IECE

Sustainable Intelligent Infrastructure
http://dx.doi.org/10.62762/SII.2025.512875

RESEARCH ARTICLE

Check for updates

Carbon Footprint Analysis on Alternate Disposal Strategies for Personal Protective Equipment Waste

Mohammed Ashfaq[1], **Mohammad Nuruddin**[2], **Arif Ali Baig Moghal**[2,*] and **Abdullah Almajed**[3]

[1] Osaimi Geotechnic Company, Khobar 34433, Saudi Arabia
[2] Department of Civil Engineering, National Institute of Technology, Warangal 506004, India
[3] Department of Civil Engineering, College of Engineering, King Saud University, Riyadh 11421, Saudi Arabia

Abstract

The use of personal protective equipment (PPE) has gained universal acceptance as a critical measure for safeguarding individuals against hazardous environments, including exposure to infectious agents and harmful substances. The increased use of PPE across various industries has resulted in a significant rise in its consumption. Primarily, the steady surge in global COVID cases has caused a sudden rise in demand for PPE. However, the indiscreet and irrational disposal method can potentially augment the impending climate change problem. In the prevailing situation, there is a need to assess their current mode of disposal in terms of carbon emissions. The present study aims to perform carbon footprint analysis (CFA) on landfilling, incineration, and recycling methods of disposal for two scenarios (1 and 100 million PPE). The results indicate that the application of the recycling option could contribute to a situation with conceivably positive emissions with net savings in emissions of approximately 0.159 million kg CO_2e/million PPE. In contrast, it shows that the emissions associated with incineration are substantially higher than the other two methods with emissions of more than 0.78 million kg CO_2e/million PPE. Additionally, transportation factors such as haulage distance and vehicle type significantly influence overall emissions. For scenario II, emissions from recycling and landfilling increase by 383% and 390%, respectively, compared to a 100% increase for incineration. Based on the net emissions, the order of preference for the three disposal methods is recycling > landfilling > incineration, which is consistent for both scenarios. However, for the hypothetical infinite periods, the emissions from landfilling can potentially rise by more than ten times compared to a surveyable period of 30 years. These findings highlight the need for sustainable PPE waste management to reduce environmental impact.

Keywords: personal protective equipment, carbon footprint analysis, incineration, landfilling, recycling.

Academic Editor:
Duc Bui Van

Submitted: 15 February 2025
Accepted: 24 March 2025
Published: 14 April 2025

Vol. 1, **No.** 1, 2025.
10.62762/SII.2025.512875

***Corresponding author:**
Arif Ali Baig Moghal
baig@nitw.ac.in, reach2arif@gmail.com

Citation
Ashfaq, M., Nuruddin, M., Moghal, A. A. B., & Almajed, A. (2025). Carbon Footprint Analysis on Alternate Disposal Strategies for Personal Protective Equipment Waste. *Sustainable Intelligent Infrastructure*, 1(1), 29–38.

1 Introduction

The widespread use of personal protective equipment (PPE) has become essential to various industries, including healthcare, manufacturing, hazardous material handling, and construction. PPE is considered the most effective barrier to protect workers in hospitals, labs, industries, etc., against hazards, harmful substances, and infectious agents. Although PPE has exceptional benefits in increasing safety and minimizing health risks, its abrupt utilization causes adverse environmental effects, followed by ecological imbalance.

Since 2021, the COVID-19 pandemic originated in China, has significantly affected many countries, and has caused panic situations everywhere. More than 240 countries worldwide, with approximately 777 million reported cases, have been affected by coronavirus (as of 14th Feb 2025, source: https://data.who.int/dashboards/covid19). On that note, the government sectors and organizations implemented strict safety protocols to curb virus transmission. The unpredictable demand for PPE during the pandemic escalated mass production and usage, resulting in a huge increase in plastic waste generation. Moreover, authorities were mainly focused on distributing PPE to every sector, especially to avoid transmitting the virus to the frontline warriors, i.e., healthcare workers, police, and paramedical staff. Considering the urgency of pandemic safety measures, the large-scale production of PPE was initiated despite concerns about waste management.

The fatality rate of earlier outbreaks (Severe Acute Respiratory Syndrome (SARS-10%), Middle East Respiratory Syndrome (MERS-34%) and Ebola virus disease (EVD-50%)) may seem much higher compared to that of COVID-19 (2%) [1, 4, 18]. However, the quantum of deaths reported for COVID-19 (7.1 Million as of 13th Feb 2025, source: https://data.who.int/dashboards/covid19) exceeds the collective deaths reported by the three pandemics (SARS- 774; MERS-858; EVD-11,323). The sheer volume of cases and fatalities make COVID-19 a pandemic of unprecedented and inconceivable scale. As stated by WHO, coronavirus spreads primarily through droplets of saliva or discharge from the nose when an infected person coughs or sneezes. The utilization of personal protective equipment (PPE) is one of the most effective methods to control the spread of the pandemic. Consequently, it has been vigorously promoted by medical agencies and experts globally [6, 10, 22, 26]. The PPE (collective term), as per the WHO definition, include gloves, medical masks, face shields/goggles, gowns and aprons. Among the materials mentioned above, masks and gloves are extensively used by health/essential workers and ordinary people equally [11, 15]. Most of the PPE materials are essentially made of synthetic polymers except for a few biodegradable latex gloves. Polypropylene (PP) in both melt-blown forms is used for masks, and non-Owen PP is utilized in the design of protective clothing [3]. Irrespective of the type of material used in their manufacture, all PPE exhibit a similar level of defense. Further, the number of tests conducted is unprecedented compared to earlier pandemic(s) owing to increased safety concerns and regulations currently prevailing. The USA alone has conducted more than 900 million tests so far. It is understood that the testing involves the collection of swab samples by medical personnel equipped with PPE. Even if the number of tests is taken as a yardstick, the amount of PPE consumed exclusively for testing globally is no less than 500 million. The rise in the number of COVID-19 cases and panic buying/stockpiling has resulted in a surge in PPE demand, which primarily comprises of plastic and rubber materials. In India alone, an estimated 2.5 million people consumed PPE daily during the pandemic. The vast volume of PPE consumption has resulted in its indiscreet dumping into the aquatic and other natural habitats which underlines "our next problem" of disposal and recycling of PPE [12]. At a global level, the direct impact of the Covid-19 pandemic on Public health is evident [4]. However, the potential repercussions of the huge volumes of waste generated are still covert to our imagination. Scientific and environmental experts have been very vocal in highlighting the lack of disposal, recycling, and treatment methods for discarded PPE [16, 17].

Further, improper disposal of PPE may result in adverse environmental implications. The soil and groundwater contamination by PPE may destroy beneficial microbes present in a septic system and a potential source of secondary contamination [27]. Many studies have focused on the remediation of organic and inorganic contaminated soils [20, 21]. However, the net emissions are of major concern. In this context, one of the widely accepted procedures to evaluate a product's environmental impacts is the application of Life cycle assessment to measure the effects of a product in terms of greenhouse gas (GHG) emissions [2, 5]. Though previous researchers

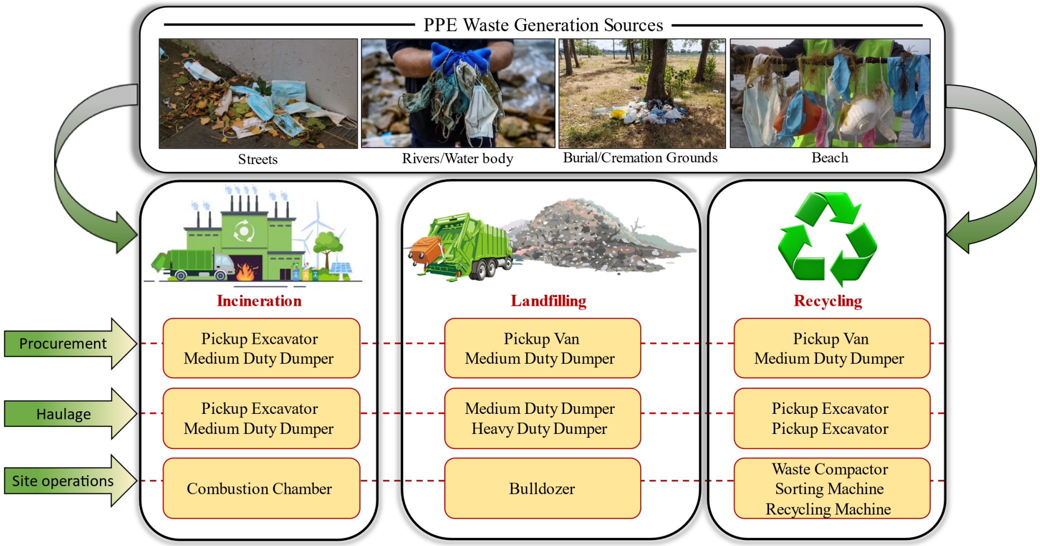

Figure 1. Schematic representation of PPE generation and disposal.

[23, 31] have evaluated the environmental impacts of wastes (plastic) in general by performing life cycle assessment (LCA), the attempts on LCA on PPE alone are sparse. Further, streamlining of LCA to specific impact components like carbon (CO_2) emissions has gained prominence in the form of carbon footprint analysis (CFA).

This study aims to assess the environmental impact of PPE waste through CFA, considering three scenarios: two disposal methods and one recycling scenario. This research provides insights into the carbon emissions associated with PPE waste management, contributing to the ongoing discourse on sustainable waste disposal practices across various industries.

2 Materials and Methods

2.1 Case Study

In order to facilitate the choice of a disposable method, CFA was performed on three disposable scenarios: incineration, landfilling, and recycling for 1 million tons of PW. A similar CFA was performed for an upscale version of 100 million tons of PW. Since non-woven polypropylene (PP) is largely used in the preparation of PW, in the current study, PW is assumed to be analogous to PP [8]. Further, in order to compare emissions from both disposal methods, a pragmatic shorter timeframe (30 years) wherein the landfill attains a pseudo-static state (the stage at which chemical modifications are slower than the initial stages), has been considered in the current study [8, 24]. In recycling, wastes are mechanically (granulation) or chemically (monomer blocks) processed with the objective of producing new raw materials. In the present study, due to brevity, only mechanical recycling is considered.

2.2 Scope and Goal of CFA

The disposal of one million tonnes of PW was carefully chosen as the functional unit for CFA. The commonly adopted PW disposal methods of landfilling, incineration, and recycling disposal methods are considered for CFA, and the different sources of PW and stages involved in CFA are presented in Figure 1. The CFA methodology adopted is based on established procedures by ISO 14044. Since the PW considered is the same for landfilling and incineration, it is assumed that emissions due to its embodied carbon are assumed to be zero. Further, to facilitate comparison, the current study considered conventional incineration. However, incineration with energy recovery option has the potential to offset emissions by converting waste into energy (WTE). While WTE is not directly considered in current CFA analysis, its imperative to explore its environmental benefits in future studies using LCA. Further, it is also assumed that emissions from heat and power supply remain the same for all three disposal methods.

2.3 System boundary of CFA

The system boundaries were formulated by adopting a gate-to-gate approach in the PW management chain. The following exclusions were made in the study:

- The production and transport of capital goods and fuel have been excluded from CFA (ISO 14044).

Table 1. CFA calculations for scenario - I.

PPE Emissions	Process	Machine/Vehicle	Fuel (L)	CC (kg CO_2/unit)	kg CO_2e
Emissions related to PPE disposal	Procurement	-	-	-	-
	Landfilling	Pickup van	91	3.25	297
	Incineration	Pickup excavator	47	3.25	152
	Haulage	-	-	-	-
	Landfilling	Medium-duty dumper	70	3.25	228
	Incineration	Pickup excavator	654	3.25	2128
	Site operation	-	-	-	-
	Landfilling	Bulldozer	14	3.25	46
	Incineration	Combustion chamber	3×10^5	2.6	7.8×10^5
Emissions related to PPE recycling	Embodied Carbon of PPE	-Nil-	-Nil-	2.04	6.08×10^5
	Procurement	Pickup van	47	3.25	152
	Haulage	Pickup excavator	9	3.25	23
	Site operations	-	-	-	-
	Compacting	Waste compactor	19	3.25	61
	Sorting	Sorting machine	14	3.25	46
	Processing	Recycling machine	51	3.25	167

Table 2. CFA calculations for scenario - II.

PPE Emissions	Process	Machine/Vehicle	Fuel (L)	CC (kg CO_2/unit)	kg CO_2e
Emissions related to PPE disposal	Procurement	-	-	-	-
	Landfilling	Medium-duty dumper	1500	3.25	48750
	Incineration	Medium-duty dumper	1500	3.25	48750
	Haulage	-	-	-	-
	Landfilling	Heavy-duty dumper	52125	3.25	169406
	Incineration	Medium-duty dumper	223214	3.25	725445
	Site operation	-	-	-	-
	Landfilling	Bulldozer	1400	3.25	4600
	Incineration	Combustion chamber	3×10^7	2.6	7.8×10^7
Emissions related to PPE recycling	Embodied Carbon of PPE	-Nil-	-Nil-	2.04	6.08×10^7
	Procurement	Medium duty dumper	1500	3.25	48750
	Haulage	Pickup excavator	6521	3.25	21195
	Site operations	-	-	-	-
	Compacting	Waste compactor	1900	3.25	6100
	Sorting	Sorting machine	1400	3.25	4600
	Processing	Recycling machine	5100	3.25	16700

- Further, the disinfection process involved in autoclaving and microwaving is typical in all scenarios and has been excluded from the study.
- Furthermore, emissions related to maintenance and end-of-life emissions post-closure for three scenarios have not been considered.

The exclusions made in the current study are in coherence with the guidelines issued by ISO 14044 [7]. The inventory of materials involved in CFA was taken from various databases like [2, 24]. To access CO_2e emissions for three scenarios, a stage-wise calculation approach is adopted and the detailed calculations for disposal and recycling methods are presented in Table 1. Similar calculations for scenario-II (upscale version) are presented in Table 2. Further, PW waste generation and disposal strategies are illustrated in Figure 1. A roundtrip distance of 100 km is assumed as the common haulage distance for all the disposal methods. The type of vehicle/machinery used in the procurement, haulage and operational stage is chosen based on the data from previous studies [14, 19, 28].

3 Results and Discussion

The net emissions (kg CO_2e) for three different scenarios are presented in Figure 2. It can be seen that the incineration method of disposal contributed to the highest amount of emissions, with net emissions of 782280 kg CO_2e/million PPE. The emissions in recycling have resulted in a scenario of the net gain in emissions. The net gain is due to the fact that the emissions from the embodied carbon of PPE, which represents the emissions generated in the production of virgin PPE (6.08×10^5 kg CO_2e/million PPE) are substantially higher compared to emissions (449 and 97345 kg CO_2e for the scenario I and scenario II respectively) in the recycling process. The net emissions in the landfilling scenario are the lowest, with a mere 571 kg CO_2e emissions.

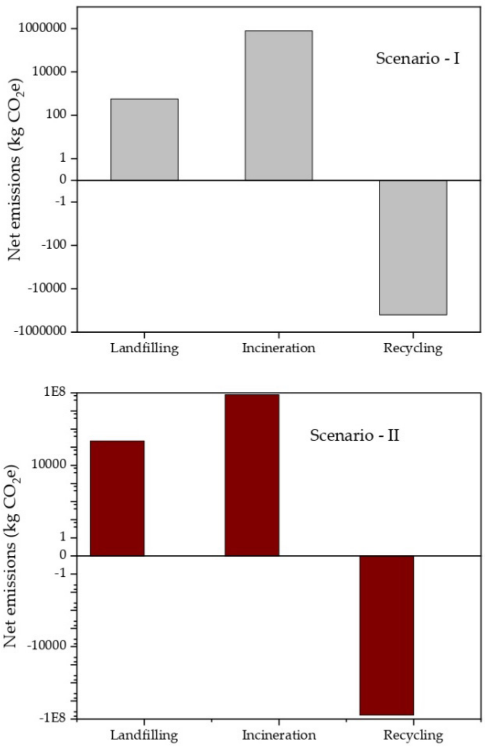

Figure 2. The variation in net emissions with the disposal method.

Based on the net emissions for all three scenarios, the order of preference for three disposal methods is Recycling > Landfilling > Incineration.

3.1 Disposal of PPE

The net emissions (kg CO_2e) for three different scenarios are presented in Figure 2, from which it can be noted that the incineration method of disposal contributed the highest amount of emission with 782280 kg CO_2e and 78774195 kg CO_2e for scenario I and scenario II respectively. The net emission in the landfilling scenario is the least, with a mere 571 and 222756 kg CO_2e for scenario I and scenario II, respectively. The results for emissions related to both disposal methods are presented in Figure 3, and it is observed that the emissions contributed by the operational stage in the incineration method are the highest for both scenarios, with emissions of 0.78 million kg CO_2e/million PPE. The substantially more elevated amount of emissions in the operational stage for the incineration method is primarily contributed by the excessive fuel consumption of combustion chambers.

The lowest amount of emissions was noted in the operational stage of the landfill, which is attributed to the minimal usage of machinery (bulldozer). The emissions from the procurement stage are higher in landfilling and are attributed to variation(s) in vehicle type employed. The emissions in the haulage stage are higher for incineration because of the higher fuel consumption by the same vehicle operated for both the procurement and haulage stages. The emissions in the operational stage for incineration are enormous, with nearly one million kg CO_2e compared to a meagre 46 kg CO_2e emission for landfilling (scenario I). Similar observations were made for scenario II. Further, the results of the CFA on two disposal methods indicate that landfilling is a preferred option over incineration, with substantially lower emissions in both haulage and site operations. The mode of emissions from incineration is immediate, with the release of all the carbon in PPE in the form of methane (CH_4) and carbon dioxide (CO_2), while the emissions from landfills are gradual and time-bound [19]. A primary difference between landfilling and incineration modes of disposal is the timeframe of CFA, which is due to the fact that the emissions from landfills may prevail for extended periods post-closure. Moreover, PPE materials such as polypropylene degrade slowly with time, leading to the formation of microplastics. These microplastics pose environmental risks including groundwater and soil contamination.

Thus, for the surveyable time of 30 years, the emissions from incineration are always higher than from landfills. Considering the total emission balance, landfilling is ranked as the preferable option for PPE [19].

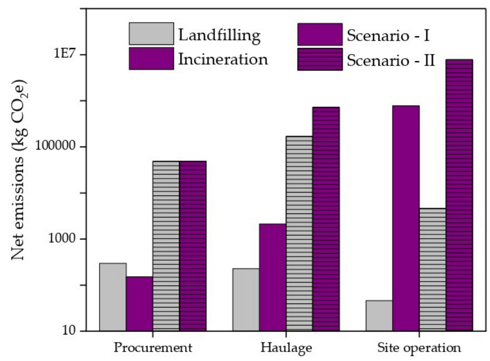

Figure 3. The variation in emissions with stages of CFA for landfilling and Incineration.

The PPE, made of polymers like PE, LDPE/HDPE, fundamentally differs from other industrial wastes like municipal solid waste and coal combustion residues with little or no biodegradation [14]. Finnveden et al. [9] have observed that landfilled PE exhibited 1-3% degradation over 30 years, which is quantified as 9-27 g of CH_4 and 8-24g of CO_2 per kg/PE. However, over hypothetical infinite time periods (beyond 500 years), the emissions substantially increase to more than ten times with 3000g CO_2 per kg/PE. Since the emissions for an infinite time period is considered beyond the purview of the current study, based on the earlier studies studies [8, 9], it can be assumed that the emissions from landfills for a surveyable time period (i.e., 30 years considered in this study) are negligible. On the other hand, PPE incineration coupled with recovery of energy (post-combustion) will offer the benefits over landfilling and are listed below:

- Eliminates the mobility of harmful pathogens
- Reduces the volume of healthcare waste by more than 90%.
- Generates inert slag, a potential alternative construction material.
- Avoids post-closure maintenance costs.
- Conserves valuable land resources.
- Similar observations are reported by [4] for incineration of non-biodegradable plastics.

Among the disposal strategies considered, in areas with inadequate facilities to perform the disinfection process (autoclaving and microwaving), incineration can be the easiest and preferred method of disinfection or decontamination of PPE. In rural areas, where incineration is also not feasible, the deep burial of PPE can be adopted. However, in resourceful regions, adopting technology-driven disposal strategies such as hydrothermal carbonization and gasification can automate waste valorization with the potential to deliver high-quality by-products.

3.2 Recycling of PPE

From the CFA results presented in Figure 2, it is observed that the emissions from recycling have resulted in positive emissions and is mainly attributed to the embodied carbon of PPE during the production of virgin PPE (6.08×10^5 kg CO_2e/million PPE) which are substantially higher compared to emissions from the recycling process (449 kg CO_2e/million PPE). The stage-wise emissions in recycling for both scenarios are presented in Figure 4, which reveals that the emissions at the operational stage are substantially higher compared to procurement and haulage owing to multi-stage complex operations notably different from the other disposal methods. It is even observed that the emissions in haulage and procurement stages are comparable to landfilling and Incineration, as shown in Figure 3. From this observation, it can be inferred that the emissions related to the operational stage are the differentiator among the studied disposal methods. Further, one distinct feature of CFA for recycling is the emissions due to the embodied carbon of PPE, which are substantially higher (6.08×10^5 kg CO_2e/million PPE) compared to collective emissions from the other three stages of recycling (449 and 973 kg CO_2e/million PPE for the scenario I and scenario II respectively).

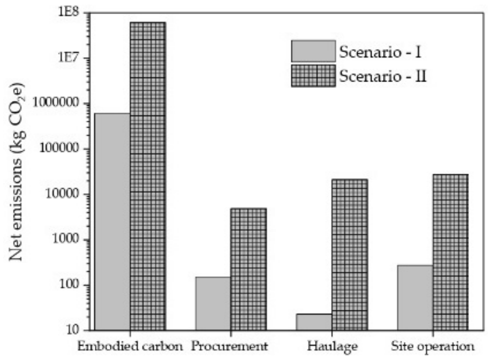

Figure 4. The variation in emissions with stages of CFA for recycling scenario.

From scenario I to scenario II, the emissions (kg CO_2e/million PPE) related to the recycling process increased by 216%, whereas the emissions (per million PPE) from embodied carbon remained constant. The difference in emissions can be mainly attributed to the variation in machinery/vehicle employed for the upscaled scenario. Another distinct observation was regarding the procurement stage, which decreased by 68% while the emissions for haulage and site operations remained constant. This decrease in emissions for procurement was attained by replacing the pickup van with a medium-duty dumper. The results confirm that PPE recycling results in a carbon-negative/sink situation, which is not achieved for landfilling and incineration modes of disposal. Based on the net emissions for all three scenarios, the order of preference for three disposal methods is recycling > landfilling > Incineration. Similar benefits of recycling plastic waste have been observed by [3, 14]. The industrial sludge or leachate associated with PPE manufacturing units is known to cause the acidification of wetlands, subsequently resulting in eutrophication by photo oxidants [30]. By opting for the recycling option for PPE, apart from the earlier mentioned adverse environmental effect (eutrophication), the demand for energy in the manufacturing of virgin PPE can also be averted [16]. Recycling also avoids emissions associated with the use of plastic as an alternative source of energy (by combustion), which reduces the thrust on non-renewable energy sources like wood and coal [23].

3.3 Comparison of CFA results from both the scenarios

From the CFA results presented in Figures 2, 3 and 4, it is evident that the increase in PPE from 1 million to 100 million has resulted in an exponential increase in the overall emissions. In general, for both scenarios, the emissions in the incineration are much higher than the other two modes of disposal (landfilling and recycling). However, for scenario II, the difference in emission is more pronounced in recycling and landfilling method which exhibited an increment of 383% and 390% respectively compared to an increment of 100% for incineration method. This distinctive spike in emissions for landfilling and recycling method in comparison to the scenario–I are primarily driven by the haulage distance and type of vehicle employed. The vast volume (100 million) of PPE procurement in scenario II necessitates the utilization of vehicles with relatively higher payload capacity and lower fuel efficiency. In the process, the overall fuel consumption is dramatically enhanced, resulting in an exponential rise in emissions. Further, the proportionate increment in emissions in scenario II for the incineration method compared to other disposal methods is primarily contributed by the site operation stage in which the machinery employed remains the same for both the scenarios. However, for landfilling, the highest contributing stage of emissions varied from procurement in the scenario I to haulage in scenario II. Thus, considering the emissions from both the scenarios, it can be inferred that the application of the landfilling method for largescale disposal remains the preferred choice of disposal over incineration in both the scenarios. Another distinct feature observed in scenario II is the increase in the contribution of haulage distance on the overall emissions in the landfilling method is considerably lower (190%) compared to incineration method which exhibited 450% increment. This observation highlights the advantage of landfilling method over ponding method of disposal, particularly for large-scale stabilization.

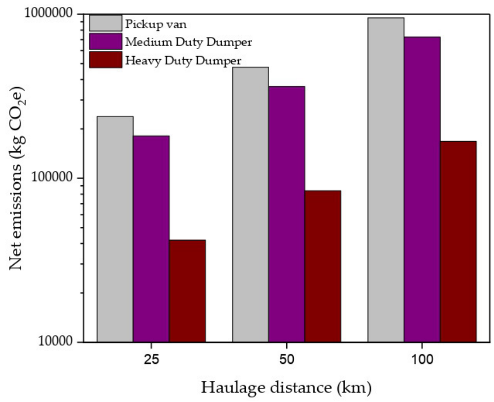

Figure 5. The variation in emissions with haulage distance.

3.4 Role of haulage distance on the emissions

The variation in emissions associated with the haulage stage with the distance for three vehicles of different payload capacities and mileage is presented in Figure 5. The payload capacity and mileage of the vehicles considered are 0.7 (tons) & 7.5 (km/L), 4 (tons) & 3.36 (km/L) and 24 (tons) & 2.42 (km/L) for pickup van (PV), medium-duty truck (MDT) and heavy-duty truck, respectively. From the results, it is evident that the distance of haulage has a direct influence on the emissions with a linear increase in emissions with the distance for both the vehicles. It is interesting to note that the PV with the best mileage has exhibited the highest emission, which can be attributed to its relatively lower payload capacity. As seen in Figure 5, with the increase in haulage distance from 25 to 100 km, the emissions increased by almost four times for all the vehicles. With the variation in haulage distance from 25 - 100 km, the difference in emissions between the PV and HDT has increased from 195652 to 782606 (kg CO_2e). Due to their relatively lower payload capacity, PV requires more trips to convey the waste, thereby causing substantially higher consumption of fuel. Thus, the higher consumption of fuel is reflected in the form of higher emissions associated with PV. The usage of vehicles like PV is typically seen in the procurement of wastes from households, beaches and street litters (Figure 1). Whereas for mass procurement from hospitals and burial/crematoriums, medium/heavy-duty dumpers of higher payload capacity are generally employed. Further, it can also be inferred that the location of waste procurement indirectly influences the emissions associated with the haulage of waste. It can be noted that the contribution of emissions by haulage to the overall emissions is substantially higher than other stages, with the only exception of emissions due to incineration.

3.5 Sustainable Disposal Approach

Though the COVID-19-induced lockdown has crashed global GHG emissions, the contemporary issue of PPEs is unforeseen and unprecedented, with implications lasting for a substantial period. Albeit the need to address the issue of plastic waste generation and disposal has been highlighted by environmental activists in the past [8, 14, 29], the COVID-19 pandemic makes it a more opportune time to augment a dialogue on the subject of plastic waste. Based on the results from the study, it can be inferred that landfilling is the most preferred disposal option over incineration for the surveyable time of 30 years. This observation is further corroborated by the fact that the landfilling with more than 58% share in total plastic disposal, generates the lowest CO_2e emissions [8, 14, 29]. It is further observed that relying on incineration as the sole method of disposal leads to an increase in global GHG emissions. On the other hand, by recycling PPE, a negative value of GHG emissions will contribute to a net gain in carbon emissions of more than 159000 kg CO_2e/ million PPE. Moreover, due to the energy-intensive production, PPEs recycling also enormously contributes to energy cost savings. Despite efficiencies and net emissions, the major factor that decides the selection of a suitable technique is cost-effectiveness. It is observed that the cost required to dispose off waste products is high compared to the recycling approach, especially waste-to-energy technology. The negative carbon emission signifies the fact that the emissions associated with the embodied carbon of PPE can be averted by choosing recycling as a preferred option over other disposal strategies. As mentioned, mechanical recycling results in a carbon-negative condition, making it an environmentally favourable approach. However, contamination issues can often hinder the feasibility of mechanical recycling. On the other hand, chemical recycling (CR) as an alternative approach to mechanical recycling has excellent potential to recycle contaminated and heterogeneous plastic wastes. The CR is based on the principle of converting complex polymers into a sustainable smaller molecule with relatively lower toxicity [25].

Further, the emerging green technologies should be incentivized to produce biodegradable material. Shifting to sustainable renewable energy sources as fuel for vehicles/machinery will contribute to the overall reduction in emissions. Recently, the authors have suggested the potential usage of molten plastic from PPE as an alternative stabilizer for the treatment of soils [3]. Further, the authors have also highlighted the possibility of fabricating bricks by incorporating molten PPE waste as a binding agent. Utilization of PPE in both applications can avert the substantial carbon emissions associated with the usage of traditional stabilizers like lime and cement [2]. Further, the emission issues related to PPE should be seen as an opportunity to revisit and revamp the fiscal and production policies associated with their manufacturing and disposal methods. With the persistent increase in global temperatures, the occurrence of catastrophic pandemics/disasters are expected to rise shortly [4]. One of the progressive approaches would be to complete adapt bio-based plastics for PPE production, which can have negative carbon footprints. However, disinfection of bio-based PPE post-usage needs comprehensive evaluation before it is promoted as a sustainable alternative to existing non-biodegradable PPE. Post pandemic, there is a need to reflect on the current flawed practice of handling healthcare waste to combat the potential pandemics of unprecedented scale [15]. Lastly, it is prudent to determine sustainable solutions for the limitations identified in the current waste disposal strategies.

3.6 Practical relevance of the research findings

The findings of the study further reinforce the positive benefits of recycling PPE in terms of net savings in emissions. The results of the study highlight the role of haulage distance on the overall emissions. Thus, the estimated emissions in the present study will enable end-users to select appropriate vehicles that are implemented in waste management practices. Though previous researchers have highlighted the role of recycling and haulage distance on emissions from non-biodegradable plastics, the attempts to focus on PPE are sparse. Furthermore, the research findings of the present have greater relevance due to the rapid rise in consumption of PPE (due to the COVID-19 pandemic). The results of the study are an honest attempt to ensure human and environmental safety during the current crisis caused by the pandemic.

4 Conclusions

In the current study, CFA was performed to measure the impact of PPE generation/disposal on the environment. From the findings of the study, the following conclusions are drawn:

- The net emissions through incineration were found to be highest at 6.08×10^5 kg CO_2e/million

PPE.

- The emissions in the procurement and haulage stage for both landfilling and incineration are found to be in the range of 200-2000 kg CO_2e.
- It is noted that the emissions from landfilling for hypothetical infinite periods can increase by more than ten times compared to the surveyable period of 30 years.
- The recycling of 1 million PPE can potentially contribute to 159000 kg CO_2e reduction in emissions.
- With the increase in PPE for scenario II, the contribution of haulage on the overall emissions in the landfilling is considerably lower (190%) compared to incineration (450%).
- Based on the net emissions for all three scenarios, the preferred method of disposal is found to be, recycling > landfilling > Incineration.

Data Availability Statement

Data will be made available on request.

Funding

This work was supported by Researchers Supporting Project Number under Grant RSP2025R279, King Saud University, Riyadh, Saudi Arabia.

Conflicts of Interest

Mohammed Ashfaq is the Engineering Manager at Osaimi Geotechnic Company, Khobar 34433, Saudi Arabia.

Ethical Approval and Consent to Participate

Not applicable.

References

[1] Del Rio, C., & Malani, P. N. (2020). COVID-19—new insights on a rapidly changing epidemic. *Jama, 323*(14), 1339-1340. [CrossRef]

[2] Ashfaq, M., Lal, M. H., Moghal, A. A. B., & Murthy, V. R. (2020). Carbon footprint analysis of coal gangue in geotechnical engineering applications. *Indian Geotechnical Journal*, *50*(4), 646–654. [CrossRef]

[3] Astrup, T., Fruergaard, T., & Christensen, T. H. (2009). Recycling of plastic: Accounting of greenhouse gases and global warming contributions. *Waste Management & Research*, *27*(8), 763–772. [CrossRef]

[4] Kim, J., Chung, Y., Jo, H. J., Lee, N., Kim, M. S., Woo, S. H., Park, S., Kim, J. W., Kim, H. M., & Han, M. (2020). Identification of coronavirus isolated from a patient in Korea with COVID-19. *Osong Public Health and Research Perspectives*, *11*(1), 3-7. [CrossRef]

[5] Chen, Y., & Lo, S. (2016). Evaluation of greenhouse gas emissions for several municipal solid waste management strategies. *Journal of Cleaner Production*, *113*, 606–612. [CrossRef]

[6] Cook, T. M. (2020). Personal protective equipment during the coronavirus disease (COVID) 2019 pandemic – a narrative review. *Anaesthesia*, *75*(7), 920–927. [CrossRef]

[7] ISO 14044:2006. (2022). Environmental management — Life cycle assessment — Requirements and guidelines. Retrieved from https://www.iso.org/cms/render/live/en/sites/isoorg/contents/data/standard/03/84/38498.html

[8] Eriksson, O., & Finnveden, G. (2009). Plastic waste as a fuel—CO2-neutral or not? *Energy & Environmental Science*, *2*(9), 907–914. [CrossRef]

[9] Finnveden, G., Albertsson, A., Berendson, J., Eriksson, E., Höglund, L. O., Karlsson, S., & Sundqvist, J. (1995). Solid waste treatment within the framework of life-cycle assessment. *Journal of Cleaner Production, 3*(4), 189-199. [CrossRef]

[10] Herron, J., Hay-David, A., Gilliam, A., & Brennan, P. (2020). Personal protective equipment and Covid 19- a risk to healthcare staff? British *Journal of Oral and Maxillofacial Surgery, 58*(5), 500-502. [CrossRef]

[11] Hong, J., Zhan, S., Yu, Z., Hong, J., & Qi, C. (2018). Life-cycle environmental and economic assessment of medical waste treatment. *Journal of Cleaner Production*, *174*, 65–73. [CrossRef]

[12] Kalina, M., & Tilley, E. (2020). "This is our next problem": Cleaning up from the COVID-19 response. *Waste Management*, *108*, 202–205. [CrossRef]

[13] Brems, A., Baeyens, J., & Dewil, R. (2012). Recycling and recovery of post-consumer plastic solid waste in a European context. *Thermal Science, 16*(3), 669-685. [CrossRef]

[14] Lea, W. R. (1996). Plastic incineration versus recycling: A comparison of energy and landfill cost savings. *Journal of Hazardous Materials*, *47*(1), 295–302. [CrossRef]

[15] Lee, C. C., & Huffman, G. L. (1996). Medical waste management/incineration. *Journal of Hazardous Materials*, *48*(1), 1–30. [CrossRef]

[16] Liu, H., You, J., Lu, C., & Chen, Y. (2015). Evaluating health-care waste treatment technologies using a hybrid multi-criteria decision making model. *Renewable and Sustainable Energy Reviews*, *41*, 932-942. [CrossRef]

[17] Livingston, E., Desai, A., & Berkwits, M. (2020). Sourcing personal protective equipment during the

COVID-19 pandemic. *JAMA*, *323*(19), 1912. [CrossRef]

[18] Mahase, E. (2020). Coronavirus: COVID-19 has killed more people than SARS and MERS combined, despite lower case fatality rate. *BMJ*, m641.[CrossRef]

[19] Moberg, Å., Finnveden, G., Johansson, J., & Lind, P. (2005). Life cycle assessment of energy from solid waste—part 2: Landfilling compared to other treatment methods. *Journal of Cleaner Production*, *13*(3), 231–240. [CrossRef]

[20] Mohammad, N., Moghal, A. A., Rasheed, R. M., & Almajed, A. (2022). Critical review on the efficacy of electrokinetic techniques in geotechnical and geoenvironmental applications. *Arabian Journal of Geosciences*, *15*(8), 781. [CrossRef]

[21] Nuruddin, M., & Moghal, A. A. (2024). State-of-the-art review on the geotechnical and geoenvironmental feasibility of select biochars. *Indian Geotechnical Journal*, *54*(3), 1073-1094. [CrossRef]

[22] Hu, Q. R., Shen, X. Y., Qian, X. M., Huang, G. Y., & Yuan, M. Q. (2023). The personal protective equipment (PPE) based on individual combat: A systematic review and trend analysis. *Defence Technology*, *28*, 195-221. [CrossRef]

[23] Perugini, F., Mastellone, M. L., & Arena, U. (2005). A life cycle assessment of mechanical and feedstock recycling options for management of plastic packaging wastes. *Environmental Progress*, *24*(2), 137–154. [CrossRef]

[24] Rabl, A., Spadaro, J. V., & Zoughaib, A. (2008). Environmental impacts and costs of solid waste: A comparison of landfill and incineration. *Waste Management & Research: The Journal for a Sustainable Circular Economy*, *26*(2), 147-162. [CrossRef]

[25] Ragaert, K., Delva, L., & Van Geem, K. (2017). Mechanical and chemical recycling of solid plastic waste. *Waste Management*, *69*, 24–58. [CrossRef]

[26] Requirements and technical specifications of personal protective equipment (PPE) for the novel coronavirus (2019-ncov) in healthcare settings—PAHO/WHO | Pan American Health Organization. (n.d.). Retrieved April 21, 2021, Retrieved from https://www.paho.org/en/documents/requirements-and-technical-specifications-personal-protective-equipment-ppe-novel

[27] Sharma, H. B., Vanapalli, K. R., Cheela, V. S., Ranjan, V. P., Jaglan, A. K., Dubey, B., Goel, S., & Bhattacharya, J. (2020). Challenges, opportunities, and innovations for effective solid waste management during and post COVID-19 pandemic. *Resources, Conservation and Recycling*, *162*, 105052. [CrossRef]

[28] Shillaber, C. M., Mitchell, J. K., & Dove, J. E. (2016). Energy and carbon assessment of ground improvement works. II: Working model and example. *Journal of Geotechnical and Geoenvironmental Engineering*, *142*(3), 04015084. [CrossRef]

[29] Soares, S. R., Finotti, A. R., da Silva, V. P., & Alvarenga, R. A. F. (2013). Applications of life cycle assessment and cost analysis in health care waste management. *Waste Management*, *33*(1), 175–183. [CrossRef]

[30] Tyskeng, S., & Finnveden, G. (2010). Comparing energy use and environmental impacts of recycling and waste incineration. *Journal of Environmental Engineering*, *136*(8), 744–748. [CrossRef]

[31] Zheng, J., & Suh, S. (2019). Strategies to reduce the global carbon footprint of plastics. *Nature climate change*, *9*(5), 374-378.[CrossRef]

Mohammed Ashfaq received the PhD degree in Civil engineering from the National Institute of Technology Warangal, Telangana 506004, India, in 2021. He has expertise in geotechnical and geoenvironmental characterization of industrial mining wastes, carbon footprint analysis and Environmental Impact Assessment. (E-mail: mohammed.ashfaq@osaimiengineering.com)

Mohammad Nuruddin received the M. Tech degree in Civil engineering from the National Institute of Technology Warangal, Telangana 506004, India, in 2022. His research interests include soil remediation, sustainable geotechniques, soil mechanics, soil stabilization, and foundation engineering. (E-mail: mn22cer1r08@student.nitw.ac.in)

Arif Ali Baig Moghal is a Distinguished Researcher and a Professor of the Department of Civil Engineering at the National Institute of Technology Warangal (NITW). Dr Arif is the author of 88 Journal Papers, 2 Edited Books, 21 Book Chapters, 35 ASCE Geotechnical Special Publications, and 40 full conference papers. He is currently an Editorial Board Member for 8 International Journals. (E-mail: reach2arif@gmail.com ; baig@nitw.ac.in)

Abdullah Alamjed's research focused on biogeotechnical engineering and biogeochemical processes for ground improvement and remediation. Dr. Almajed investigated the mechanical properties of enzyme-induced carbonate precipitation (EICP) treated soil under different carbonate contents and different treatments. His expertise includes experimentation and analytical testing related to mineral precipitation using biological processes and macromolecules such as free urease enzymes and biopolymers. He is also involved in several projects related to the improvements of the mechanical properties of the soil, surficial soil stabilization, and environmental remediation. (E-mail: alabduallah@ksu.edu.sa)