A Study on AI-based Waste Management Strategies for the COVID-19 Pandemic

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Abstract

COVID-19 has swept across the globe and disrupted all vectors of social life. Every informed measure must be taken to stop its spread, bring down number of new infections and move to normalization of daily life. Contemporary research has not identified waste management as one of the critical transmission vectors for COVID-19 virus. However, most underdeveloped countries are facing problems in waste management processes due to the general inadequacy and inability of waste management. In that context, smart intervention will be needed to contain possibility of the COVID-19 spread due to inadequate waste management. This paper presents a comparative study of the artificial intelligence/ machine learning based techniques, and potential applications in the COVID-19 waste management cycle (WMC). A general integrated solid waste management (ISWM) strategy is mapped for both short-term and long-term goals of COVID-19 WMC, making use of the techniques investigated. By aligning current health/waste-related guidelines from health organizations and governments worldwide and contemporary, relevant research in area, the challenge of COVID-19 waste management and, subsequently, slowing the pandemic down may be assisted.

Keywords: Artificial intelligence, COVID-19, Infectious diseases, Machine learning, Solid waste, Waste management cycle

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1 Introduction

As of March 2021, there have been more than 127 million contaminated cases and 2.7 million deaths due to COVID-19 worldwide. Since its inception from the epicenter in December 2019, the world has spared no effort to contain the pandemic. The globally issued directions from the health advisories and relevant authorities, call for a greater emphasis on the waste management processes and strategies especially in the third world. This can be efficiently managed in today's technical world by the introduction of technology including artificial-intelligence (AI) and machine learning (ML), were made to address the gigantic challenge of halting the spread of the viral disease at a global scale as well as on industry work layouts [1–3]. This paper reviews and analyzes the current state of art in the use of AI and ML techniques on the problem of waste management and finally presents a possible framework that may be employed to mitigate the risks emanating from inadequate waste management facilities and processes in most countries.

Best practices should be followed in the solid waste management cycle for COVID-19 as per the directions coming from the health authorities locally and globally. This includes efficiently handling health care materials, checking for the proper isolation and recycling of waste, and appropriate human and material resources. As of now, there is no scientific evidence to support the idea of transmission of the COVID-19 virus through direct and unprotected human interaction during the handling of healthcare waste. However, according to the recommendations, all waste created during the care of patients, including those with confirmed sickness, is deemed contagious (contagious and pathological waste) and should be stored securely in well-marked waste boxes. Such waste would ideally be processed and disposed of safely. It is essential to understand where and how the waste is treated and disposed of when moving off-site. Wastes from waiting areas in the hospitals and healthcare units can be classified as less hazardous and disposed of through municipal waste collection procedures.

As per the World Health Organization (WHO) directions, all those who treat healthcare waste should wear acceptable PPE

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(personal protective equipment; boots, long-sleeved gowns, heavy-duty gloves, helmets, goggles, or face shields) and practice hand hygiene upon removal. The amount of infectious waste during the pandemic of COVID-19 has increased, with the usage of PPE [4]. It is, therefore, necessary to improve the capacity to manage and address this excess in health-care-related waste. Another key factor is that it is not only specific healthcare units like hospitals and clinics that are the sole producers of such waste. The pandemic's scale and nature are such that most of the affected population have been advised to stay home and to nurse their conditions while practicing social distancing. This means that the application and practice of the specific measures related to the spread of the COVID-19 disease have transcended the boundaries of the healthcare providers to the patients' homes.

Consequently, the waste which must be handled with extreme care is potentially being generated in neighborhoods and municipalities. The general directions for the domestic waste generated at home during quarantine while caring for a sick family member or during the recovery period should be packed in strong black bags and closed completely before disposal and eventual collection by municipal waste services. Finally, it has been established that even asymptomatic and unaffected people can act as the carriers of the virus. The waste generated by these people in houses or offices can act as an unexpected source of the virus if contacted by the waste management personnel. Therefore, reducing human contact during waste management is also crucial for municipal waste. Moreover, the nature and distribution of waste have also changed during the pandemic due to a drastic lifestyle change. In short, the overall picture of waste management in the pandemic demands a comprehensive response to the challenge, from the collection phase to the safe disposal, including safe handling and processing.

The waste collection contains the most significant operational aspect of the solid WMC and is the most critical for the involvement of the human element, with current facilities and practices in place. In most underdeveloped neighborhoods, cities, and countries, the basic structure of waste collection may even need to be up scaled or, in some cases, built from scratch. That aspect of the waste management facilities is not the direct focus of this study. However, it is essential to understand that the nature of the COVID-19 pandemic is such that the inadequacies and unavailability of waste management may have consequences for even those areas which do possess such facilities. AI and ML techniques can be used to improve several aspects of the waste collection part of the solid WMC, which will be discuss ed in the relevant sections in this paper.

Waste collection is followed by safe and effective waste handling and processing. This is the step which can be automated through the application of recent advancements in AI/ML techniques. Automated classification using AI-based image processing, sorting, enabling automated processing of waste etc., are some of the areas where these techniques can be effectively used. Waste treatment capacity, preferably through alternative treatment technologies, such as autoclaving or high-temperature incinerators, may need to be acquired, and systems may need to be put in place to ensure their continued operation. The strategy discussion for the COVID-19 WMC will cover more details, keeping in view the directions issued by relevant healthcare information-providing authorities.

Lastly, solutions to current and future waste management challenges are creatively developed by using AI during the pandemic [5]. For example, the disease spread and infection progress within the community or city is being investigated with the help of AI [6, 7]. Currently, AI for waste management is generally being employed for the sorting and classification of wastes. State-of-the-art smart waste management technologies, such as AI-equipped robotics, capable of automatic sorting and reliable item detection by ML through image classification, not only reduces the human intervention needed for solid waste management but also efficiently recycles specific types of materials for improved ecological sustainability after the pandemic [8]. All such technological interventions will reduce the risk of infections in the human element in the waste management cycle, thus, breaking a crucial link in the potential spread chain for the COVID-19 and similar viral situations.

The main contributions of this work focus on compiling state-of-the-art, AI-based waste management solutions presented in the literature and try to present a possible framework where these solutions may be aggregated to try and solve the waste management issues in the developing countries. Some of the key contributions are listed out below:

- A comparative study of potential and in-use AI/ML techniques and methods to positively affect the solid waste-management cycle in the COVID-19 environment.
- A proposed general strategy for effective COVID-19 waste management, considering the directions from relevant health authorities worldwide.
- Detailed discussion on the active or passive aspects of the recent AI advancements on several different parameters, relevant to the effective waste management.
- A discussion on the way forward given the use of technology and its potential impact on societies given their state of being digitally ready to adapt the proposed strategy.

The rest of this paper is organized as follows. Sect. 2 presents the methodology adopted for this research. Sect. 3 discusses the COVID-19 solid waste and associated risks. Sect. 4 highlights the applications of AI in waste management with the relevant details to the COVID-19 situation. Sect. 5 presents the proposed general waste management strategies (short and long term) with salient features, constraints, available solutions, and potential benefits. Finally, Sect. 6 concludes the paper, followed by the acknowledgments and references.

2 Methodology

In the quest of an ultimate solution for waste management that employs key modern technologies like AI and ML, it is critical to understand which of the smaller subset of problems have been solved by use of these technologies. So, this paper studies the available solutions and tries to fit them in an end-to-end ecosystem by proposing a framework that will show a way on how these individual solutions can be aggregated to form a comprehensive waste-management solution in developing countries. It follows a stepwise strategy of understanding the COVID-19 solid waste generation sources, followed by their specific types and the risks associated with this specific kind of waste in the pandemic. The need to have an effective solid WMC depends on the clear understanding of these accounts as the subsequent application of artificial intelligence strategy depends on it. Once the sources and the types of the COVID-19 solid waste have been identified, the actual application of AI can be explored in different aspects of the WMC. This critical step involves reviewing the different techniques used in AI/ML fields to optimize the processes like routing, classification of materials, and their sorting for ultimate disposal. The detailed review will provide the tools to lay out the key points in the AI-based integrated waste management strategy. Fig. 1 provides the overall flow of the presentation of these points in this paper.

3 COVID-19 Solid Waste and Associated Risks

Various protection measures have been utilized during COVID-19, as mentioned by WHO, which have resulted in the mass production of safety products. Masks and surgical PPEs are the front-line fighters' tools, since they are more vulnerable to contamination than anybody else. WHO has urged industry and government to expand supply by 40 % to satisfy the rising demand for surgical gloves, N95 masks, and standard surgical masks. The extensive usage of plastic and medical-based PPEs in everyday life is increasing the amount of municipal solid waste (MSW), and thus, the treatment of these wastes according to medical waste guidelines has become a growing issue of the world; since the disposal and utilization of MSW in even developed countries has not been explicitly planned.

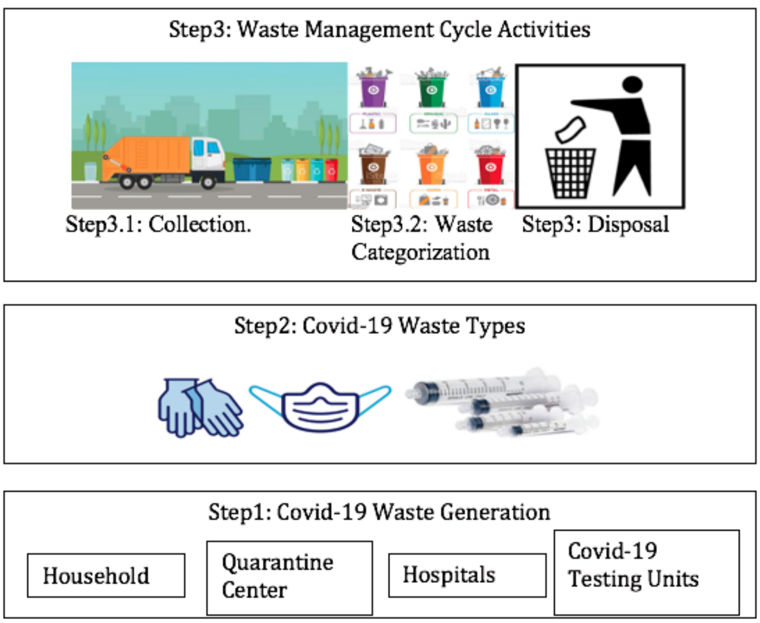


Figure 1. COVID-19 waste management aspects for AI smart intervention. These include the problems related to route detection, object detection/classification, and disposal.

Countries with stabilized economies and higher income have already put facilities for solid waste management and implemented new policies to expandability to deal with these new crises of medical PPE disposal among the general public. However, in the middle- and lower-income countries, open dumping and the lack of suitable landfill sites with municipal services are the only options. It has been observed that the local waste management agencies and waste operators were not prepared to confront difficult such situation, so they now have to deal with the plastic contamination, which may continue for a long time, by various practices such as re-evaluate the situation, share best practices, and implement revised policies.

It has been observed that during COVID-19, a significant volume of toxic hospital waste is created. In Pakistan, 0.5 million samples have been performed in different labs, resulting in radioactive waste such as discarded syringes, bandages, intravenous drip bottles, NG Tubes, and granules and blood sample bottles. Hence, they are classified as toxic waste because they may contain coronavirus, and they must be handled with extreme caution in terms of processing, storage, transportation, care, and disposal. This health waste must be transported by trained workers and handled at approved hazardous waste facilities. However, due to a lack of funds, low-income countries such as developing counties have a less efficient protocol for the safe disposal of radioactive COVID-19 waste. Therefore, the challenges have to be faced by the developing countries where the usage of plastics has been increased extremely which has increased the hazards with many folds.

Thus, there is a need to define a safety management system that can incorporate various challenges. These include identification, processing, isolation, packaging, transportation, care, and disposal are all measures in successful coronavirus waste control, as is disinfection, sanitary worker personal safety, and training sessions. Hence, the usage of AI and ML techniques may help manage a safe disposal system for COVID-19.

4 Applications of Artificial Intelligence: Waste Management

There are many aspects to the response measures that need to be undertaken in a pandemic situation like COVID-19. One of the most important measures is the effective management of clinical waste to prevent the virus from spreading at a higher rate. In some advanced countries, with effective early interventions, it is estimated that each patient disposes of about 10 kg of clinical waste per day. Governments need to manage these wastes properly, considering the sharp increase in infectious waste over a short period. To undertake safe waste management against COVID-19, the authorities must incorporate extraordinary measures and routines. This waste comes from hospitals, treatment facilities, and the self-quarantined population in their homes. Usage of PPE, including medical gloves, facemasks, and aprons, has been recommended for essential service workers and those who treat patients. More and more countries propose to their populations to wear facemasks. Adapting the already in-place waste management routines by the administrations to newly strengthened measures of managing medical waste is not a trivial task. To investigate the possible use of AI models in solving the collection, sorting/classification, and ultimate disposal of clinical waste of COVID-19, a comprehensive discussion about the current work, any relevant implementations, and recorded results is essential. This exercise will help to understand state-of-the-art AI and encourage further developments in this area. This paper presents a detailed systematic literature review and discussion on available AI models that may be suitable to boost existing clinical waste management techniques in their relevant stages, from collection to final and safe disposal.

4.1 AI Models/Techniques: Collection

Collection of the COVID-19 or any infectious waste is a key part of the efficient strategy for clinical waste management. Effective COVID-19 waste collection is also one of the main parts of the overall strategy where costs would grow compared to the traditional clinical or solid waste management techniques. In addition, inefficient collection protocols may cause higher operational costs, which also creates difficulties in situations of partial or total lock-down, as recommended by authorities around the globe to fight the spread of the pandemic effectively. A comparison of some essential AI techniques to achieve optimized routes for clinical waste collection is presented below.

4.1.1 Artificial Neural Networks

Modeling clinical waste management processes is complex due to several variables that may have nonlinear behavior. Artificial neural networks (ANNs) are designed to mimic the way nervous systems work to perform real-world tasks. ANNs effectively model processes with imprecise data streams and human actions that are complex to model. ANNs usually have an input layer, hidden layers, and an output layer. Each layer has several nodes linked to each node, followed by edges that carry certain weights [9]. For traditional waste management, ANNs have been shown to predict optimized collection routes successfully. ANNs are found to be robust and fault-tolerant, even with the limited number of parameters compared to the number required in deterministic models. However, few studies have implemented models of ANN in routing waste processing. A study was done with a combination of the nonlinear auto-regressive neural networks with optimization of GIS routes focused on the impact of waste composition and weight on vehicle routes and emissions optimization [10]. Another research [11], focused on determining the optimized collection frequency for different locations using ANNs. In COVID-19, like pandemics, which are affecting countries all over the globe, the collection frequency prediction can help optimize the collection process by tuning the models according to the factors like population, economics, and types of inhabited areas.

4.1.2 Genetic Algorithms

Genetic algorithms (GA) are a class of meta-heuristic algorithms emulating natural evolution [12]. In a binary search space, GAs perform optimization techniques to improve a set of solutions rather than optimizing a single solution [13]. GAs have been widely used in solving waste management problems, including waste classification, forecasting of waste generation, prediction of waste accumulation and location of the facility, and estimation of waste heating value and biogas generation. Another key area where GAs is useful is managing waste-related collection paths, maintenance costs, and environmental impacts. Thus, the AI use for efficient collection can be employed for the COVID-19 waste collection as well. A variety of studies have established models for the route preparation of waste collection; several of these use GA and its hybrid versions. GA has been extended to route optimization [14] by collecting electrical and mechanical household waste. It reduced collection costs due to optimized distance to the road, number of collection vehicles, and personnel. The work proposes that the users be involved in generating and subsequently scheduling requests for waste collection. The same can be done in the COVID-19 situation, especially from the hot spots and sealed areas of a particular city and hospitals. The results showed shortened routes but increased the service time by almost 1.85×, which may be attributed to other factors. GIS systems provide key information to traveling vehicles regarding the area, road state, and other relevant factors. A recent study coupled GA with GIS to try and optimize vehicle routing [15]. The work focused on the optimal route calculation by using an updated GIS Dijkstra algorithm. Their solution increased operational space, travel time, and fuel consumption by 8, 28, and 3 %, respectively.

Another study found that hybrid GA effectively optimized transport costs and the number of waste collection and disposal vehicles [16]. Likewise, another study [17] utilized cellular GA to maximize the amount of waste collected and the waste collection points visited. The other goals were minimizing the travel distance and the number of vehicles used in the process. Another research developed a program that combined GIS with hybrid GA to optimize vehicle routing while also considering the conditions on the road and the route. These conditions would include traffic patterns, road suitability, and road structures like U-turn availability [18]. The results showed optimization on the parameters like fuel consumption by operating lighter-weight vehicles on steeper roads even though the routes calculated were longer than unoptimized ones. Results show that genetic algorithms suggested routes were strongly associated with optimum values, with small error rates (up to 3.15 %). Another research that focused on creating a distributed network of waste collection locations was done based on the comparison of heuristic GA and greedy randomized adaptive search (GRASP) procedures [19]. The findings of the work show that GRASP heuristics suited rather well to the randomness of the dataset in the study performed better than GA in calculating the distance to the collection points for the waste material.

GA is more sensitive to the parameters being used than the GRASP. However, GRASP required significantly more computational resources than GA for the problem, which can be a challenge in case of the application of the technique in the parts of the world that are not digitally equipped at a certain level. In case of a pandemic, much effort can be saved by properly educating the public and allowing them the facilities nearby where they can collect their infectious waste from the household. This is especially necessary for those cities or municipalities which are densely populated so that the spread of the disease may not get triggered by the careless handling and dumping of the infectious waste by the residents. A recent study [15] compared the Page-Rank system with the non-dominated sorting genetic algorithm NSGA II to develop the aggregation points for the waste materials. The results from this study can help the administrations reduce costs by installing the waste collection bins at points where the usability of those bins is maximized based on the specific area. This solution enhanced the accuracy to 40 % more than any other method and improved the cost-effectiveness by 38 %.

Another similar problem is related to the ultimate landfills. In conditions like the COVID-19 pandemic, it is essential to have the treatments facilities and landfills be appropriately located with due concern given to the proximity of populated neighborhoods, residential areas, transportation points, and water-supplying facilities. Safe water, hygiene, and health conditions are essential for human health protection during all outbreaks of infectious diseases, including the COVID-19 outbreak. Another study in [20] predicted the locations of such landfills while verifying the results from the work from google maps. Another research [21] utilized hybrid GA to try and reduce costs on medical waste reverse logistics networks, including health, storage, and recycling schemes and industrial waste quotas. Several types of operating costs (transportation, operational, capital, and processing units) were incorporated in the model used in the study.

4.2 AI Models/Techniques: Classification

Classification is another key function that needs to be carefully studied to efficiently be able to handle and dispose of the COVID-19 related waste. The most important applications of AI technology in this context would be the application of image classification that will lead to the identification of the different waste types [22-25]. Following is the discussion of different types of AI methods that can help in this context.

4.2.1 Artificial Neural Networks

Several studies have been performed to classify waste material to be used in automated sorting systems to eliminate the manual separation of waste. This capability can be critical in handling infectious wastes like in the COVID-19 case, where the virus can survive on many material surfaces for longer times. To identify and Most of these studies have used ANNs to identify various fractions of waste. Research [22] was conducted to identify various forms of e-waste plastics used multi-layered and hyperspectral imaging ANNs. It proved a highly effective technique as the results showed 99 % of the material identification. Additional researchers have tried to automate the sorting process of the waste using deep CNN (convolutional neural network) [23]. However, the study reported an increased sorting and rating time for garbage compared to manual sorting, which might still be beneficial considering the infectious nature of the waste. Some parts of the collection and sorting process may be optimized to benefit from applying techniques used in this research. A recent study [26] reported that the virus is detectable for up to 24 h on cardboard, among other surfaces. Thus, an automated way of dealing with the different types of materials can be very beneficial in safely handling the COVID-19 waste. Deep CNNs have been in use to distinguish different forms of paper and cardboard [24]. The mean model accuracy in this study was 61.9 to 77.5 %, but that may improve with a more extensive data set compared to the constrained data set used in the study.

Another study [25] used two different techniques for feature extraction and waste segregation. The goal was to identify the recyclables from the non-recyclables. This combination of techniques shows an accuracy of 98.2 %, which is about 10 % better than using merely CNNs.

Water efficiency in the classification of waste was also tested by few studies [27, 28], one of them demonstrated the excellent quality of RF, Nu- and C-LibSVM, with accuracy above 90 % [27].

4.2.2 Other Data Mining Techniques

A few researchers have studied the effect of different parameters on waste generation. For example, research [29] studied the possibility of contribution from socio-demographical and behavioral attributes in waste generation using data mining techniques like cluster analysis and decision tree classifiers. Unfortunately, the tree classification efficiency is as high as 3.6 %, resulting in error rates. Also, [30] studied waste generation based on the type of housing. Lastly,[31] developed and tested a model using various components and characteristics of solid waste, including dry density, water content, and biodegradable fraction. The model performance in the testing method was adequate, with a correlation coefficient of 0.92. Such studies can help understand the potential increase in waste generation in particular societies and neighborhoods given a pandemic situation. This information can help channel the resources for better management of infectious waste and in combination with techniques (Fig. 2).

4.3 AI Models/Techniques: Disposal

COVID-19 waste disposal is the last of the main aspects of COVID-19 waste handling that may use the already developed and demonstrated techniques using AI. However, the handling of the waste may just be the same as other infectious and clinical waste may be handled as the only important information

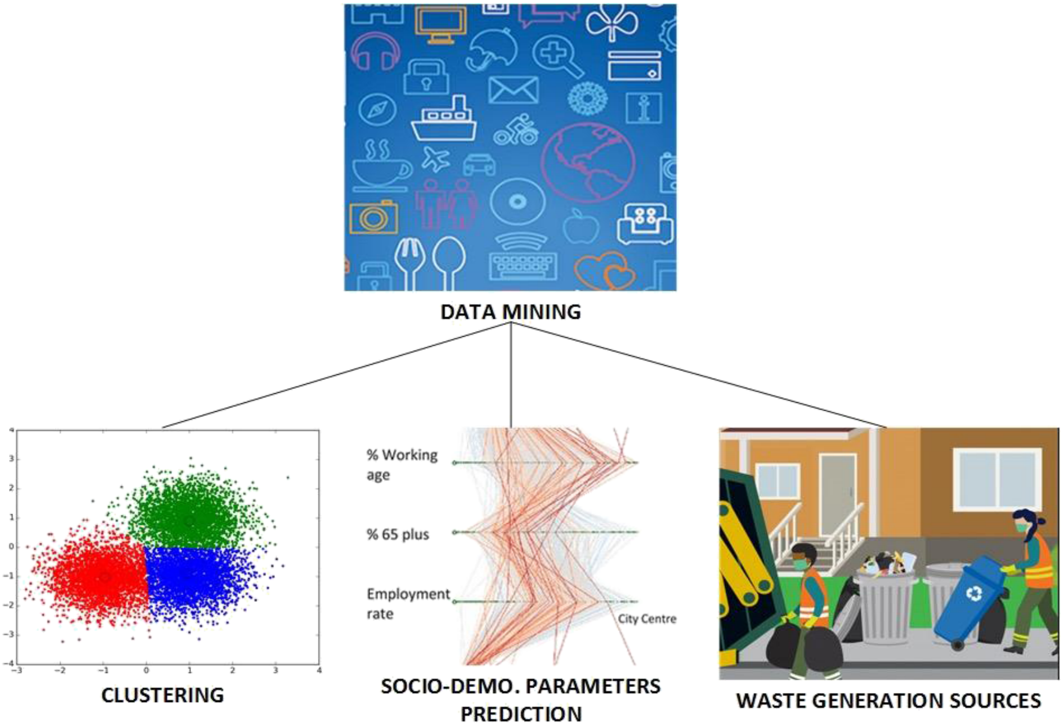


Figure 2. Data mining techniques for waste management.

about the COVID-19 viruses has been about their existence on surfaces. This essentially means that while disposal will need to be done with attention to the different types of surfaces and materials that the virus can survive on, the AI techniques and the goals of the process would remain similar to the other clinical and infectious waste being handled. The following discussion lists out some of the relevant research done inefficiently disposing of clinical waste using AI techniques that may be used while dealing with the COVID-19 waste.

4.3.1 Artificial Neural Networks

By using the ANNs, studies have shown that waste conversion systems like gasification, pyrolysis, and burning can derive sustainable power from MSW [32]. There is a key role in modeling and optimizing process variables in the design and operation of the waste-to-energy producing systems. AI can be used to predict these variables, like predicting high / low-temperature heating and solid waste co-melting [33–36]. Another study [33] uses single/double-layer neural network models to forecast low heating values and syngas yield in a fluidized bed reactor gasification process by utilizing single/double-layer neural network models. Models in the study were trained using the Levenberg-Marquardt BP algorithm. The predictable efficiency of MIMO was better in comparison with a single output model with MSE as small as 0.00074. However, the study also reported a significantly higher computational time for ANNs having double-layer compared to the single-layer model of the ANN. Another research studied the efficiency of ANNs to predict low heating values for solid waste [34]. It was found that it is exact to use feed-forward ANNs with waste composition inputs trained with the BP algorithm. Results showed adequate R^2 and the average error values in training and test phases with 0.992 and 0.0913 during the training and 0.981 and 0.096 during the test phase. Fig. 3 presents a brief description of using ANN for waste management.

4.3.2 Genetic Algorithms

To predict the high heating value of solid waste, another study [36] developed an LS-SVM with GA optimization. The study reported an absolute average error of around 0.327 and a R^2 of 1, which was highly accurate in prediction. Waste management may be carried out using genetic algorithms, as illustrated in Fig. 4.

Tab. 1 presents the summary of applications of AI models/ techniques in different phases and activities in the waste management cycle.

5 AI-based Integrated Waste Management Strategy

Integrated solid waste management (ISWM) is a systematic approach of SMW which includes the strategies that can reduce the amount of waste to be managed. An illustration of the ISWM is shown in Fig. 5. Firstly, the public is encouraged to segregate waste at the waste generation points. This is achieved by implementing a multiple-bin system, in which the house owners segregate each category of trash into bins labeled as

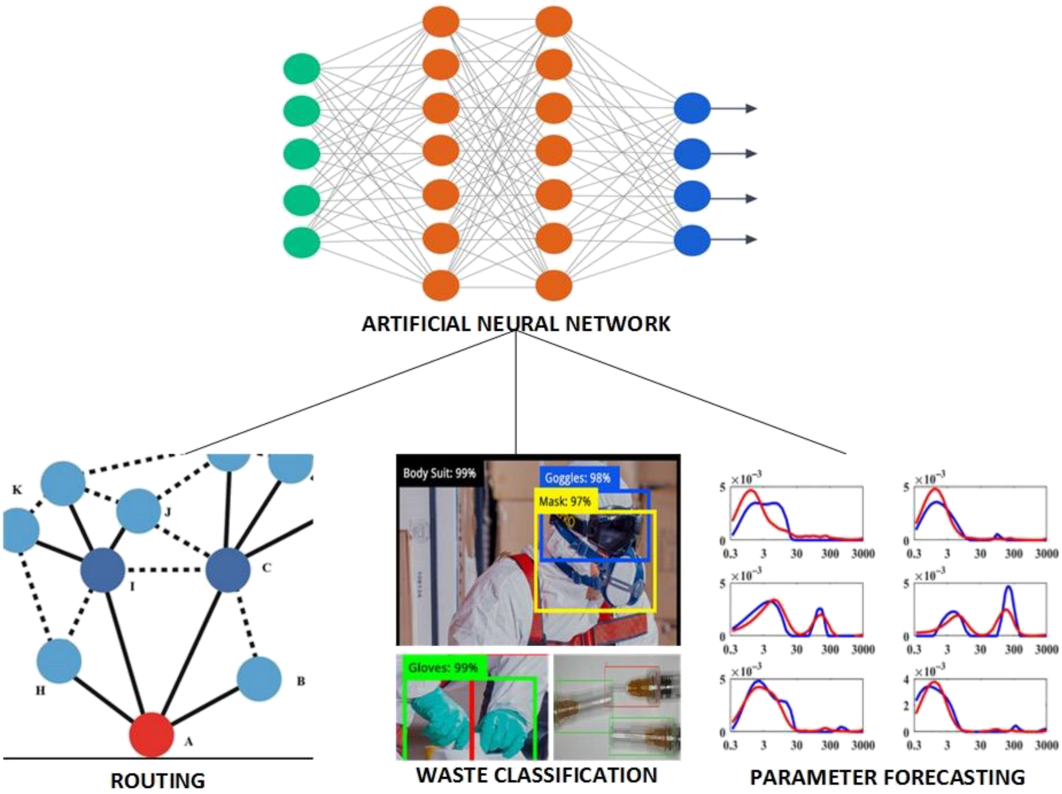


Figure 3. Artificial neural networks for waste management.

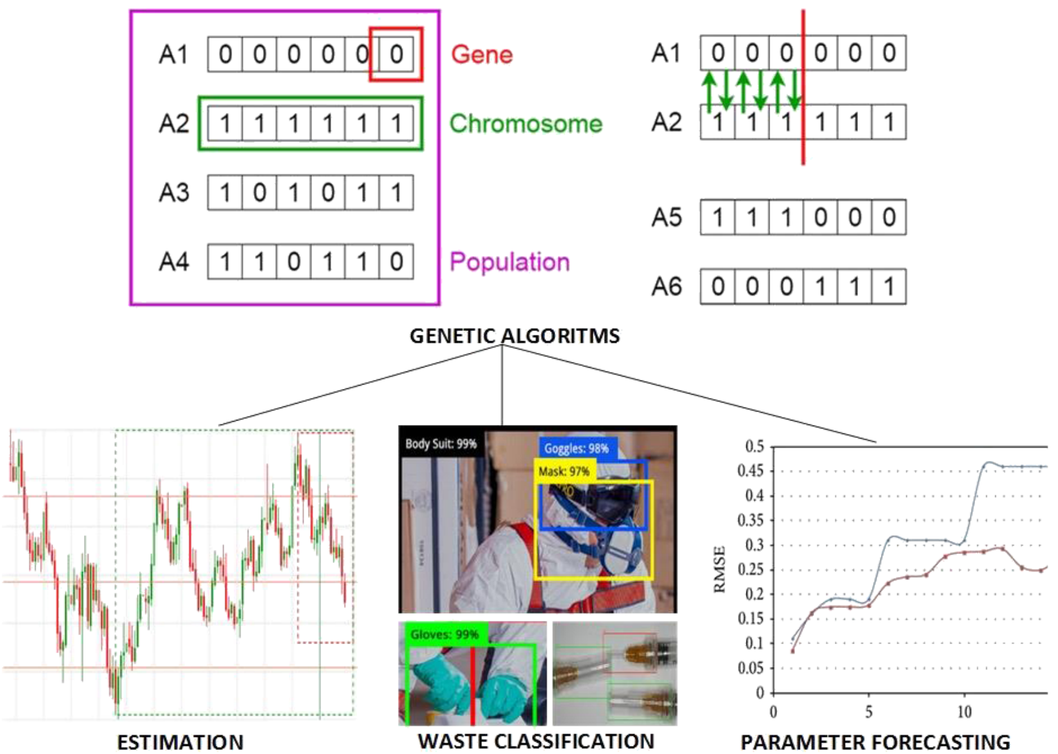


Figure 4. Genetic algorithms for waste management.

Table 1. Applications of AI models in associated waste management activities.

AI Models	Applications	Collection	Classification	Disposal
ANN	Impact on routes, optimized collection frequency, sorting and detection of waste materials, waste feature extraction, forecasting parameters for waste disposal system	[10, 11]	[22–28]	[32–36]
Genetic algorithms	Heat value predictions for disposal system, waste classification, waste generation and accumulation forecasts, and estimation of biogas generation, CO_2 emissions predictions	[12–16, 18–21, 37]	–	[36]
Other data mining techniques	Impact prediction from socio-demographical attributes, waste generation, optimized resource allocation for waste handling	–	[29–31]	–

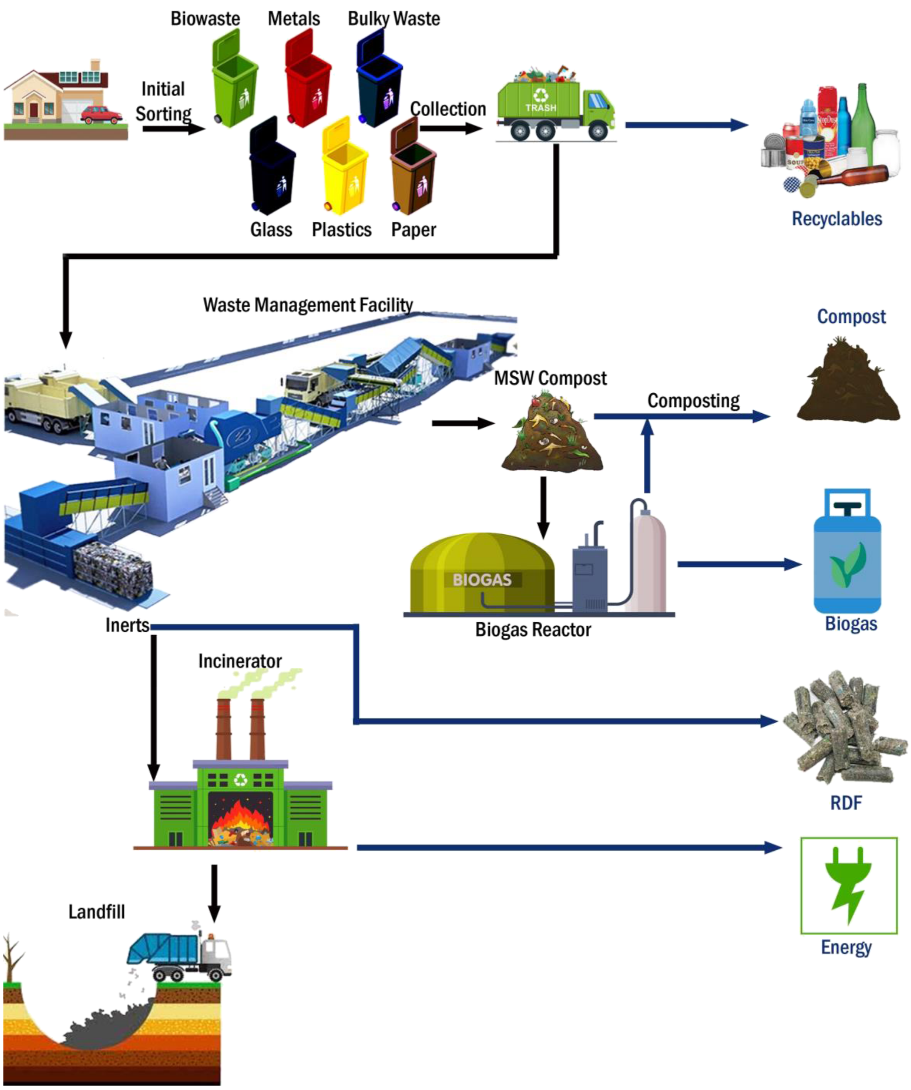


Figure 5. Generalized scheme of integrated solid waste management encompassing the main stages of waste generation, collection, processing and disposal.

(WMF). Next, the segregated trash bins are collected via trash vehicles which may be automated or use human intervention for MSW collection. These vans carry the waste and the recyclables to the waste management facility, where the recyclables are ready separated/hand-picked by workers.

A series of trammel screens separate the waste into MSW composts and inserts in the waste management facility. A part of MSW compost is fed to a biogas reactor for anaerobic biological treatment, which produces biogas, while the rest of the MSW compost is mixed with the residue of the biogas reactor and subjected to the composting process, which is an aerobic biological treatment. The compost produced as a result is collected as a product. A part of the inserts produced at the WMF may be marketed as RDF (refuse-derived fuel) while the remaining inserts are mixed with the residues of the previous processes and burnt in an incinerator to generate power. The rejects of the incinerator are then sent for landfilling.

metals, glass, plastics, bulky waste, and bio-waste. Depending on the type of locality, the categories may be altered for efficient collection. It has been reported that source segregation is more efficient than segregation at waste management facilities

5.1 Target Areas of ISWM

The description of ISWM explains why this approach has received a significant hit in this pandemic due to the health considerations and dangers of transmittance through reuse of items. The current scheme involves significant human interaction and is susceptible to virus transmission. Such a situation demands even more optimized techniques for ISWM while considering the SOPs from WHO. There are some areas of ISWM where the role of AI may be optimized during this pandemic:

5.1.1 Prediction of Solid Waste Characteristics

The lock-down in various countries have left positive effects throughout the world, such as cleaner skies and rivers. However, the same cannot be said for solid waste due to increased generations of medical waste having varying fractions of infected waste [38]. On the other hand, the closure of schools, offices and public places should also reduce the amount and nature of waste generated from such locations. Due to the increased culture of online delivery of groceries and other essential items. Spending more time at home, stockpiling of food items, and a broken supply chain also cause more waste. Therefore, estimation of the characteristics of waste generated during the pandemic holds great promise for an ISWM designing for a pandemic.

Many undeveloped countries usually have no predictions of the waste characteristics, thus requiring manual labor and decision-making throughout the process. However, any efficient solid waste management system is influenced by the estimation accuracy of waste characteristics [39]. These characteristics depend on many legal, socioeconomic, technical, environmental and political factors, thus requiring a lot of training data and robust modeling. Unconventional modeling techniques can handle these issues well, as evident from its frequent usage in the literature for the solid waste characteristics [40–43]. Forecasting the waste generation was the prime focus of such studies, in which ANN, SVMs and various other techniques were employed. Other studies emphasized on waste classification to improve automated waste sorting mechanisms, which reduces manual contact and increases process speed [22–25].

5.1.2 Bin-Level Detection

Detection of bin level may serve two benefits: avoiding the overloaded bins that will result in the potentially infected waste exposure to the environment and reducing the frequency of waste collection that will reduce the social interaction, as directed by the SOPs from WHO. This may be achieved by using smart bins installed with level or image sensors via AI. A considerable number of research have been reported in this regard using AI and achieving high accuracy [39, 44, 45]. Nevertheless, the amount of data required as well as the implementation of the strategy might pose varying issues based on locality. For example, third world countries might not be able to invest in such a system, and, if implemented, some low-income people might be tempted to steal the level/image sensors.

5.1.3 Process Output and Parameter Prediction

Estimating the amount of beneficial and harmful products is also an important factor in the efficient waste management process. For example, the quality of organic matter present in the waste may decide its usage as a biogas source or as compost. Since both processes would require different protocols and are affected differently by the pandemic protocols, these predictions become even more important. Similarly, the optimized parameters for gasification, pyrolysis or combustion processes may also be determined. Researchers have used AI for such predictions, including ANN, adaptive neuro-fuzzy inference system (ANFIS) and GA [33, 36, 46, 47]. In addition, some other work has been reported for optimization of chief constituents in biogas produced using proximate and ultimate analyses, the latter of which was found to be more related to the biogas production [48, 49].

5.2 Short-term Strategy for ISWM

For immediate responses, a readily adoptable strategy must be proposed with the existing facilities and database. Therefore, the following strategy may be adopted based on limited AI database:

- All SMW employees must follow the SOPs declared by the government and WHO.
- Trash collection frequency may be reduced by encouraging the public to use larger bins with lids to avoid exposure. Optimum frequency (in terms of hours or days) may be defined if the average percentage of the bin filled at the time of collection may be estimated using AI.
- Transportation routes may be optimized using AI to minimize workforce and contact.
- Segregation and recycling may be preceded by intermediate holdup so that the virus dies on the surfaces of trash. The holdup time may be optimized based on the existing information of the waste characteristics as shown in Tab. 2, in which AI based estimations may be helpful.

5.3 Long-term Strategy for ISWM

Unlike the initial speculations, it is observed that the COVID-19 is not a seasonal or a regional virus. It can survive many kinds of environments found on various continents of this planet. Moreover, the search for its cure is still underway

Table 2. D-values, i.e., time taken for 90 % reduction of SARS-CoV-2 on common surfaces at various temperatures which defines the need of proper designing and operation of silos for intermediate holdup of potentially COVID-infected waste.

Surface	D-values (90 % reduction of virus on surface)		
	At 20 °C [h (days)]	At 30 °C [h (days)]	At 40 °C [h]
Cotton	133.68 (5.57)	39.6 (1.65)	0
Polymer Notes	164.4 (6.85)	48.96 (2.04)	4.78
Stainless Steel	143.04 (5.96)	41.76 (1.74)	4.86
Paper Note	219.12 (9.13)	103.68 (4.32)	5.39
Glass	151.68 (6.32)	34.8 (1.45)	6.55
Vinyl	152.16 (6.34)	33.6 (1.4)	9.9

and its vaccine may not be available to the masses anytime soon [37]. Therefore, it is very important to develop a long-term ISWM strategy for this pandemic. The following strategy is proposed in this regard (Fig. 6).

5.3.1 ISWM Planning

1. Optimize the routes and the frequencies of trash collection via AI using prior data, optimizing the collection process and reducing exposure.
2. Perform the sizing of large storage silos, Chemical, and biological treatment units by AI-based estimation of amount and types of waste generated at homes/offices.
3. Select the landfill locations and incineration plants optimally.
4. The number of landfill locations and incineration plants may be increased to reduce transportation and increase human resource utilization while observing SOPs.

5.3.2 ISWM Implementation

1. Enforce trash segregation into recyclables (metals, paper, plastic, glass, and batteries), food waste and residual wastes. This will eliminate the subsequent segregation after collection, which involves many health hazards.
2. Encourage the trash segregation into recyclables in the form of concessions/discounts by the government.
3. Collect the trash generated (and segregated) by the collection vehicles that automatically empty the bins into themselves. Such vehicles will eliminate the human contact, thus reducing the spread of the virus.
4. Physical segregation of the trash is reduced to the storage of already segregated waste due to the prior segregation at homes.
5. Use large storage silos with optimum capacities to store metallic, plastic and glass waste as the virus can stay alive on such surfaces for up to 5 days.
6. Use optimum number of landfill locations and incineration plants for waste disposal.

A schematic of this implementation scheme is presented in Fig. 7. It should be noted that this strategy is proposed for the developing countries, which might not be financially strong enough to invest on the options of bin-level detection or self-driven cars. However, the extent of the AI role is evident in the strategy, and thus it can be concluded that AI may reinvent ISWM if the governments are willing to invest in a healthy and environmental-friendly future.

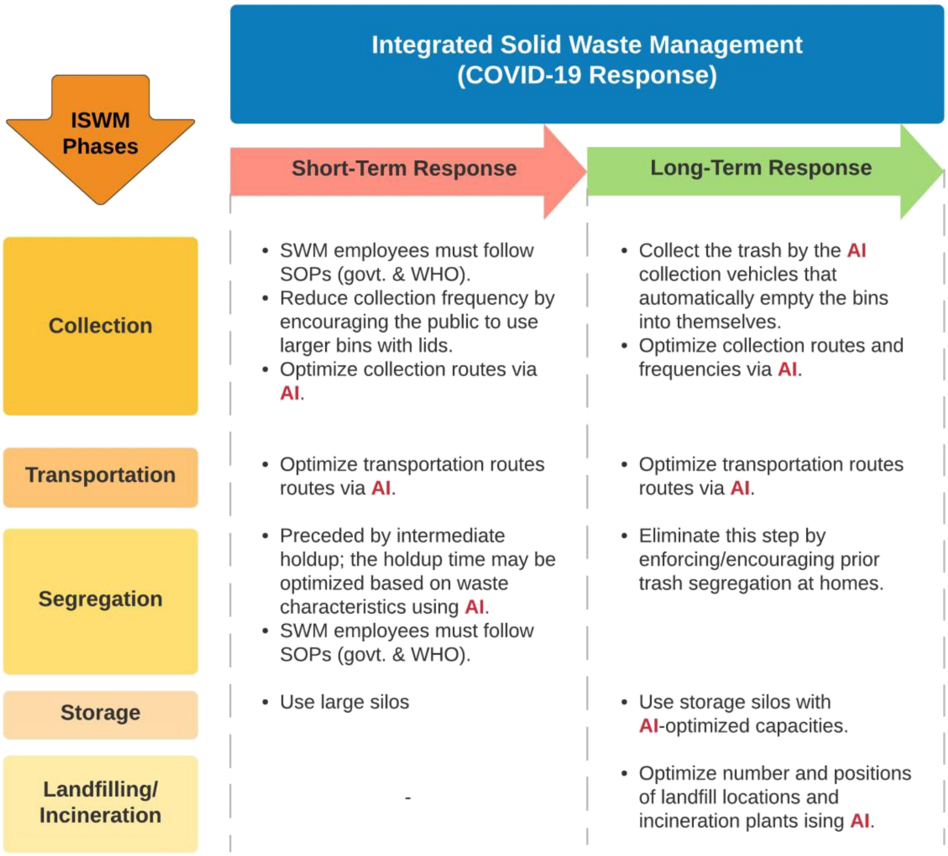


Figure 6. AI-based ISWM: Short- and long-term response to COVID-19 for solid waste management using AI in various stages. This may be incorporated in whole or in part, depending on the available resources and demographics.

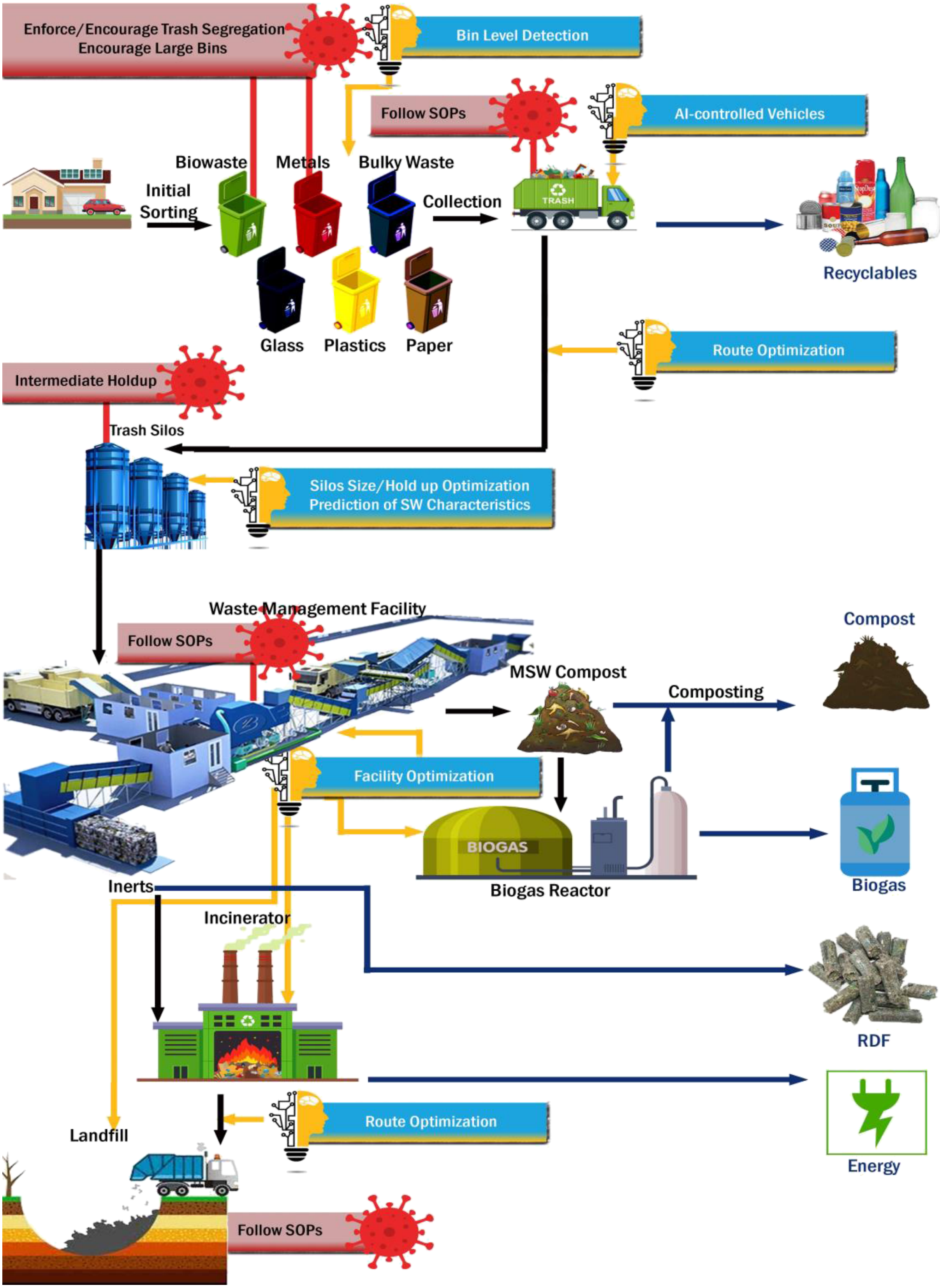


Figure 7. AI incorporation in the integrated solid waste management system to incorporate both short-term and long-term response of COVID-19 by reducing human contact and optimization of routes and resources.

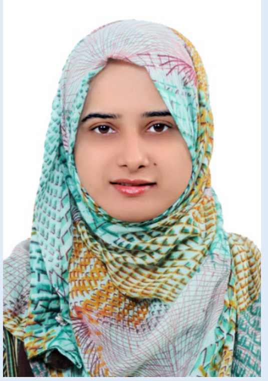
6 Conclusion

This paper identifies the COVID-19 solid waste generation sources and the different types of waste, and the threats that come with them during pandemics. The need for a strong WMC is explained as dependent on this input, as are the key features of the eventual implementation of an AI-based strategy. After establishing the origins and forms of COVID-19 solid waste, the paper presented the use of AI in various areas of the WMC. With all the background discussion in the relevant areas, the paper presented the different methods from the AI/ ML domain that may help some of the critical phases of the waste management that included content routing, grading, and sorting for ultimate disposal. These techniques and processes were combined to present an integrated solid waste management approach that was presented with the need for optimization and customization given the stricter SOPs for COVID-19, as set by WHO. The short-term strategy is devised to use the current systems and facilities and optimize them with the latest directions of WHO in terms of operative instructions for waste handlers. This means that the current systems may be introduced with specific waste handling activities and other ingredients like optimizing route calculation and increasing the time of handling the waste to avoid humans contracting the virus that may be present on the surfaces. As it comes to long-term strategy, more structural changes in the waste management strategy and resources are proposed, emphasizing the setup of landfills and silos at the physical level augmented with the AI/ML-based systems to be set up in collection classification and disposal of the COVID-19 waste. The validation of the proposed strategy needs full scale implementation. However, given the scope of this work, we can rely implicitly on the verification of the individual parts of the strategy that come from reviewed and published work, that has been used in proposing the comprehensive short and long term strategies in this paper.

Overall, it can be seen that AI/ML-based methods can be employed to improve the performance of several different activities in the waste management process that can provide a safe and scalable setup together with the physical measures as laid out in the discussion a long-term waste management -strategy.

Conflicts of Interest

The authors declare no conflict of interest.



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