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# Artificial Intelligence and Machine Learning Techniques for Next-Generation Waste Management System: An Overview

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## Abstract

This article presents an overview of artificial intelligence and machine learning techniques for next-generation waste management systems. Due to the rapidly increasing energy demand, waste management has gained popularity among energy sector professionals. Reutilizing waste resources is essential for achieving highly efficient energy use and improving human living standards. Waste management plays a critical role in developing resource-efficient lifestyles.

This article also highlights several case studies that address energy convergence and the generation of smart energy from waste. Moreover, it provides an overview of emerging techniques involving artificial intelligence, machine learning, and internet of things for waste utilization, ensuring optimal resource use in waste management systems. Finally, through the examples and insights presented, the article demonstrates that waste management is central to advancing next-generation recycling energy systems and fostering sustainable development.

**Categories:** AI applications, Energy Efficiency and Sustainability, Machine Learning (ML)
**Keywords:** environmental sustainability, blockchain technology, waste management, iot, artificial intelligence, machine learning

## Introduction And Background

The demand for energy is on rise, especially in urban areas, presenting significant sustainability and resource management as the leading challenges. The energy demand is mainly affected by factors such as urbanization, infrastructural expansion, public health concerns, and the desire for a human living standard. Next-generation emerging technology-based smart waste management strategies can meet energy demands and address environmental issues, as shown in Figure *1*. An overview of frequently used artificial intelligence (AI) and machine learning (ML) techniques is provided in Table *1*. The table addresses the operational principles and specific applications within the field of solid waste management. Municipal solid waste (MSW) plays a vital role in converting waste to energy. Waste-to-energy (WtE) conversion methods may solve the problems associated with waste management and energy generation. Integrated solid waste management systems that combine WtE technologies have been explored, and some worldwide examples have been documented [1,2]. Many researcher have focused on the WtE conversion. In this article, the literature selection was conducted very carefully to ensure that only the most relevant, high-quality studies have been incorporated. The analysis of the research collaboration network of waste management and MSW is shown in Figure *2* made using VOSviewer and openalex.org. United States, India and China are the most prominent countries in the research field of “waste management and MSW”.

Table *2* represents the top countries based on the number of publications and citations. Their density visualization of the collaboration network is given in Figure *3*. Author co-citation networks can find the most contributing authors in a specific field, as shown in Figure *4*. The most cited organizations with citation frequency are shown in Table *3*.

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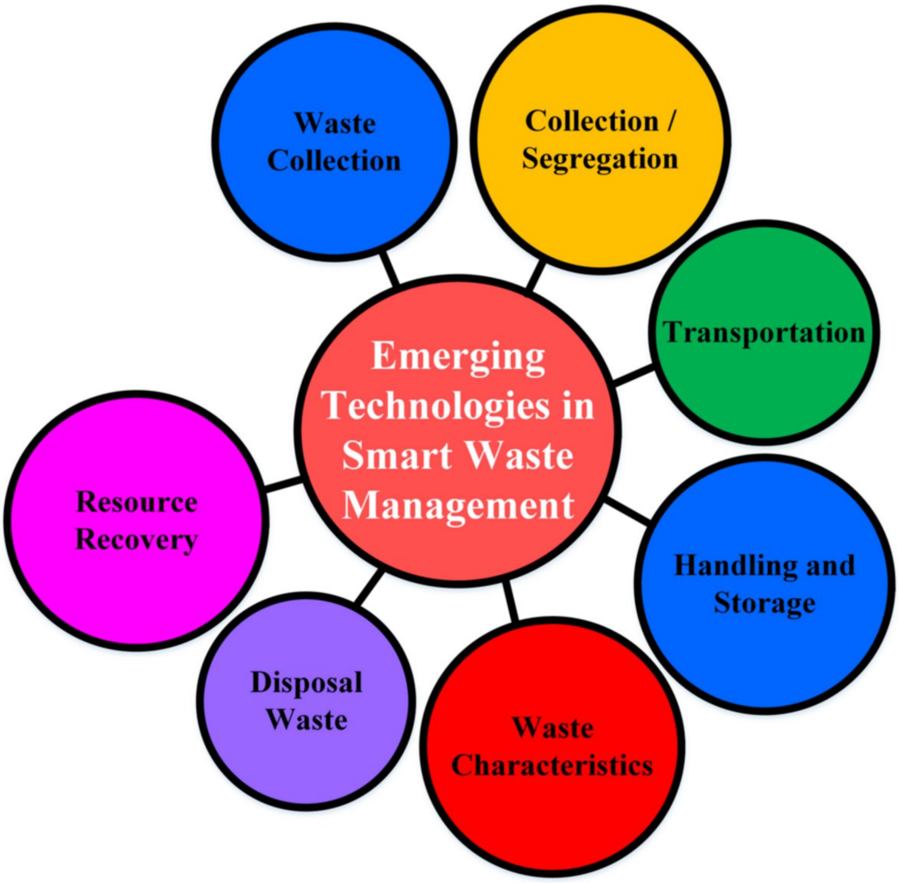


**FIGURE 1: Smart waste management system**

| AI/ML Technique | Main Findings | Limitations | Application |
|---|---|---|---|
| Artificial Neural Networks (ANNs) | High accuracy in complex pattern recognition. | Requires large datasets. | Prediction |
| | Adaptive learning for dynamic environments. | Computationally intensive. | Regression |
| | Handles nonlinear relationships effectively. | Prone to overfitting. | Classification |
| Support Vector Machines (SVM) | Effective in high-dimensional spaces. | Computationally expensive for large datasets. | Classification |
| | Works well with small datasets. | Requires careful kernel selection. | Regression |
| | Robust against overfitting with proper kernel. | Less effective with noisy data. | |
| Fuzzy Logic (FL) | Handles uncertainty and imprecise data. | Requires expert-defined rules. | Classification |
| | Provides human-like reasoning. | Increased complexity with more rules. | Regression |
| | Effective for control systems. | Not ideal for large datasets. | |
| Genetic Algorithms (GA) | Effective in optimization problems. | High computational time. | Prediction |
| | Finds near-optimal solutions efficiently. | No guarantee of finding the global optimum. | Optimization |
| | Does not require gradient information. | Requires careful parameter tuning. | |
| Reinforcement Learning (RL) | Learns optimal strategies through trial and error. | Requires extensive training time. | Prediction |
| | Adapts to dynamic environments. | Difficult to interpret learned policies. | Optimization |
| | Suitable for sequential decision-making. | May converge to suboptimal solutions. | |
| Deep Learning (DL) | High accuracy in feature extraction. | Requires high computational power. | Prediction |
| | Handles large, unstructured data well. | Difficult to interpret decisions. | Classification |
| | Suitable for complex decision-making. | Prone to adversarial attacks. | |

**TABLE 1: Advantages and limitations of commonly used AI/ML techniques**

AI, Artificial Intelligence; ML, Machine Learning

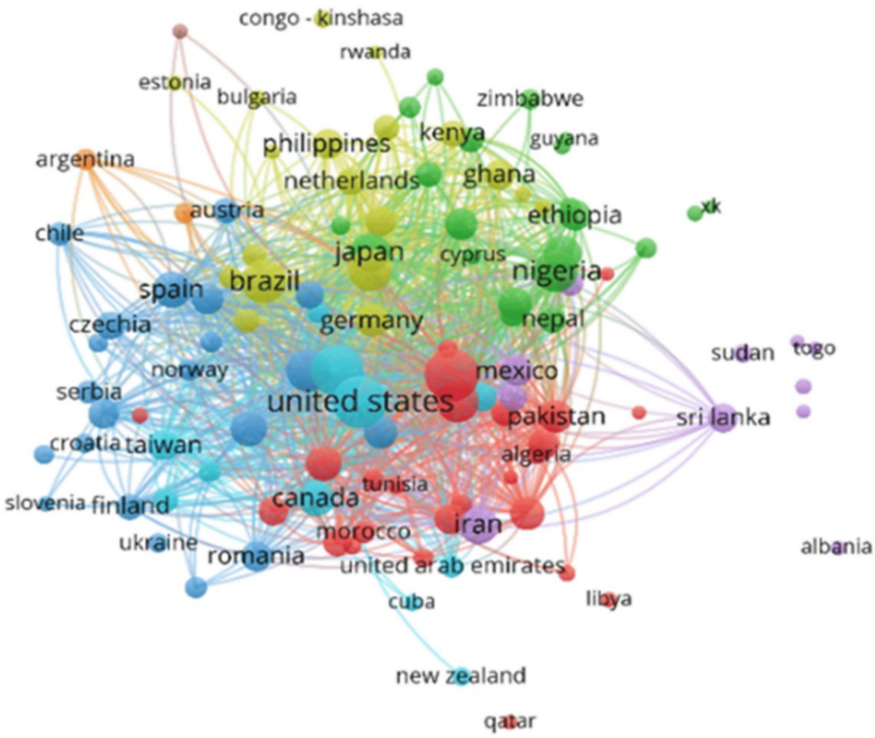


**FIGURE 2: Countries/regions collaboration network (minimum five documents) in the research field of "waste management and municipal solid waste"**

| Rank | Country | Documents | Citations | Total Link Strength |
|---|---|---|---|---|
| 1 | United States | 862 | 28,005 | 6,628 |
| 2 | India | 847 | 20,748 | 7,067 |
| 3 | China | 798 | 25,337 | 8,487 |
| 4 | Brazil | 427 | 7,359 | 3,062 |
| 5 | Nigeria | 366 | 5,442 | 1,724 |
| 6 | Italy | 345 | 12,982 | 4,436 |
| 7 | United Kingdom | 345 | 13,243 | 4,403 |
| 8 | Malaysia | 325 | 11,099 | 3,427 |
| 9 | Japan | 254 | 7,689 | 2,902 |
| 10 | Iran | 234 | 5,674 | 2,920 |

**TABLE 2: Top countries based on the number of publications (VOSviewer and openalex.org)**

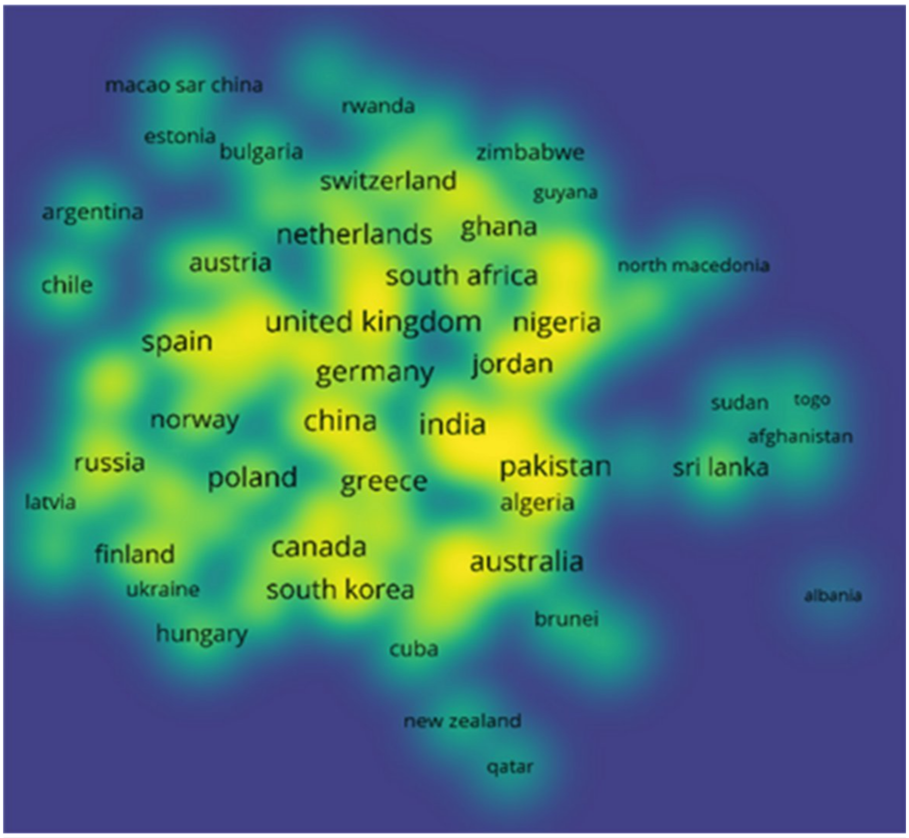


**FIGURE 3: Density visualization clusters of institutional cooperation (minimum five documents) in the research field of “waste management and municipal solid waste”**

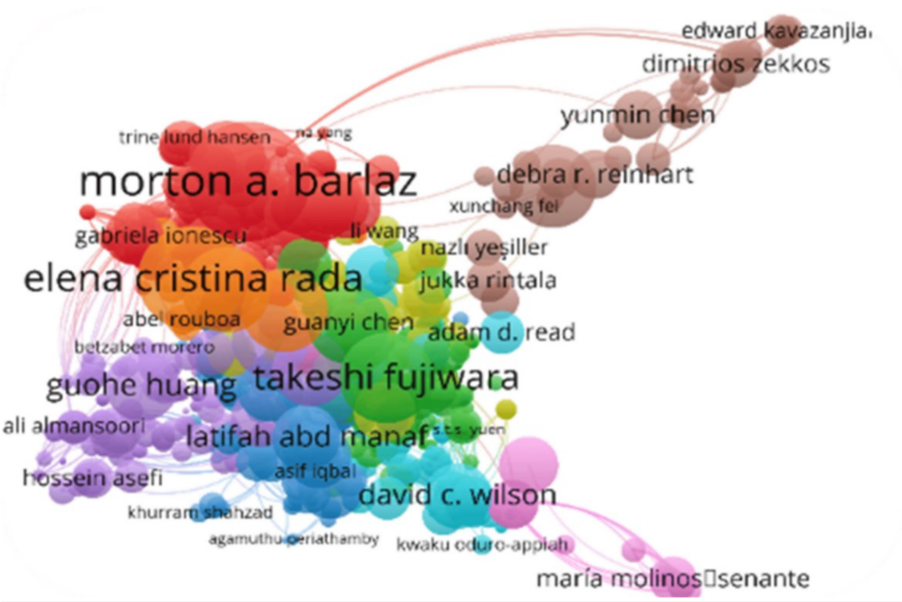


**FIGURE 4: A visualization of author co-citation network**

| Rank | Organization | Country | Documents | Citations | Total Link Strength |
|---|---|---|---|---|---|
| 1 | Tsinghua University | China | 81 | 3,905 | 1,595 |
| 2 | University of Tehran | Iran | 65 | 2,066 | 989 |
| 3 | University of Technology Malaysia | Malaysia | 42 | 2,235 | 884 |
| 4 | University of Trento | Italy | 40 | 1,551 | 864 |
| 5 | Chinese Academy of Sciences | China | 60 | 2,127 | 826 |
| 6 | Imperial College London | United Kingdom | 30 | 2,298 | 727 |
| 7 | University of Insubria | Italy | 31 | 730 | 717 |
| 8 | Technical University of Denmark | Denmark | 43 | 2,940 | 705 |
| 9 | Zhejiang University | China | 44 | 1,926 | 678 |
| 10 | National Environmental Engineering Research Institute | India | 34 | 1,699 | 676 |

**TABLE 3: Top organization based on the number of publications (VOSviewer and openalex.org)**

The contributions of this article include the following:

1. The AI, IoT, and blockchain techniques in waste management systems are systematically investigated from a techno economical, operational, and sustainability perspective, highlighting their emerging applications, advantages and limitations, and potential for future development.

2. Proposed several real-world case studies, discussing existing challenges and outlining future research directions to advance smart waste management systems.

3. Identified current challenges and highlighted opportunities for future research and development in next-generation waste management.

# Review

## Case study

*Case 1: MSW Management at Urta-Chirchik*

Nowadays, the demand for eco-friendly energy generation is growing in popularity due to environmental concerns, reliability, low cost, and ease of availability. Recently, MSW has been utilized globally as a source of sustainable and environmentally friendly energy [3,4]. MSW has a significant impact on both society and the ecosystem. These impacts can be broadly categorized, as shown in Table *4*.

| Impact Type | Short-Term Impacts | Long-Term Impacts |
|---|---|---|
| Resource Destruction | Destruction of natural resources | Permanent loss of resources |
| Aesthetic Value | Loss of aesthetic value to human well-being | Environmental degradation |
| Economic Impact | Economical resources | Instability in economy, increased poverty |
| Biological Changes | Biological change | Permanent changes in biodiversity, species extinction |
| Environmental Changes | Environmental issues | Water quality and habitat loss |
| Social Economy & Viability | Economic instability | Challenges to social stability and viability |

**TABLE 4: Impacts of municipal solid waste**

Source: [5]

One of the most concerning issues with MSW is the decomposition of biodegradable waste, such as food waste. When this waste breaks down in landfills, it releases methane gas. Methane is a potent greenhouse gas, significantly more harmful to the ozone layer than carbon dioxide. Its release contributes to global warming and climate change, posing severe environmental threats.

Moreover, when an open MSW landfill site accidentally ignites, it emits toxic smoke. Consequently, landfilling of MSW has become unpopular in many countries [6,7], and efforts are being made to reduce reliance on landfills. Civil squanders are a sustainable additional energy resource, produced in enormous quantities, but when unmanaged, it can be unusable and harmful to the environment. The separated organic material can be used to generate heat or electricity. At the same time, the WtE approach helps address real environmental pollution problems in urban areas through the use of MSW [3,8]. Uzbekistan, with a population of more than 32 million, is the most densely populated country in Central Asia. So, the amount of MSW produced there is considerably higher than in other Central Asian countries. The problem of solid waste collection is relevant in all parts of the world, and the Republic of Uzbekistan is no exception. According to the State Committee of Statistics of the Republic of Uzbekistan, the country generates 35 million cubic meters of MSW annually. In total, the state has over 100 million tons of mechanical trash standing in landfills that need to be disposed of in order to open new territories for waste sorting sites. Currently, two billion tons of waste are collected across the country [9,10]. When heat recovery is required, waste is increasingly incinerated. New waste treatment methods can reduce waste volume by up to 90% or reduce solid bulk by 70% [11,12]. Current methods used for the dissipation of waste heat treatment are deemed efficient. They also generate huge amounts of undesirable by-products (e.g., waste, tar, and unstable compounds). These reactions must be carefully monitored to prevent harm to both the environment and human health. Typically, waste is either dumped in landfills or recycled in the best-case scenario. Many countries have already implemented plans to reduce landfill volumes while simultaneously advancing modern waste recycling technologies [13]. Due to the vast amounts and varying composition of waste, one has to first characterize them by virtue of cutting-agent methods and then adopt the best blending technology on that basis.

Thus, the goal of this study is to thoroughly examine the specific characteristics and attributes of MSW produced at the landfill in the Urta-Chirchik region. This case study investigates the characteristics and synthesis of MSW generated at Urta-Chirchik, arguably the best site in the Tashkent region. The findings showed that the level of wood waste was the highest among the various MSW components. Subsequently, two groups were created for the MSW tests: a) mixed MSW and b) wood waste. The cases were analyzed both in accordance with and in deviation from the European Pn-En and American Society for Testing and Materials (ASTM) universal standards. An important recovery analysis was carried out using a bomb calorimeter (model: V-08 MA) and an ASTM measurement tool. The estimated calorific values (kcal/kg) were 2,479.34 for mixed waste and 2,190.02 for wood waste. For these tests, a CHNS/O elemental analyzer was used to perform the necessary analysis. X-ray fluorescence data showed that the main constituents of MSW and wood waste are CaO, $SiO_2$, $Fe_2O_3$, and 15 other associated oxides. It was observed that, compared to coal, MSW is less ignitable. However, the pre-rewarding process can increase its reactivity by reducing non-combustible elements such as oxygen and debris. It is also recommended to present the current MSW thermochemical transformation processes to illustrate the progress of solid waste-to-energy systems and the production of value-added commodities. The comparison between MSW and wood is shown in Figure *5*.

This study presents the MSW and wood waste profile of the Urta-Chirchik District in the Republic of Uzbekistan. Both MSW and wood waste were closely examined, and it was found that MSW had a lower moisture content than wood waste. This contributes to a more optimistic calorific estimate for MSW in the Urta-Chirchik region. The higher estimated calorific value of MSW compared to wood waste can be attributed to its less waste and fixed carbon content. A conclusive analysis revealed no significant differences in carbon (C) generation between MSW and wood biomass. However, hydrogen (H) showed an adverse effect, likely due to its correlation with moisture content. Notably, higher moisture content reduces the high heating value of biomass sources; hence, hydrogen shows inverse relation to the heat produced during combustion. Sulfur and nitrogen levels in the wood sample were found to be lower than those in MSW, suggesting that emissions of these elements during thermochemical conversion of wood waste will be substantially lower than those from MSW. However, highly selective and efficient metal catalysts supported by high-temperature-resistant oxides can significantly reduce or even eliminate such emissions. The thermochemical characterization of MSW and wood biomass from the Urta-Chirchik landfill suggests that these waste types are viable options for bioenergy production and represent a promising convenience [14].

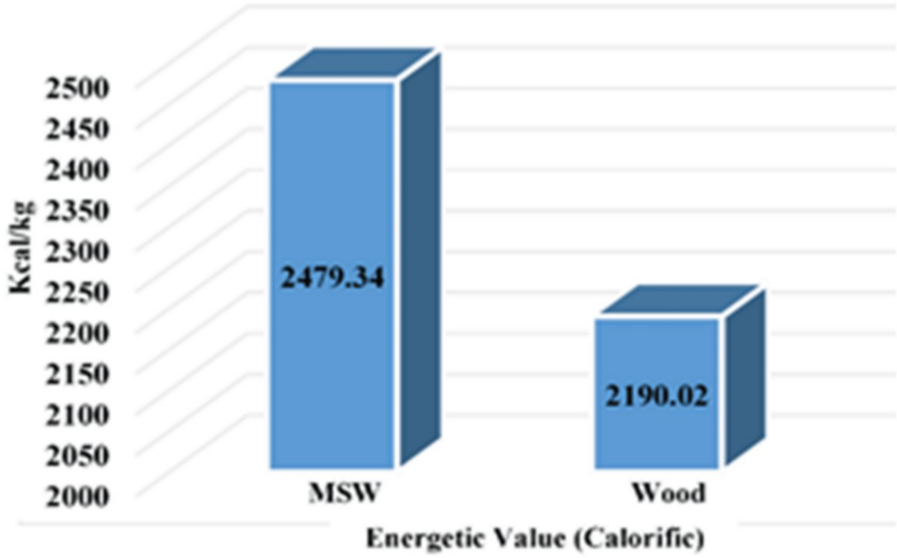


**FIGURE 5: A comparative analysis of municipal solid waste (MSW) and common wood**

Source: [14]

*Case 2: WtE Technologies of Energy Recovery in Ecuador*

The World Bank estimates that 1.3 billion tons of waste are generated annually worldwide, and this figure is projected to increase to 2.2 billion tons per year by 2025 [15]. As a result, there will be an increasing need for MSW removal and treatment across the globe. The worldview of solid waste management involves developing nations. Innovations to employ MSW for fertilizer, heat, solid biofuel, and energy were established in developed countries [16-18]. The truth is that the establishment of landfills and the collection and transportation of trash remain significant challenges in the developing world [19,20]. Impromptu administration, social and financial angles, industrialization, low living standards, approaches, and global impacts have hindered a satisfactory solid waste management in creating nations [21,22]. In this context, WtE technologies are indispensable for achieving economical solid waste management worldwide, with particular emphasis on creating countries. MSW is a critical, inexhaustible asset with the potential to generate heat and limited biogas products through the application of appropriate WtE technologies [23]. These advances must be chosen depending on the waste organization appraisal and financial aspects [24]. Determination of the fitting WtE technologies is a complex undertaking because the age of the solid waste is affected by irregularity and the financial degree of makers [25]. Strategy instruments for economic waste administration likewise have a considerable effect in determining WtE technologies [26]. Squander to-vitality advances can be grouped into biochemical and thermochemical forms, while MSW can be named biodegradable and non-biodegradable, which are appropriate for biochemical and thermochemical forms individually [27,28]. Biochemical procedures are identified with anaerobic assimilation advancements to deliver biogas [29], and thermochemical forms are recognized with pyrolysis [30], gasification [31], and burning advances [32]. Different creators additionally consider landfill gas use advances [33] alongside biorefineries as WtE technologies [34,35]. These advancements can potentially decrease ozone-harming substance emanations in decentralized vitality from squandered frameworks [36]. The Ecuadorian Ministry of the Environment (MAE) has recently designed the National Program for the Integral Management of Solid Waste (PNGIDS) [37,38]. There are 221 Decentralized Autonomous Governments (GADs - Municipalities) in the country. Only 24% of GADs have started the process of removing waste from its origin. Before the end of 2017, 5.4 million metric tons of MSW would be produced annually at a rate of 300 kg per person annually, according to MAE-PNGIDS.

Moreover, waste-to-vitality developments are seen by MAE-PNGIDS as a crucial aspect of the program. A few jobs are being implemented in GADs. For instance, it is predicted that extracting methane and running a thermal power plant at Cuenca's Pichacay landfill will produce 1.6 MWh of energy [39]. A variety of WtE technology venture cases are concentrated in Quininde [40] and Quito [41]. Nevertheless, the connected research has not addressed the methodology to assess the possibility of vitality recovery from MSW in the nation or in GADs. This analysis uses standard models in conjunction with biochemical and thermochemical forms to determine the MSW from Quito that has the capacity to sustain life. Using nonexclusive models, this analysis assessed the biochemical and thermochemical energy potential of MSW in Quito, Ecuador. According to the results, Quito's MSW includes 81.4% putrescible trash, 30.7% non-biodegradable waste, and 69.3% biodegradable garbage. Individual energy output potential for the thermochemical and biochemical courses was found to be 5,970 kWh/tMSW and 62 kWh/tMSW, respectively. Additionally, the power potentials for the thermochemical and biochemical forms separately were evaluated at 0.07 and 0.78 MW/tMSW, respectively. Thus, this analysis suggests that there is a great deal of potential for producing biogas and thermal output energy from Quito's MSW.

This study examined the viability of using municipal solid trash in order to determine the amount of energy that may be produced in Ecuador's capital, Quito. According to the data, Quito's waste management system has a positive percentage of biochemical and thermochemical forms, with 69.31% of its trash being biodegradable and 30.69% being non-biodegradable. Reliable scientific models were employed to assess the biogas quality, output energy, and power potential. The output energy potential was calculated using thermochemical forms to be 5,970 kWh/tMSW, and biochemical techniques were used to calculate the output energy potential to be 62 kWh/tMSW. Using this information can help select the suitable invention to turn solid waste into electricity or heat. It is advised to conduct additional research to ascertain the massive input of waste and apply models that make use of various aspects [42].

*Case 3: Malaysian Palm Oil Industry's Utilization of Biomass Wastes for Energy Recovery*

A tremendous amount of biomass waste - including empty fruit bunches (EFBs), fibers, shells, and palm oil mill effluent - is generated during the palm oil extraction process due to the rapidly growing palm oil industry [43-45]. This biomass residue can be used as boiler fuel or converted into organic fertilizer. Palm oil mills operate on a cogeneration system to produce electricity and steam for palm oil production, utilizing solid biomass waste as the primary source of stored energy input.

Petroleum products are the fundamental wellsprings of vitality used in industries today. However, the subsequent deficiency of vitality and an unnatural weather change have emerged as serious issues, making the development of inexhaustible and feasible output energy sources critically important for the future of human race. Biomass-based energy is among the most promising candidates for alternative, sustainable, and environmentally friendly energy sources. In this context, palm oil is one of the most important types of oil in the world and is used to produce biodiesel, food products, fats, and associated products. A tremendous amount of biomass waste, which includes void organic product pack, fiber, shell, and palm oil factory effluent, is created from the palm oil removal process on account of the rapidly developing palm oil industry [43-45]. Biomass buildup can be used as heater fuel or be changed into natural manure. Palm oil factories work on a cogeneration framework to deliver power and steam to create palm oil, utilizing solid biomass squanders as a primary wellspring of stored energy as input. Explorations connected to this field have received increased attention since the beginning of this century, namely in Malaysia, Indonesia, Columbia, and Brazil [46-51]. The biomass that is available in the plants has the potential to provide more excess power than what is needed for processing, according to the estimates of power age that are reliant on mass and vitality parity [50]. The possibility of co-shooting coal and oil palm biomass to minimize the quantity of coal required has been demonstrated by thermogravimetric analysis of the burning properties of bit shell, mesocarp fiber, and less dense natural product bundles in oil palm biomass and coal/biomass blends [52]. In addition to the social and economic viability and manageability of turning oil palm biomass into bio-based business products, many experts concentrated on the development and utilization of energy in palm oil facilities [53-55]. Life cycle assessment depicted the natural effects of two palm oil creation frameworks [56]. A diagnostic device was created that coordinates cost, vitality investment funds, ozone-harming substance contemplations, situation examination, and a Geographic Information System to give an exhaustive investigation to powerful utilization of palm oil squander as vitality assets [57]. The main characteristics, quantities, and existing practices of biomass in palm oil plants and ranches were summarized by Garcı 'a-Nunez et al. [58]. It was emphasized how important it is to develop valuable products from biomass waste and to move palm oil mills into bio-treatment facilities. According to Chiew and Shimada [59], Malaysia is developing seven innovations for using oil palm buildup: producing ethanol, recovering methane, making briquettes, producing biofuel for combined heat and power (CHP) plants, treating the soil, producing medium-thickness fiberboard, and producing mash and paper. Soil remediation and methane recovery were perceived as more inherently beneficial than other advances. Meanwhile, there has been a lot of interest in the production of biogas and hydrogen from POME and solid waste buildups from the palm oil plant industry [60,61]. It is anticipated that oil palm biomass will be a potential raw material for hydrogen gas generation [62,63]. Researchers also investigated the best conditions for producing methane from oil palm biomass by solid-state anaerobic absorption by adjusting the ratios of carbon to nitrogen, feedstock to inoculum, and all-out solids [64]. A novel process based on two-phase thermophilic and mesophilic maturation has been developed to enhance the production of hydrogen and methane from palm oil plant material [65]. Kanchanasuta and Pisutpaisal [66] found that the slop seed's close proximity to the cake in the palm oil decanter seemed to encourage hydrolysis and methanogenesis. Nevertheless, the main barriers to the increased use of biogas are its poor calorific value, the existence of harmful gases in the mixture, and the high cost of refinement. Flameless ignition is unique among other practical methods for using biogas, as evidenced by the presentation of a flameless ignition chamber powered by biogas and the adoption of a lab-scale flameless burning heater [67]. The attributes of biogas under different ignition systems in consolidated warmth and force age framework additionally demonstrated this point [68]. It was discovered that the pace of intensity age expanded while including a limited quantity of hydrogen into biogas utilizing a autothermal reactor in a burning framework [69]. Be that as it may, some reports concern explicit investigation and improvement for compelling biomass usage for heat and power in a palm oil factory. Through contextual analysis, it is crucial to investigate and optimize the deterioration process of concentration and heat from the waste biomass in the palm oil sector. In this study, one of the largest palm oil-supplying countries, Malaysia, had a palm oil factory. Using ECLIPSE programming, a recreation and improvement examination of the palm oil biomass based thermal power plant was directed. One of the most important oils in the world is palm oil, and the process of separating it from other oils produces enormous amounts of biomass that could endanger the environment. In the interim, the lack of petroleum goods is making the electricity shortage worse. Converting biomasses from the palm oil industry is helpful for the power age since it forces shortages and lessens ecological deterioration. In order to better understand and enhance the process of quantity and heat degradation from waste biomass in the palm oil industry, an exploratory study of a thermal power plant in a palm oil plant supported by realistic and limitless biomass was carried out using ECLIPSE programming through a contextual investigation in Malaysia. Examples were collected nearby, and the benefits of the biomass wastes from the factory were noted. Waste samples were examined in a research institution to find out their calorific value, ability to synthesize compounds by concoction, and potential to produce biomethane. After that, a replica model was constructed using ECLIPSE programming, and it was given the go-ahead to make use of the CHP plant's common sense data. Three different biomass waste combinations were employed in the replication: MF co-shooting with biogas, energy production using shell and EFB as fuel, and power age using kernel shell (KS), EFB, and biogas with preheaters. The three combinations were discovered to produce enough heat (steam) and electrical force to meet the necessary force and temperature criteria for the creation process. The solid biomass waste from palm plants was revealed by the recreation results. The biogas produced by the facility might provide a sufficient and endless supply of fuel for the process of producing palm oil. Giving the surrounding area more electricity is feasible, which is remarkable when compared to another option for using biomass waste from palm oil.

In a palm oil factory in Sabah, Malaysia, an attainability study of the modification and improvement of the palm oil biomass-based thermal power plant was carried out. The area's biomass wastes were gathered, and their ability to produce chemicals, biomethane, and calories was assessed in a research facility. Using ECLIPSE programming, a replication of CHP plant was shown. The results indicate that the power plant can generate 16.1 GWh of electricity annually when it is powered with EFB and KS, producing 2.2 MW of power. Rebuilding possibility also focuses on replacing KS with biogas to power the current CHP system. The reproduction's findings indicate that when paired with preheating vent gas, biogas, which produced 1.3 MW of power, would be an acceptable fuel substitute for KS. The net force produced by this force plant annually is 17.4 GWh and 2.4 MW, according to the third replication using biogas, KS, and EFB. Reproductions of continuous power from biomass derived from palm oil indicate that it can supply energy to the lattice. It will greatly aid the country in lowering the carbon emissions from the electrical power output and help it recognize its obligation to reduce carbon outflows [70].

*Case 4: Saudi Arabia's Potential for Waste Conversion to Energy*

By 2025, the world's population is expected to reach 8.2 billion, growing at a rate of 1% year [71]. The developing countries will see tremendous population growth, with Africa accounting for the majority of this growth [72]. A segment of the population lives in or migrates to urban areas at a pace of 1.5% higher than that of population growth [72]. Urbanization will increase in developing nations, particularly in Asia, as industrialization gains up speed [73]. According to the Food and Agriculture Organization of the United Nations [74], it can be deduced that there will be a global increase in energy output, consumption, and waste. Essentially, by 2025, it is expected that the world's energy demand will have increased by 58%, compared to the existing demand of 46%. For example, the demand for energy in Asia is predicted to rise at a rate of 3.7% every year [75], changing this district into a zone of high enthusiasm for future vitality improvements. Petroleum products are the most dependent wellspring of vitality flexibly overall [75]. Coal, raw petroleum, and flammable gas are utilized to create 13,700 TWh of power, around 84% of the worldwide power creation. They are causing genuine ecological contamination, particularly the age of ozone-harming substances (greenhouse gas) and environmental change. Hence, sustainable power sources have increased consideration over the last 20 years [76]. The WtE section of the sustainable power source market has been more competitive in the energy marketplace because to factors such as mechanical advancements, process-cost reductions, and administrative incentives [77]. WtE is ideal for producing sustainable power sources and eliminating MSW. By 2025, there will likely be up to 2.6 billion tons of MSW generated yearly worldwide, compared to the current amount of 2.4 billion tons [78].

Consequently, the treatment of MSW that ties down their economic commitment to expanding vitality requests is fundamental [79]. Saudi Arabia has one of the world's most extensively energy generation nations because of its regularly expanding populace, urbanization, and expectations for everyday comforts [80]. In 2013, the nation was among the world's 12 biggest essential vitality customer nations with absolute vitality utilization of 9 quadrillion British warm units [81]. By 2032, the power flow peak interest is expected to double to 120 GW from its current value of 55 GW [82]. The majority of the country's energy needs are met by non-renewable resources; around 55% of Saudi Arabia's energy needs are met by oil, and approximately 45% by gaseous gasoline [83]. The government aims to produce roughly 72 GW of power from renewable sources, including nuclear, solar, wind, and water thermal energy, by 2032 [82-84]. In 2014, the Kingdom of Saudi Arabia produced 15.3 million tons of MSW at a rate of 1.4 kg per capita per day on average. By 2033, this amount is predicted to double [80]. After the fractional reuse of paper and cardboard, which accounts for 10-15% of total MSW, the collected MSW is arranged in landfills or dumpsites [83]. Up to 2.8 million $m^2$/year are currently expressed interest in creating additional landfills in land zones [76,82]. Natural and general medical problems are being brought on by the waste management practices [83]. Accordingly, the KSA Government is looking for feasible answers for MSW the board, including its treatment and vitality recuperation to connect the regularly expanding vitality request [82] gracefully. In KSA, such a WtE office exists to remain the same as MSW in vitality, and the capability of MSW is analyzed as a vitality source [78]. This examination will increase the value of practical waste administration systems and the creation of sustainable power sources for KSA [80]. This case study looks at the capability of intensity age from 2012 to 2035 utilizing WtE innovations for the Saudi Arabia. Two situations were applied to be specific burning and refuse-derived fuel (RDF) alongside biomethanation. These situations were chosen because of a broad writing audit regarding monetary, natural, and innovative qualities, the country squander arrangement, and its vitality substance. This case study audits the worldwide status of WtE advancements as a means for sustainable power source creation and MSW removal strategy.

A contextual investigation of the country was conducted using this idea. The WtE openings in the country are attempted in two situations: (1) incineration and (2) RDF alongside biomethanation from 2012 to 2035. Given (a) the availability of a large volume of food waste (37% of total MSW) that can be used as a feedstock, (b) higher productivity (25-30%), and (c) the lowest annual capital ($0.1-0.14/ton) and operating expense, biomethanation may prove to be the most sensible WtE innovation for the country. In any case, the requirement for enormous space for persistent activity may increment operational expenses. The RDF has a small quantity of leeway over burning because of (a) less yearly capital ($7.5-11.3/ton) and (b) operational expense ($0.3-0.55/ton), yet the high work aptitudes necessities will most presumably impede if proper preparing and related framework are not booked to be incorporated as an essential. The burning innovation also becomes productive with moderately higher effectiveness (25%) and lower operational expense ($1.5-2.5/ton). One factor limiting the advancement of this innovation in Saudi Arabia may be the need to treat pollutants and waste that are airborne and aqueous within the incineration office. The force age potential of KSA was estimated in 2012 to be 671 MW and 319.4 MW from burning and RDF with biomethanation scenarios, respectively. By 2035, it was predicted to increase to 1447 MW and 699.76 MW for the two scenarios separately. Hence, WtE innovations could significantly contribute to creating sustainable power sources in KSA, just as they would ease the expense of landfilling and its related ecological effects. Choosing between the two situations requires further inside and out budgetary, specialized, and natural investigation utilizing the life cycle assessment (LCA) instrument.

The investigation shows a worldwide developing pattern towards sustainable power source creation with accentuation on WtE advances. Bio-methanation innovation is the most feasible of all the WtE advancements that have been highlighted due to its generally better productivity and low capital and operating expenses. Because of the greater procedural proficiency and lower natural contamination, RDF has a larger potential development and inclination over incineration in this country. The underlying capital and operational expense and work aptitude necessities are the confinements of RDF. Treating air and waterborne toxins and debris inside the burning office is basic before creating incineration plants in the country. When the yearly power potential was evaluated in 2012, it was calculated to be 671 MW for burning and 319.40 MW for RDF with biomethanation, respectively. The two scenarios were expected to separately reach 1,447 MW and 699.76 MW by 2035. It illustrates the immense potential of these WtE discoveries for power generation and how, if further developed, they may assist renewable energy sources and drive up the cost of landfills and the associated environmental issues [85].

*Case 5: Organic Waste Utilization in Europe*

Currently, energy frameworks are commanded by huge plants taken care of by ordinary fuel, working in focal areas and associated with conclusive clients by transmission and conveyance systems. In recent years, there has been a pattern in the power age towards distributed generation, utilizing little scope of vitality change units arranged near the purpose of vitality use. The incorporated age worldview is progressively addressed, considering the weakness of complex frameworks and the shortage of conventional non-renewable energy sources commonly utilized in plants of enormous scope. However, there is limited evidence that energy innovations may effectively use locally available, regularly generated electricity from Renewable Energy Sources, such as wood biomass and biogas from waste, to enhance the flexibility and ecological maintainability of the energy system. Biogas is an elective source of petroleum products, which can prompt a decrease in $CO_2$ outflows just as meeting European and national focuses on the extent of sustainable power sources [86]. Most biogas is produced through the anaerobic digestion of biodegradable materials, including waste, sewage, biomass, and animal fertilizer. In the last few years, the possibility of producing biogas from natural reserves has altered public perceptions about trash, making it seem less rejected and more like a possible energy source. Between 118 and 138 million tons of bio-waste are produced in the European Union each year, with the Organic Fraction of Municipal Solid Waste accounting for over 70% of this total. CHP can be produced from biogas, which basically consists of carbon dioxide and methane [87]. It is a more likely choice than gaseous fuel. Biogas combustion can lower greenhouse gas emissions since the carbon dioxide it produces is generally regarded as biogenic and does not enter greenhouse gas inventories. Small-scale CHP units, which provide heat and power for a single building, can be powered by biogas.

A few small-scale CHP innovations have recently been grown for applications at the local scale. A general rundown incorporates responding motors, Stirling motors, low and high-temperature power modules, small-scale turbines, photovoltaic frameworks, and Organic Rankine Cycle frameworks. Smaller-scale CHP may find a wider market if gas-heated boilers are replaced. The UK is currently the largest advertiser of evaporators in Europe, selling 1.6 million boilers annually and introducing 17 million frameworks. The main reason for this is that heat circulation techniques, like site warming, are disliked in the UK [88]. According to estimates made by the Department of Energy and Climate Change, installing small-scale CHP systems in the UK instead of relying only on electricity from the network and consolidating boilers could reduce $CO_2$ emissions by as much as 2.1 tons annually per family unit. Alternately, in Italy, smaller-scale age advances are highly restricted due, for the most part, to the resistance of the power and petroleum gas businesses. In this manner, micro-cogeneration unimportantly adds to the last Italy vitality blend [89]. By methods for the existence cycle appraisal procedure, this case study evaluates the natural effect of biomethane from natural waste created at the private level being utilized to gracefully vitalize a gathering of residences in the dispersed age worldview. Three distinct frameworks for CHP, including energy components, Stirling motors, and smaller gas turbines introduced at the family unit level, were surveyed in two different settings: one in northern Europe (UK) and the other in southern Europe (Italy). Diverse working techniques are researched for every innovation. In addition, peripheral power creation advancements are broken down to evaluate their effect on the outcomes. This investigation has shown that the sort of bio-methane that took care of small-scale CHP innovation utilized has an essentially unique ecological effect: energy units are the most naturally cordial arrangement in each classification examined; Stirling motors, even though they can flexibly warmth to the most significant number of abodes are the most miniature earth amicable innovation. Critical variables explored in the model introduced in this paper impact the dynamic of the kind of innovation received and the working procedure to be actualised. Fig. 6 investigates the likelihood of fuel cell installation instead of internal combustion engines.

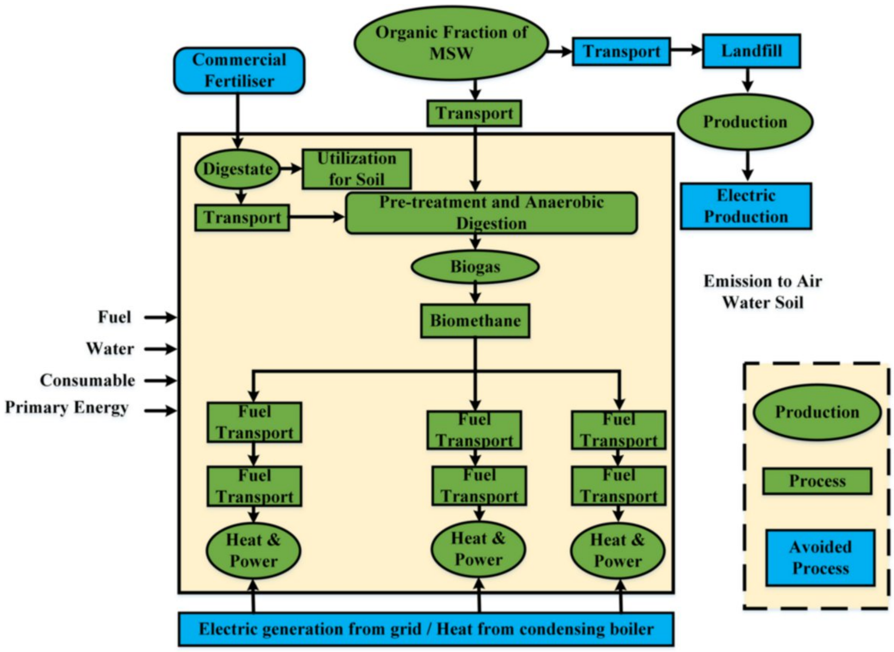


**FIGURE 6: System boundary approach for comparison between the feasibility of fuel cell and internal combustion engine**

Source: [89]

*Case 6: University of Cincinnati Turns Campus WtE*

Another finding highlighted three advanced WtE initiatives implemented at the University of Cincinnati, where used cooking oil is converted into biodiesel, used paper into fuel pellets, and food waste into biogas. By reducing dumpster use, increasing recycling, and decreasing the usage of non-renewable energy sources, these WtE systems promote sustainability at the ground level. Specific and financial aspects were examined, and the resulting reduction in greenhouse gas emissions was measured. The findings showed that if these tasks were carried out on-site, 3,682 L (974 gallons) of waste cooking oil could be converted into 3,712 L (982 gallons) of biodiesel; 133 tons of waste paper could be converted into 138 tons of fuel pellets (with the addition of 20.75 tons of plastics) to replace 121 tons of massive amounts of coal; and 146 tons of food waste could be converted into biogas, which could replace 12,767 $m^3$ of flammable gas annually. Financially, the three operations' restitution period was estimated to take 16 months for biodiesel, 155 months for fuel pellets, and 74 months for biogas activities. Significant reductions in $CO_2$-equivalent emissions would also be achieved annually by each WtE initiative: 37 tonnes for biodiesel, 260.49 tonnes for fuel pellets, and 11.36 tonnes for biogas [90].

This analysis presents the different types of waste generated and used at University of Cincinnati for vitality production, particularly through cooking oil, paper, and food waste. Thus, by utilizing the stock analysis plausibility, the resulting biodiesel, fuel pellets, and biogas can effectively substitute 121 tons of coal, 12,767 $m^3$ of gaseous gasoline, and 3,153 L (834 US gallons) of petrochemical diesel. The on-location change of waste into vitality empowers decrease in capital and working costs of the three waste administration choices. The economic analysis showed that the biodiesel option is only marginally more expensive in terms of minor capital investment compared to the fuel pellet and biogas alternatives. The payback periods for biodiesel, fuel pellets, and biogas were estimated at 16 months, 155 months, and 74 months, respectively. The expected reductions in greenhouse gas emissions from the three WtE systems were 9.37 tonnes $CO_2$-eq/year for biodiesel, 260.49 tonnes $CO_2$-eq/year for fuel pellets, and 11.36 billion tonnes $CO_2$-eq/year for biogas [91].

*Case 7: Sustainability of Process Industry in Spain*

This case presents a specialized framework based on an actual existence methodology for conducting the Ecological Sustainability Assessment (ESA) of several WtE plants in Spain. The method incorporates two main sustainability indicators: the ECOWAS Ecological Burden Sustainability (EBS) and the North American Natural Resources Sustainability (NRS). The NRS considers the consumption of energy, materials, and water during construction, while the EBS includes five impact weights for air, five for water, and two for land. To simplify the ESA process, the weights were assigned and normalized with reference to the threshold values established in the European Pollutant Release and Transfer Register regulation. The findings showed that, compared to the Spanish baseline, the studied plants consumed natural resources at a significantly higher rate, ranging from 1.1 to 2.0 times more than the national reference levels. Focusing solely on material-related components, Spain's usage was 1.80 times lower than that defined by the BREF standard, based on a correlation between the two countries regarding garbage burning.

Air and land impacts were the most notable proponents to the global weight in terms of EBS. Only one plant exceeded the typical weight in a location well-known in Spain, but the WtE plants contributed more heavily to air and water impacts than those in Spain [92]. Finally, our study showed how the ESA system may simplify LCA and support the constantly changing process in determining the optimal choice from an ecological perspective [93]. This technique can be utilized to get a review of the ecological performance of WtE plants, survey singular weights, and consequently decide the fundamental natural hotspots, thus improving the basic purposes of the procedure. It has been shown that an ESA of a few WtE plants in Spain can be effectively guided by LCA. In such a manner, the proposed procedure lessens the intricacy of LCA and disentangles dynamics using two dimensionless factors: NR $X1*$ and EB $X*2$. These two factors can take care of a multi-target work in which two lists depict natural maintainability. The standardization and weighting methodology used to acquire the EBS variable present an approach weighted dependent on the edge estimations of the E-PRTR guideline. The WtE plants might then examine their ecological display in relation to the European guidelines and the current situation with reference to the Best Available Techniques as outlined in the BREF study. However, using a global EB may obscure certain results, even though standardizing and weighting the EB to produce a single list simplifies the dynamic process. Thus, possessing a high weight in one of the natural compartments and a low or negative incentive in the others, a plant can balance the weights in those compartments and put on the best ecological show. Hence, determination of a small number of plants solely in terms of methods for a global list can be useful for further development of the idea of the natural behavior of the plant and improvement of the process of creating procedures. In any case, singular EBs need to be assessed with a view to finding out the first environmental concerns and, therefore, openings for enhancing the elementary environmental objectives of the undertaking. The outcomes of this investigation apparently depended upon on the significance of the framework confines and data nature. Especially, the outcomes would have been exceptional to this work if vitality creation had not been included in the research. Thus, it can be stated that the plants under investigation had a higher database NRS compared to both the Spanish reference information as well as the X1TM list. This list, in particular, follows the typical Spanish convention for enumerating the first range of instances, from 1.1 to 2.0. Likewise, only the variable for material X1 and 2 had declined in esteem when NR was compared to the information provided by BREF on Spain. Therefore, regulating the use of water and enhancing the production of energy in Spanish plants will enhance both their natural performance and the financial aspects of combustion in the country. Many plants showed natural weights that were typical for land loads in Spain. Because of the residue of the metal, overpowering metal, and polychlorinated dibenzo-p-dioxins and dibenzofurans emission, the upper limit of compartment X2 air was limited by an health hazard evaluation. However, since vitality creation was a strong point in both Material Economics and Argon Oxygen Decarburization, they showed the best commitment to the water segment. However, it was noted that even as all the plants applied heated treatment to the gas mixture, some differences were noted in the reagents applied in treating pipe gasses and the burnability of different plants. Hence, it can be concluded that the major objective is to enhance the efficiency or operating conditions of the overburden vent gas treatment to minimize the impact of the EB. The fouling weight can also be reduced in a similar manner by using less polluted reagents, which include salts and slaked lime instead of urea and lime. Lastly, it is surprising that companies with an ecological management system could utilize this strategy to describe the natural objectives and the norms and then evaluate the subject places' adherence to such norms. From the ecological perspective, having proposed the markers, it can be concluded that these contribute to the further development of the mechanical plant exhibition and its progress. In addition, according to these measurements, businesses could establish their natural course, which is the report that ecological management system requires that has duties to increase the efficient ecological appearance and natural enactments and train or supply the representative's adequate training to work within the agreement [94].

The transition toward sustainable waste management practices is increasingly critical in addressing environmental challenges associated with waste disposal and energy generation. Recent studies highlight the potential of WtE technologies as a viable solution for managing MSW while simultaneously generating energy. Hsu et al. [95] emphasize that WtE systems can significantly reduce the volume of waste sent to landfills, thereby mitigating the associated greenhouse gas emissions and land use concerns. Their comprehensive overview suggests that integrating advanced technologies in WtE processes can enhance energy recovery and minimize environmental impacts, making these systems more sustainable in the long term. Furthermore, the comparative analysis conducted by Unegg et al. [96] reveals that while recycling is often viewed as the most environmentally friendly waste management option, incineration - when equipped with modern emission control technologies - can also play a crucial role in reducing $CO_2$ emissions. This underscores the importance of evaluating the full lifecycle impacts of different waste management strategies, including their energy recovery potential. Additionally, Salem et al. [97] provide insights into emerging technologies that optimize solid waste management, focusing on the conversion of waste into valuable feedstocks for energy production. Their findings suggest that innovative approaches, such as chemical recycling and anaerobic digestion, can significantly enhance the sustainability of waste management systems. The environmental implications of food waste are also critical, as highlighted by Kohli et al. [98], who discuss the need for effective solutions to minimize food waste generation and promote its recovery for energy and composting. As the global community continues to grapple with waste management challenges, the integration of these diverse strategies and technologies will be essential in fostering a circular economy and achieving sustainability goals. The collective insights from these studies illustrate a clear path forward, advocating for a multifaceted approach that balances waste reduction, energy recovery, and environmental protection [99].

## Emerging technologies in waste management

Nowadays, emerging technologies play a vital role in revolutionizing the waste management industry. Many studies in the literature have addressed various emerging technologies aimed at enhancing waste management efficiency, reducing costs and environmental issues, and promoting sustainability, as shown in Table *5*.

*Smart Waste Management*

| Emerging Technologies/Ref. No. | Main Findings | Limitations | Applications/AI and ML Algorithms |
|---|---|---|---|
| ML, IoT, Blockchain [100] | Systematic review of waste management using ML, IoT, and blockchain. | Scalability challenges. | Application: Smart waste classification. |
| | Identifies state-of-the-art technologies. | Data privacy concerns. | AI & ML: ML |
| | Discusses methodologies and challenges. | | |
| Blockchain [101] | Blockchain enhances waste tracking, transparency, and efficiency. | High implementation costs. | Application: Waste supply chain management. |
| | Reduces fraudulent activities in waste management. | Regulatory barriers. | |
| AI, IoT [102] | AI improves waste classification and predictive analytics. | Lack of standardization. | Application: Smart waste sorting. |
| | Enhances real-time waste management efficiency. | High computational costs. | AI & ML: Deep learning |
| Blockchain [103] | Ensures transparent and secure waste transactions. | Complex implementation. | Application: Smart waste auditing. |
| | Reduces waste fraud and inefficiencies. | High power consumption. | |
| AI [104] | AI improves waste segregation and disposal. | Limited real-world applications. | Application: Predictive waste collection. |
| | Reduces manual efforts in waste classification. | High initial costs. | AI & ML: Support vector machines |
| Blockchain [105] | Blockchain application in plastic waste management governance. | Legal and ethical concerns. | Application: Plastic waste tracking. |

| | | | |
|---|---|---|---|
| | Enhances data security and transparency. | Security risks. | |
| IoT, Blockchain [106] | IoT and blockchain integration in smart waste systems. | High energy consumption. | Application: City-wide waste monitoring. |
| | Provides efficient tracking and monitoring. | Lack of interoperability. | |
| IoT [107] | IoT-enabled waste management improves efficiency. | Security vulnerabilities. | Application: Smart bin monitoring. |
| | Real-time monitoring and automation. | Potential data breaches. | |
| AI, ML, IoT [108] | AI and ML models enhance waste management. | Requires large datasets. | Application: Automated waste collection. |
| | Predictive analytics optimize collection schedules. | High model complexity. | AI & ML: Decision tree |
| IoT, AI [109] | IoT-based waste tracking for smart cities. | High implementation costs. | Application: City-wide waste collection. |
| | Provides real-time data and analytics. | Limited adoption in developing regions. | |
| IoT, AI [110] | IoT and AI improve solid waste management. | High energy consumption. | Application: Smart city waste monitoring. |
| | Sensors provide real-time tracking. | Data integration challenges. | |
| IoT, ML [111] | IoT-based waste monitoring in universities. | Integration issues with legacy systems. | Application: Campus waste management. |
| | Predictive waste analytics. | | AI & ML: Decision tree |
| AI, ML [112] | AI enhances solid waste classification. | High computational complexity. | Application: Automated waste segregation. |
| | Automates recycling processes. | Large dataset requirement. | AI & ML: Deep learning, CNN |
| AI, ML [113] | AI-driven solid waste management strategies. | Data availability issues. | Application: Smart waste classification. |
| | Reduces manual labor in waste collection. | Model interpretability challenges. | AI & ML: Neural networks |
| AI, ML [114] | AI applications optimize solid waste recycling. | Need for extensive labeled datasets. | Application: E-waste sorting. |
| | Enhances efficiency in sorting. | Model validation required. | AI & ML: CNN, ANN |
| Blockchain, IoT [115] | Secure and transparent nuclear waste management. | High processing power requirements. | Application: Nuclear waste tracking. |
| | Prevents illegal disposal. | Limited adoption. | |
| IoT, AI [116] | IoT-based intelligent waste monitoring. | High energy consumption. | Application: City-wide waste collection. |
| | Improves waste collection schedules. | Cost constraints. | AI & ML: Reinforcement learning |
| AI, ML [117] | AI enhances biological wastewater treatment. | High dependency on training data. | Application: Wastewater treatment. |
| | Optimizes resource allocation. | Complex modeling. | AI & ML: ML |
| AI, ML [118] | AI-driven optimization of solid waste processing. | Lack of real-time adaptability. | Application: Smart city waste management. |
| | Smart automation reduces manual efforts. | High system costs. | |
| AI, ML [119] | AI-driven waste management comparison in USA and Africa. | Infrastructure limitations. | Application: AI-powered waste logistics. |
| | Identifies efficiency gaps in developing nations. | Data scarcity in low-income regions. | |
| IoT, AI, Android [120] | AI- and Android-based sustainable waste solutions. | Security vulnerabilities. | Application: Municipal waste management. |
| | Improves local government waste tracking. | Limited real-world adoption. | |
| AI, ML [121] | AI applications in solid waste reduction. | Model generalization issues. | Application: AI-based waste forecasting. |
| | Predictive analytics for waste generation. | Lack of policy framework. | |
| | Optimized deep learning for e-waste tracking. | High computational resource demand. | Application: E-waste monitoring. |

| | | | |
|---|---|---|---|
| AI, ML, IoT [122] | Energy-efficient IoT integration. | Expensive IoT sensor deployment. | AI & ML: Deep learning |
| Blockchain, IoT [123] | Blockchain integration for smart waste 4.0. | High data storage requirements. | Application: Waste logistics management. |
| | Ensures waste traceability. | Scalability challenges. | |
| Blockchain, IoT [124] | Safe and transparent nuclear waste disposal. | Cost-intensive blockchain setup. | Application: Nuclear waste disposal security. |
| | Secure, immutable records for waste tracking. | Limited real-world implementation. | |
| IoT, AI [125] | Smart IoT-based solid waste management. | Requires advanced infrastructure. | Application: Automated waste monitoring. |
| | Reduces manual intervention in waste collection. | High initial costs. | |

**TABLE 5: Emerging technologies-based smart waste management schemes**

AI, Artificial Intelligence; ANN, Artificial Neural Network; CNN, Convolutional Neural Network; IoT, Internet of Things; ML, Machine Learning

This article presents the integration of AI, IoT, and blockchain schemes for effective smart waste management. Singh et al [100] and Jiang et al [101] addressed the applications of ML, IoT, and blockchain in waste management systems, identifying the significant challenges.

*Future Scopes and Opportunities*

In the context of global urbanization and industrial development, waste management systems play a vital role in becoming more intelligent, reliable, and efficient. The capabilities of AI, ML, IoT, and smart energy technologies offer transformative potential to address complex waste-related challenges. As the field continues to evolve, several future directions and opportunities are emerging. Table 6 presents the current trends that highlight the key areas of focus.

| Future Scopes | Opportunities |
|---|---|
| AI-based Recycle Economy Strategy | Optimize resource recycle, waste lifecycle tracking, and recycle materials for sustainable production and utilization. |
| Real-time Monitoring and Analytics | Use emerging technology such as IoT sensor-based AI/ML for waste tracking, route optimization, and forecasting. |
| Smart Infrastructure Integration | Organize AI-based systems in smart cities for intelligent waste management. |
| Intelligent Waste Cataloguing | Use deep learning for high-accuracy, real-time classification and segregation of recyclable/non-recyclable waste. |
| Blockchain for Waste Traceability | Transparent tracking of waste streams. |
| Integration with Renewables and ESS | Waste-to-energy systems integrate the renewable energy and energy storage system for decentralized, resilient microgrid solutions. |
| Policy Modelling and Urban Planning | AI-based systems for evaluating and optimizing long-term waste management strategies and regulatory outlines. |
| Interdisciplinary Research | Encourage various sector collaboration among AI experts, environmental engineers, and policymakers to design scalable, real-world solutions. |

**TABLE 6: Future scopes and opportunities**

AI, Artificial Intelligence; ESS, Energy Storage Systems; ML, Machine Learning

## Conclusions

In the present era, waste management is an important issue across all developing countries. Additionally, the waste generated in developing countries is increasing due to rapidly rising population density. This paper presents an overview of waste management and emerging technologies being developed to recycle or reutilize waste as a form of energy. Furthermore, the seven examined cases in this paper implement waste management strategies and improve human quality of life. Case 1: MSW in Urta-Chirchik has a higher calorific value than wood waste because of lower moisture content and fixed carbon; however, the carbon value is not significantly different. Case 2: An administrative solution was simply imposed for Quito's waste management, mainly addressing the 69.31% biodegradable and 30.69% non-biodegradable waste, which can effectively support energy generation using biochemical and thermochemical conversions. Case 3: The Sabah palm oil biomass study illustrates high potential for grid electricity, aiding Malaysia in reducing carbon emissions from the electricity sector. Case 4: Biomethanation is cost-effective. RDF is growing in Saudi Arabia despite high costs, offering efficient, less-polluting renewable energy and reducing landfill usage. Case 5: Fuel cells are environmentally friendly for bio-methane micro-CHP, while Stirling engines, despite higher capacity, have greater environmental impacts. Case 6: University of Cincinnati's waste produces biogas, fuel pellets, and biodiesel, which replace fossil fuels, lower costs, and reduce greenhouse gas emissions by half. Case 7: Circular approach can greatly affect the results related to Spanish WtE plants by defining system boundaries, the quality of data used, and the inclusion of energy generation.

The integration of AI, ML, IoT, and blockchain technologies in waste management systems transforms waste into a valuable asset, adopting a cleaner ecosystem and a healthier environment for next generations. Overall, these cases illustrate the diverse approaches to waste management and their potential to improve environmental sustainability and community well-being.

# Additional Information

## Author Contributions

All authors have reviewed the final version to be published and agreed to be accountable for all aspects of the work.

**Concept and design:** Nayan Kumar, Prabhansu .

**Acquisition, analysis, or interpretation of data:** Nayan Kumar, Prabhansu .

**Drafting of the manuscript:** Nayan Kumar, Prabhansu .

**Critical review of the manuscript for important intellectual content:** Nayan Kumar, Prabhansu .

**Supervision:** Nayan Kumar, Prabhansu .

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