemic will require regular updating of the guidelines and policies in order to continually improve on ways to curtail the virus from spreading further.

Furthermore, in South Africa and other developing countries it is important to give adequate attention to the informal waste collectors, considering that they are among the most vulnerable population despite

the tangible contribution they make to the recycling sector. Options to consider are, for example, the provision of protective gear for this set of workers.

A long-term systematic analysis of the lasting impact of the COVID-19 pandemic on waste management systems and the environment is required. In formulating future disaster management plans and policy for the country, effective and broader waste management systems should be included. National, provincial and municipal policy guidelines and response measures for disaster waste management to tackle waste generation dynamics during a future crisis should be considered. This will enable a sustainable healthcare waste management system.

The authors acknowledge that the study on COVID-19 PPE waste was based on limited data sets given that the pandemic was still unfolding during the course of the study. Collective, organised, controlled studies will be required to improve the accuracy and integrity of COVID-19 PPE data. Furthermore, the authors recommend that both sensitivity analysis and uncertainty analysis be used to explore implications of estimated data. This is particularly important if the information is used to inform policy that will have an impact on society.

### 9. Conclusions

Considering the growing concern regarding the continued and increasing volume of plastic PPE waste being generated in South Africa in the context of the ongoing COVID-19 pandemic, this study provided quantitative insights into the mass flow of COVID-19 plastic PPE during this pandemic and that of plastic flows pre-COVID-19.

- Using MFA, the mass flow of plastics through the plastics supply chain was quantified for 2019 to provide knowledge for government and

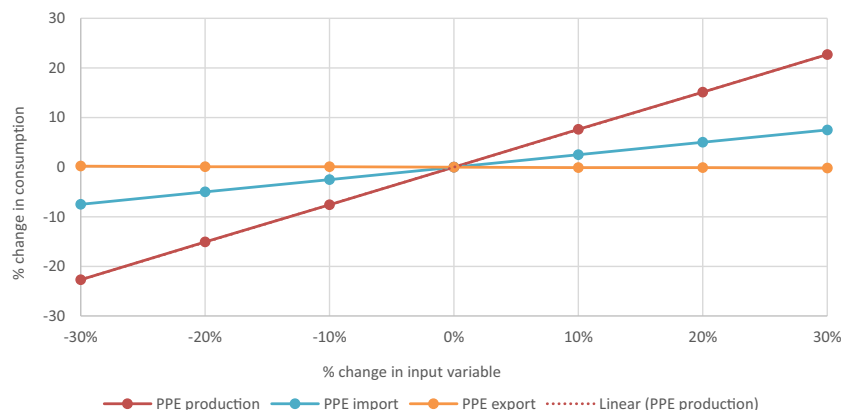


Fig. 5. Sensitivity of PPE (mask) consumption to variation in production, imports and exports in 2020.

**Table 9**  
Assessment of healthcare/COVID-19 waste management guidelines of some countries and agencies.

Country/agency	Guidelines	Assessment		
		Storage	Transportation	Disposal and treatment
World Health Organisation (WHO, 2020b)	Healthcare facilities <ul style="list-style-type: none"> <li>COVID-19 waste generated needs to be safely collected in assigned bags, treated on-site (preferably) or off-site and thereafter disposed of safely.</li> <li>Waste produced in the waiting areas or sections of healthcare facilities can be categorised as non-hazardous and disposed of using strong black bags.</li> <li>Proper and suitable PPE must be worn by all personnel in charge of healthcare waste management. Hand hygiene must be observed after the use of PPE.</li> </ul>	Guideline is adequate on segregation and storage at source of the waste	Lack of information on waste transportation	Lack of information
	Home quarantine/self-isolation <ul style="list-style-type: none"> <li>Waste produced needs to be packaged, collected and disposed of using strong black bags.</li> <li>Used tissues/materials for sneezing and coughing must be disposed of in a waste bag/bin immediately, and proper hand hygiene observed.</li> </ul>	Adequate for waste generated	Lack of information	Lack of information
South Africa (DOH, 2020)	Healthcare facilities <ul style="list-style-type: none"> <li>Healthcare waste safely disposed of in red liners using designated single-use box sets (marked "infectious waste") and properly sealed prior to internal collection.</li> <li>Yellow-coloured sharps container used for all sharps waste, and marked with: "Danger contaminated sharps" and bio-hazard symbol.</li> <li>Three-quarter full sealed box sets must be stored at central storage areas for collection by officers or designated service providers.</li> <li>Treatment and disposal of waste must be conducted at a licensed healthcare waste treatment and disposal facility.</li> </ul>	Adequate, fairly detailed information provided in the guideline	Lack of information	Inadequate information provided in the guideline
	Home quarantine/self-isolation <ul style="list-style-type: none"> <li>Waste in contact with suspected/confirmed cases of COVID-19 must be stored in leak-proof and heavy-duty disposable plastic bags or bins.</li> <li>Waste bag must be tied when full.</li> <li>Full bag or bin must be stored separately and securely from other domestic waste for collection by the relevant municipality.</li> </ul>	Adequate guideline	Lack of information	Lack of information
United States (USOSHA (2020)	Healthcare facilities <ul style="list-style-type: none"> <li>Waste suspected or confirmed to be infected with COVID-19 only requires the usual precautions applied in protecting solid waste and wastewater management workers against hazards inherent in their regular job responsibilities.</li> <li>Municipal solid waste suspected or confirmed to be infected with the virus must be managed in the same way as other non-contaminated municipal waste, although strict PPE use, administrative and engineering controls and safe work practices must be followed.</li> </ul>	Lack of information	Lack of information	Lack of information
	Healthcare facilities <ul style="list-style-type: none"> <li>Medical infectious waste produced while preventing and treating pneumonia epidemics must be packed using specialised bags or containers, and tagged with warning symbols.</li> <li>Priority must be given when collecting and disposing such medical infectious waste by the disposal units.</li> <li>Hazardous, industrial, domestic and other waste facilities for incineration of epidemic medical waste must be operated in compliance with the regulations of professional health authorities.</li> <li>The collection, storage, transfer and disposal of such medical waste must support the protection of personnel hygiene.</li> </ul>	Adequate guideline	Lack of information	Inadequate information provided
China (MEE, 2020)	Home quarantine/self-isolation <ul style="list-style-type: none"> <li>Used masks must be collected in special waste plastic bags or bins before disposal.</li> <li>Used medical masks by healthy people must be disposed of together with domestic waste.</li> </ul>	Guideline is adequate	Lack of information	Lack of information
	Healthcare facilities <ul style="list-style-type: none"> <li>Dedicated bins and trolleys labelled COVID-19 waste should be used.</li> <li>Use of 1% sodium hypochlorite to disinfect the outer and inner surface of the bin and trolley.</li> <li>The collection bins should be colour-coded for proper waste segregation.</li> <li>General solid waste must be collected in separate bins.</li> <li>Used face shield, apron, goggles, nitrile gloves and plastic coverall should be collected in red bags.</li> <li>Used mask, gown, tissues, toiletries, shoe cover, head cover and non-plastic coverall must be collected in yellow bags.</li> <li>Use dedicated vehicle to collect COVID-19 ward waste.</li> </ul>	Detailed and adequate contained in the guideline	Adequate guideline	Lack of information
India (CPCB, 2020)	Healthcare facilities <ul style="list-style-type: none"> <li>Dedicated bins and trolleys labelled COVID-19 waste should be used.</li> <li>Use of 1% sodium hypochlorite to disinfect the outer and inner surface of the bin and trolley.</li> <li>The collection bins should be colour-coded for proper waste segregation.</li> <li>General solid waste must be collected in separate bins.</li> <li>Used face shield, apron, goggles, nitrile gloves and plastic coverall should be collected in red bags.</li> <li>Used mask, gown, tissues, toiletries, shoe cover, head cover and non-plastic coverall must be collected in yellow bags.</li> <li>Use dedicated vehicle to collect COVID-19 ward waste.</li> </ul>	Detailed and adequate contained in the guideline	Adequate guideline	Lack of information

Table 9 (continued)

Country/agency	Guidelines	Assessment		
		Storage	Transportation	Disposal and treatment
European Union (European Commission, 2020)	<ul style="list-style-type: none"> <li>Vehicle should be sanitised with sodium hypochlorite or any appropriate chemical disinfectant after every trip.</li> </ul> Home quarantine/self-isolation	Information is adequate	Lack of information	Lack of information
	<ul style="list-style-type: none"> <li>General household waste must be collected in bags.</li> <li>Generated waste such as used face masks, tissues, gloves, syringes infected with the body fluids or blood of a COVID-19 patient must be classified as biomedical waste.</li> <li>Biomedical waste must be collected in yellow bags.</li> </ul> Healthcare facilities	Lack of information	Lack of information	Lack of information
	<ul style="list-style-type: none"> <li>Waste relating to COVID-19 patients must be managed in accordance with the EU law on waste (particularly hazardous waste and permitting requirements) and the most updated guidelines issued by the ECDC4. The national requirements for infectious waste must also be considered.</li> </ul> Home quarantine/self-isolation	Adequate and detailed information provided	Lack of information	Lack of information
	<ul style="list-style-type: none"> <li>Separate waste bag for used masks and tissues must be put in the room of the patient. The bag must be closed and not be emptied into another bag.</li> <li>Another waste bag for used masks and gloves by the caretaker and cleaner must be put close to the door of the patient's room.</li> <li>The two waste bags can be collected together and put in a general refuse bag.</li> <li>Hand hygiene must be strictly followed after handling waste bags.</li> </ul>			

related stakeholders on the volume of plastics produced (primary – 1,380,000 tons, 24 kg/capita; product – 2,195,162 tons, 37 kg/capita; consumed (primary – 1,841,745 tons, 31 kg/capita; product – 2,441,363 tons, 42 kg/capita); imported (primary – 813,274 tons; product – 436,831 tons); exported (primary – 357,789 tons; product – 190,630 tons) and waste generated (1,855,436 tons, 32 kg/capita) pre-COVID-19 pandemic, thereby collating all available flow data (from reports and literature) and computed (generated) flow data into a unitary plastics data source.

- Modelling the mass flow of PPE during the COVID-19 pandemic showed that 304,453 kg were produced, 402,960 kg consumed, 100,400 kg imported, 1893 kg exported and 306,250 kg waste were generated from January to December 2020.
- Considering the fact that used PPE and other related COVID-19 waste is already being littered and dumped indiscriminately in the environment in South Africa, this study further emphasises the importance of sustainable waste management of COVID-19 waste by highlighting the regulated guidelines for the waste management of healthcare waste in country according to the national Department of Health, Republic of South Africa.
- The COVID-19 PPE flow result shows the need for further extensive search for scientific data to support the claims by some studies that the generation of PPE waste added to the existing tons of plastic cum medical waste is resulting in an overload increase in waste generation. This comes against the backdrop of the comparative flow results of plastics and PPE showing that the COVID-19 PPE waste generated is apparently low when quantified in mass (306,2504 kg) but high in terms of pieces (153,125,123 units), suggesting that the bigger challenge is the volume in loose units and these as contamination vectors. COVID-19 PPE needs to be properly packed and compacted to reduce its potential to spread infections.
- Policy implications and recommendations were discussed for South Africa.

#### CRediT authorship contribution statement

Kunle Ibukun Olatayo: Methodology, Data analysis, Software, Writing- Original draft preparation, Investigation.

Paul T. Mativenga: Conceptualization, Supervision, Validation, Writing - Review & Editing.

Annlizé L. Marnewick: Conceptualization, Supervision, Validation, Writing - Review & Editing.

#### Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

#### Acknowledgements

This research received no definite grant from funding agencies in the public, commercial, or not-for-profit sectors. No sponsor was involved in the processes of design, data collection, analysis, reporting and submission of the study for publication.

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