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Forecasting medical waste generation and estimating waste to energy potentials with associated greenhouse gas emissions: A holistic analysis

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ABSTRACT

Three novel semi-empirical models are generated in this study to forecast Türkiye's medical waste (MW) generation till 2040 based on different scenarios. Scenarios for models 1 to 3 provides a spectrum of data that covers potential stagnancy, exponential and linear rise scenarios for MW generation till 2040. All models alluded high goodness of fit and accuracy based on RMSE, MAPE (%), R^2 and residual analysis values. Model 3 is deemed as the best fit among them. Türkiye's average MW generation in 2040 is forecasted to be 380 thousand tons and energy worth equal to the consumption of 206.5 million m^3 of natural gas (NG) could be produced if all the combustible portion of MW, which is 92 % of the total, is collected and incinerated. It is also estimated that from incineration of MW energy worth equal to 0.13–0.21 % of Türkiye's annual NG consumption valued at 26.2–77.4 million US$ could be generated between 2022 and 2040. In 2040, if all the MW generated is collected and further processed for energy generation theoretical NO_x, CO, and SO_2 emissions from Tier 2 uncontrolled air and Tier 1 rotary kiln incineration are estimated as nearly 680, 570, 420 and 980, 8, 120 tons, respectively. Lastly, this study could be used as a basis for estimating MW generation in different countries with associated energy equivalence analysis and GHG emission calculations.

1. Introduction

Türkiye has a growing economy and population. Türkiye's economy displayed a record growth in the last two decades and its gross domestic product (GDP) based on purchasing power parity (PPP) increased from 18th place to 11th globally between 2003 and 2021 [1]. Türkiye's population was recorded as 85.2 million in 2022, and it is expected to keep its growth momentum till 2040s [2]. In the last 50 years, Türkiye had a fast-growing young population, but this is now changing. In 2023, Türkiye's annual population growth rate decreased to 1.1 per thousand, which is considered as critically low [3]. The ratio of Türkiye's population aged over 65 is lower than that of Europe and the United States (U. S.), but it is predicted to exceed 10 % by 2026, which inevitably will increase Türkiye's overall healthcare expenditures [4].

The Ministry of Health (MoH) is the largest provider of healthcare services in Türkiye, and it is responsible for the planning of national healthcare policy. Key facts about Türkiye's healthcare system are reported in Table 1 [4]. Türkiye is among the top 10 in global health sector with its modern infrastructure [5]. The country is also a top destination for high quality medical tourism [5]. Within a four-hour flight radius, Türkiye offers easy access for high quality healthcare services to nearly 1.3 billion people located in Central Asia, Middle East and North Africa (MENA) regions, and Europe with a combined GDP of worth nearly 28 trillion US$ [6].

The number of patients served and hosted in Türkiye will increase in the following years due to the increasing number of international patients visiting for medical tourism and the country's growing overall and elder population. There are economic benefits of increased patient numbers but from the environmental and sustainability perspective this growth also leads to a serious problem known as medical waste management.

Medical waste (MW) otherwise known as "health care waste", "clinical waste" or "infectious waste" is a subcategory of waste generated from medical treatment and diagnosis [7,8]. MW poses potential health threats and 15–35 % of MW is generally considered hazardous [9]. Poor MW disposal practices could create serious environmental, health and economic problems [10]. Effective management of MW via development of appropriate decision-making tools is essential [11]. Choosing MW disposal methods is complicated due to the number of alternatives and contradictory criteria [12]. Therefore, collection, storage and further processing of MW must be carefully planned and monitored.

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Table 1
Key facts about Türkiye's healthcare system.

Key parameters	Data
Number of hospitals	879 MoH, 571 private, 68 university
Number of hospital beds	225,863
Health care expenditure	4.5 % of GDP
Per capita spending on healthcare	Nearly 869 US$ (a 3.5-fold increase since 2002)
Medical devices market	Growing between 5–10 % per annum in the 10 ten years.
City hospitals project	In 2013, the MoH launched a project to construct 31 large hospital complexes across Türkiye. As of 2024, majority of these city hospitals are now operational.

Common MW includes single use gloves, masks, needles, syringe, etc. [13]. The main constituent of MW is plastics (long carbon-chain polymers), which require nearly 450 years to be decomposed in the nature [13]. Most of the MW ends in landfills after treatment [14]. Selection of an appropriate MW treatment method can be classified as a critical multi-criteria decision-making problem due to combination of a number of conflicting criteria [15,16]. Main MW treatment routes are thermochemical conversion, microwave and chemical disinfection and sterilization [17,18]. Steam sterilization kills microbes in MW using heat, which is produced from saturated steam [19]. Combustion (incineration), gasification and pyrolysis are considered as the primary thermochemical conversion technologies that are used for disposal and handling of MW [20]. Direct combustion is the most common method used for MW thermochemical management due to reduction in volume and high efficiency in microbial elimination [21].

Non-incineration friction heat treatment is a relatively new MW treatment process, by which MW is completely crushed through by a spinning blade in a compact sterilization chamber, where pathogens are eliminated via friction and heating [22]. Mechanical shredding systems are also used for handling certain types of MW. These systems offer volume drop and MW surface area enlargement for sterilization [23]. Yet, these systems do not provide any energy or economic return.

MW production is globally increasing each year due to population growth, rising chronic diseases, ageing population and ease of access to medical facilities [24,25]. Handling of MW is becoming a challenging problem due to limited disposal capacity and environmental concerns [26]. Research on MW recycling networks is increasing with advances in technological innovation and sustainability concerns [27]. Researchers are focusing on reutilization of MW due to their severe environmental, economic and health impacts [28]. Economic, environmental, and social sustainability pillars are drawing attention on MW disposal [29,30]. Among different treatment methods, waste to energy technologies could provide a sustainable alternative and a synergistic solution for the MW problem. MW has usable energy potential due to its ingredients such as single use plastics (SUP) from personal protection equipment (PPE) such as body aprons, nose masks, and protective gloves [31], paper and different types of combustibles [32]. In that context, energy generation from MW can be viewed as an innovative topic [33,34].

On the way to perform energy analysis, MW generation must be properly estimated. Successful MW management requires accurate forecasting of waste production [35]. Main limitations in front of such studies are the availability and quality of the data that will be used in forecasting. Detailed analysis of the literature, which is delivered in the following section, clearly showed that timeline data on Türkiye's MW generation is limited or incomplete in the published literature. Thus, such a constraint on datasets may affect the accuracy and reliability of the forecasting models unless unique and sound solutions are found. The novel solution developed in this study to overcome these limitations are explained in the data and methodology section of this paper.

The aim of this study was to generate sound and novel forecasts of Türkiye's MW generation and calculate waste-to-energy potentials with associated greenhouse gas (GHG) emissions. The outline of this paper followed this structure: First, a literature review about reutilization routes of MW was presented. Then, the methodology, data, and statistical techniques used for model development and testing were explained. Afterwards, the results were given and evaluated with a related discussion. Finally, the conclusions were summarized, along with some suggestions for future research.

2. Literature review: studies on energy and value-added products generation from medical waste

MW generation data for different countries is limited in published literature. Still, after a detailed review the following data was found. Annual per capita MW generation in Lebanon and Greece were reported as 1.42 and 0.70 kg [36], MW generation in different regions of China were estimated to change between 0.7 and 1.5 kg per capita per annum, averaging at 1.0 kg [37] and annual per capita MW generation in South Korea was estimated as to 7.2 kg [38].

Hou and co-workers analyzed relevant empirical studies on quantification of MW generation and reported that the major influencing factors are economic growth, medical policy, population size, age distribution, aging degree, and quality and quantity of medical institutions [39]. Out of these different influencing factors, previous studies showed that MW generation is mainly affected by population change [39]. Thus, population or per capita based models could provide a better understanding of MW generation, and it would be beneficial to assess MW generation modelling studies covering time series-based regression or other types of analyses.

Jahandideh and colleagues studied two forecasting models including multiple linear regression and artificial neural networks for predicting MW generation [40]. They found that linear rule-based models can clarify the weight of each parameter, which emphasize their performance in predicting the rate of MW generation [40]. Erdebilli and Devrim-İçtenbaş developed a machine learning methodology to forecast MW generation in Türkiye by using yearly timeline data between 2004 and 2020 [41]. Altin and co-workers forecasted MW generation for a hospital in Türkiye by utilizing deep learning methods and Kernel-based support vector machine algorithms on timeline data [42].

Komilis and co-workers analyzed MW production from medical research laboratories and found that a linear regression could be used to assess MW generation [43]. Minoglou and co-workers developed a linear regression-based model taking into account different economic and social parameters, which change the MW generation rate, by using data from 44 countries [44]. The model provided sound forecasting results and recently Dihan and colleagues used the analogy developed by Minoglou and co-workers to estimate MW generation in Bangladesh [45].

Korkut obtained a linear relation between the yearly projected MW generation and daily production rates and used annual population and total MW generation data to forecast MW production in İstanbul between 2000 and 2017 [46]. He estimated that total MW increased from nearly 7200 to 26,400 tons between 2000 and 2017, and MW production rose from nearly 0.40 to 1.60 kg/bed-day in the same period [46]. He concluded that there are strong correlations between variances [46].

Melikoglu developed semi-empirical regression models based on per unit area and per bed data to estimate food waste (FW) production from hospitals in Türkiye and calculated their energy potentials based on different scenarios [47]. He calculated that hospitals in Türkiye could have consumed 8600 GWh of energy and generated up to 50,000 tons of FW in 2018 [47].

As stated above, per capita based regression analysis is carried in this study to forecast MW generation in Türkiye. This is because such models provide high accuracy forecasts for Türkiye's municipal solid waste (MSW) generation and MW can be considered as a hazardous fraction of MSW [48,49]. In addition, regression based per capita modelling also delivers precise forecasts of Türkiye's energy demand and GHG emissions [50,51]. Therefore, encompassing both aims of the current study.

Energy recovery and different valuable products generation from

MW is an important research topic that also deals with sustainability related issues. In the remainder of this section key literature on these two topics are scrutinized in detail. A summary table is given at the end of this section for easier comparison by the reader.

Fang and colleagues studied pyrolysis of dried and pulverized MW at 500 °C [52]. They found that the combustibles in the product gas stream were nearly 83 % and with a heat value of nearly 11,000 kcal/Nm^3. The liquid and solid products heat values were nearly 8970 and 5450 kcal/kg, respectively [52]. Kumar and co-workers characterized the wet torrefaction of MW consisting of skewers, bamboo swabs, splints, tongue depressors, cotton balls, chopsticks, and toothpicks followed by co-pyrolysis with medical waste plastic including drapes, catheter bags, test tubes, IV bags, syringes, oxygen masks and IV tubing [53]. They found that the activation energies reached nearly 222 and 150 kJ/mol [53].

Li and colleagues proposed a hybrid system that uses MW for plasma gasification and use the product syngas to generate power [54]. The system offered nearly 80 % and 84 % exergy and energy efficiencies, respectively [54]. It was estimated that the proposed hybrid system could achieve a net present value of nearly 477,000 k$ over 25 years and nearly 2.6 years of dynamic payback period [54]. Zheng and co-workers studied a plasma hybrid peak shaving system for energy generation from MW [55]. The system exergy and energy efficiencies were estimated as 36.2 % and 37.4 %, respectively [55]. The net-present value was calculated as nearly 178,400 k$ with an average daily profit nearly of 141 k$ [55].

Pokson and Chaiyat studied energy generation from MW via a combined heat and power system (CHP) [56]. Levelized cost of energy and overall energy efficiency was estimated as nearly 0.35 US$/kWh and 13.4 %, respectively [56]. The system showed efficiency, sustainability, and quality advantages [56]. Zhou and colleagues proposed a plasma gasification system to convert MW into syngas [57]. The levelized emissions were calculated as nearly 1.3 kg CO_2 eq/kg MW and 5.2 CO_2 eq/kg H_2, respectively, and they concluded that the system showed benefits in MW treatment and H_2 generation [57].

Ji and co-workers assessed major MW disposal technologies including chemical disinfection with residue incineration or landfill, pyrolysis and rotary kiln incineration and steam and microwave sterilization in China via life cycle net present value analysis [58]. They calculated that 1 ton of MW produced 0.94–1.2 tons of CO_2, net present value and life cycle costing results indicated that steam sterilization with landfill as the best solution, 10 megacities employ microwave sterilization - municipal solid waste incineration technology for 279,000 tons of reduction in carbon dioxide (CO_2) emissions [58].

Zhao and others assessed five different MW disposal technologies including pyrolysis incineration, rotary kiln incineration, plasma melting, microwave sterilization with landfill and steam sterilization with landfill [59]. Their energy recovery and life cycle costing analysis showed that the highest energy recovery efficiency is achieved via steam and microwave sterilization and incineration as ≥83 %; and lowest and highest economic costs belong to pyrolysis and plasma melting, respectively [59].

Yin and colleagues assessed H_2 production from MW by plasma gasification coupled with ionic liquid-based CO_2 capture [60]. They found that higher heating value of syngas, production cost, exergy efficiency, and raw material consumption were nearly 27 MJ/kg, 2115 US $, 78 %, and 2.6 t/t H_2, respectively [60]. Chen and co-workers designed an integrated system for syngas generation by plasma gasification of MW [61]. The proposed system suggested a dynamic payback period of nearly 3.8 years and a net present value of nearly 45,240 k$ [61]. They found that exergy and energy efficiencies of MW to electricity could reach up to 35 % and 38 %, respectively [61].

Erdogan and colleagues investigated the gasification characteristics of MW using ANSYS Fluent software [62]. They found enhanced H_2 generation and reduced carbon monoxide (CO) in the syngas [62]. The maximum H_2 concentration was recorded as 54.7 % [62]. Li and co-workers carried out techno-economic and thermodynamic analyses on three MW to H_2 and methanol routes using plasma gasification modelled by Aspen Plus [63]. The results showed that the 1st route had the optimum conditions for dynamic payback period and net present value as nearly 3.8 years and 13,780 k$ [63].

Ramanathan and colleagues studied carbonization of MW to produce MW derived carbon [64]. They found that the proposed MWC zinc oxide nanocomposite could be used for aquatic and MW pollutants [64]. Zhao and colleagues designed a H_2 generation hybrid system using MW and biogas [65]. H_2 generation processes energy and exergy efficiencies from MW and biogas reached nearly 63 % and 59 %, respectively [65]. It is estimated that the proposed system could recover its initial cost in nearly 3.3 years, with a net present value of nearly 125,200 k$ over its lifetime of 25 years [65].

Wu and colleagues carried out a gray correlation analysis on MW pyrolysis products [66]. They found that extending solid residence time and increasing temperature were favorable to the transformation of solid products to liquid and gas products [66]. Ullah and co-workers studied pyrolysis of different MW [67]. According to the KAS method, the average activation energies for the mono-pyrolysis of medical gloves, syringe, and cotton swab sticks were calculated as nearly 226, 241, and 148 kJ•mol^{-1}, respectively [67]. Thus, uncovering a noticeable synergistic effect [67].

Qin and colleagues studied MW gasification by a converter gas [68]. The results showed that H_2, CO_2, and CO reached 38.1 %, 0.1 %, 46.5 % due to water-gas shift reaction and Boudouard reaction [68]. Chu and co-workers compared a thorough review on different waste-to-energy technologies including gasification, incineration, pyrolysis, hydrogenation, plasma-based treatments, carbonization, biomethanation, liquefaction, esterification and fermentation for further processing of MW from a circular economy perspective [69]. They concluded that gasification, incineration, carbonization and pyrolysis are fairly feasible techniques for MW valorization [69].

There are also studies focusing on non-energy related valorization of MW but the number of these are relatively small. In a recent study, Ramgopal and co-workers analyzed effects of using MW ash instead of fine aggregate on the compressive strength of cement mortar mixes and found that 15 % replacement level as the optimal proportion [70]. Navaneeth and colleagues used MW X-ray films to produce a triboelectric nanogenerator (TENG) and found that the TENG produced showed meaningful instantaneous power density, current, and output voltage values [71]. Chen and co-workers studied the effect of MW on bioleaching of low-grade copper sulfide ore and found that the optimal distribution of bacterial species and maximum copper recovery of nearly 83 % were achieved when 30 mg/L MW was used [72].

A summary table showcasing the different studies scrutinized above, components of medical waste, and the corresponding energy and value-added products generated is given in Table 2 to further enhance the depth and comprehensiveness of the literature review given in this section.

While this literature review provides a foundational understanding of energy recovery and value-added product generation from medical waste, the author acknowledges that the scope of cited studies is not exhaustive in covering the full spectrum of global medical waste management practices, particularly in low-income countries. Research and data concerning these regions are often limited in published literature. The primary focus of this study is on developing novel forecasting models and conducting a detailed energy equivalence analysis specifically tailored to Türkiye's context. Future research endeavors could benefit from a more in-depth exploration of the diverse challenges and innovative solutions being implemented in medical waste management across a wider range of economic settings.

Finally, the review clearly showed there is a gap in the literature on studies on energy generation from MW in Türkiye. Therefore, supporting the novelty claim of the current work.

Table 2
Summary of recent studies focusing on energy and other value-added products generation from MW.

MW disposal or treatment method	Major findings	Reference
Energy related studies		
Pyrolysis of dried and pulverized MW at 500 °C.	Combustibles in the product gas stream were nearly 83 % and with a heat value of nearly 11,000 kcal/Nm^3. The liquid and solid products heat values were nearly 8970 and 5450 kcal/kg, respectively.	[52]
Wet torrefaction of MW consisting of skewers, bamboo swabs, splints, tongue depressors, cotton balls, chopsticks, and toothpicks followed by co-pyrolysis with medical waste plastic including drapes, catheter bags, test tubes, IV bags, syringes, oxygen masks and IV tubing.	The activation energies reached nearly 222 and 150 kJ/mol.	[53]
A hybrid system design that uses MW for plasma gasification and use syngas to generate power.	The system offered nearly 80 % and 84 % exergy and energy efficiencies, respectively. It was estimated that the proposed hybrid system could achieve a net present value of nearly 477,000 k$ over 25 years and nearly 2.6 years of dynamic payback period.	[54]
A MW plasma hybrid peak shaving system for energy generation from MW.	The system exergy and energy efficiencies were estimated as 36.2 % and 37.4 %, respectively. The net present value was calculated as nearly 178,400 k$ with an average daily profit of nearly 141 k$.	[55]
Study on energy generation from MW via combined heat and power system (CHP).	Levelized cost of energy and overall energy efficiency was estimated as nearly 0.35 US $/kWh and 13.4 %, respectively. The system showed efficiency, sustainability, and quality advantages.	[56]
Design of a plasma gasification system to convert MW into syngas.	The levelized emissions were calculated as nearly 1.3 kg CO_2 eq/kg MW and 5.2 CO_2 eq/kg H_2, respectively. The system showed benefits in MW treatment and H_2 generation.	[57]
Assessment of major MW disposal technologies including chemical disinfection with residue incineration or landfill, pyrolysis and rotary kiln incineration and steam and microwave sterilization in China via life cycle net present value analysis.	They calculated that 1 ton of MW produced 0.94–1.2 tons of CO_2, net present value and life cycle costing results indicated that steam sterilization with landfill as the best solution, 10 megacities employ microwave sterilization - municipal solid waste incineration technology for 279,000 tons of reduction in CO_2 emissions.	[58]
Five different MW disposal technologies including pyrolysis incineration, rotary kiln incineration, plasma melting, microwave sterilization with landfill and steam sterilization with landfill are analyzed.	Their energy recovery and life cycle costing analysis showed that the highest energy recovery efficiency is achieved via steam and microwave sterilization and incineration as ≥83 %; and lowest and highest economic costs belong to pyrolysis and plasma melting, respectively.	[59]
Assessment of H_2 production from MW by plasma gasification coupled with ionic liquid-based CO_2 capture.	They found that higher heating value of syngas, production cost, exergy efficiency, and raw material cost were nearly 27 MJ/kg, 2115 US$, 78 %, and 2.6 t/t H_2, respectively.	[60]
Design of an integrated system for syngas generation by the plasma gasification of MW.	The proposed system suggested a dynamic payback period of nearly 3.8 years and a net present value of nearly 45,240 k $. They found that exergy and energy efficiencies of MW to electricity could reach up to 35 % and 38 % and respectively.	[61]
Investigation on the gasification characteristics of MW using ANSYS Fluent software.	They found enhanced H_2 generation and reduced CO in the syngas. The maximum H_2 concentration was recorded as 54.7 %.	[62]
Techno-economic and thermodynamic analyses on three MW to H_2 and methanol routes using plasma gasification modelled by Aspen Plus.	The results showed that the 1st route had the optimum conditions for dynamic payback period and net present value as nearly 3.8 years and 13,780 k$.	[63]
Carbonization of MW to produce MW derived carbon.	They found that the proposed MWC zinc oxide nanocomposite could be used for aquatic and MW pollutants.	[64]
Design of a H_2 generation hybrid system using MW and biogas.	H_2 generation processes energy and exergy efficiencies from MW and biogas reached nearly 63 % and 59 %. It is estimated that the proposed system could recover its initial cost in nearly 3.3 years, with a net present value of nearly 125,200 k$ over its lifetime of 25 years.	[65]
A gray correlation analysis on MW pyrolysis products.	They found that extending solid residence time and increasing temperature were favorable to the transformation of solid products to liquid and gas products.	[66]
Study on pyrolysis of different MW.	According to the KAS method, the average activation energies for the mono-pyrolysis of medical gloves, syringe, and cotton swab sticks were calculated as nearly 226, 241, and 148 kJ•mol^{-1}, respectively. Thus, uncovering a noticeable synergistic effect.	[67]
MW gasification by a converter gas.	The results showed that H_2, CO_2, and CO reached 38.1 %, 0.1 %, 46.5 % due to water-gas shift reaction and Boudouard reaction.	[68]
A thorough review on different waste-to-energy technologies including gasification, incineration, pyrolysis, hydrogenation, plasma-based treatments, carbonization, biomethanation, liquefaction, esterification and fermentation for further processing of MW from a circular economy perspective.	They concluded that gasification, incineration, carbonization and pyrolysis are fairly feasible techniques for MW valorization.	[69]
Non-energy related studies		
Analysis on the effects of using MW ash instead of fine aggregate on the compressive strength of cement mortar mixes.	15 % replacement level was chosen as the optimal proportion.	[70]
MW X-ray films to produce a TENG.	TENG produced showed meaningful instantaneous power density, current, and output voltage values.	[71]

(continued on next page)

Table 2 (*continued*)

MW disposal or treatment method	Major findings	Reference
Analysis of the effect of MW on bioleaching of low-grade copper sulfide ore.	The optimal distribution of bacterial species and maximum copper recovery of nearly 83 % were achieved when 30 mg/L MW was used.	[72]

3. Data and methodology

3.1. Data: amount of medical waste generation in Türkiye and its composition

Governments and private sectors around the globe are building larger hospitals in major cities to meet health requirements of increasing urban population [73]. This has consequently led to an increase in MW generation around the globe [73]. As stated in the previous sections, this is also the case in Türkiye. The health reform carried out after 2002 changed Türkiye's healthcare system, and as of 2022, Türkiye has 1555 hospitals (915 MoH, 68 university and 572 private) [74]. As of 2024, there are 24 city hospitals in Türkiye, which are classified as mega hospitals due to their size and patient capacities [75]. At this size and capacity Türkiye's healthcare system provides one of the world's most efficient medical service to local and global patients [76]. Unfortunately, this continuous and mega-scale healthcare operation also generates colossal amounts of MW.

In 2020, nearly 110,000 tons of MW was collected from Türkiye's health institutions [77]. Nearly, 24 % of the total MW was collected in İstanbul, 8 % in Ankara and 6 % in İzmir, which means that these 3 metropolitan cities generated nearly 38 % of Türkiye's total MW from health institutions [77]. Overall, 91 % of the MW collected was sent to landfills after sterilization, and 9 % was sent to incineration plants [77]. In 2022, nearly 10.5 thousand tons of hazardous waste (HW) were incinerated in thermal power plants [78], and the majority of this incinerated HW was MW. Per capita HW generation between in Türkiye between 2004 and 2016 are shown in Fig. 1 [79].

Aggregate annual per capita MW generation data for Türkiye is not available in the published literature. Yet, using MW [80] and population data [81] (see Table 3), Türkiye's per capita MW generation between 2013 and 2020 is calculated for the first time in literature and reported in Fig. 2.

Table 3
Türkiye's population data and forecast between 2013 and 2040 [81,86].

Year	Population (million people)
2013	76.7
2014	77.7
2015	78.7
2016	79.8
2017	80.8
2018	82.0
2019	83.2
2020	83.6
2021	84.7
2022	85.9
2023	86.9
2024	87.9
2025	88.8
2026	89.8
2027	90.7
2028	91.6
2029	92.5
2030	93.3
2031	94.2
2032	95.0
2033	95.7
2034	96.5
2035	97.2
2036	97.9
2037	98.5
2038	99.2
2039	99.8
2040	100.3

MW generated in Türkiye has a similar composition with the MW generated in developed countries, which include plastics, paper, gloves, masks, needles, glass, food waste etc. [82,83]. General composition of MW generated in Türkiye is shown in Fig. 3 [84,85].

It is crucial to clarify that this study primarily utilized secondary, aggregated data on medical waste generation from official sources and publicly available literature. No primary data was collected directly from individuals, including waste workers or other potentially vulnerable populations. Therefore, there were no direct interactions with human participants during the data collection phase of this research.

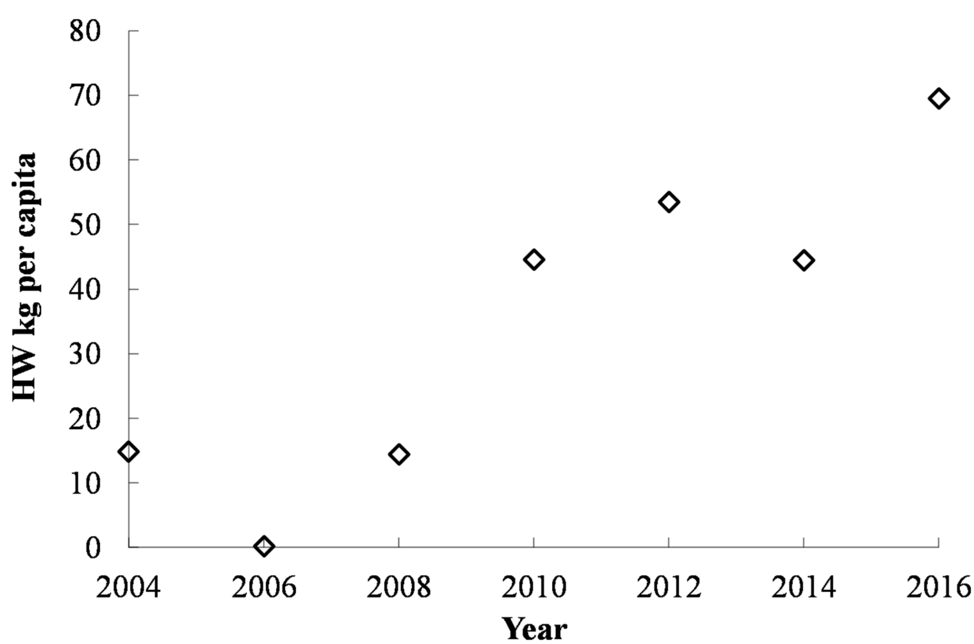

Fig. 1. Per capita HW generation Türkiye between 2004 and 2016.

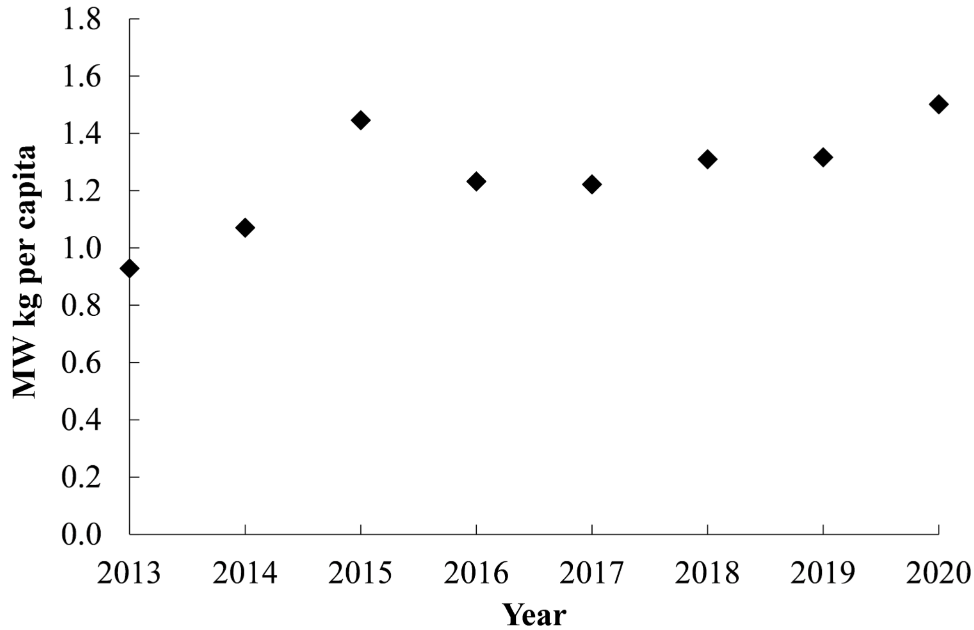

Fig. 2. Per capita MW generation in Türkiye between 2013 and 2020.

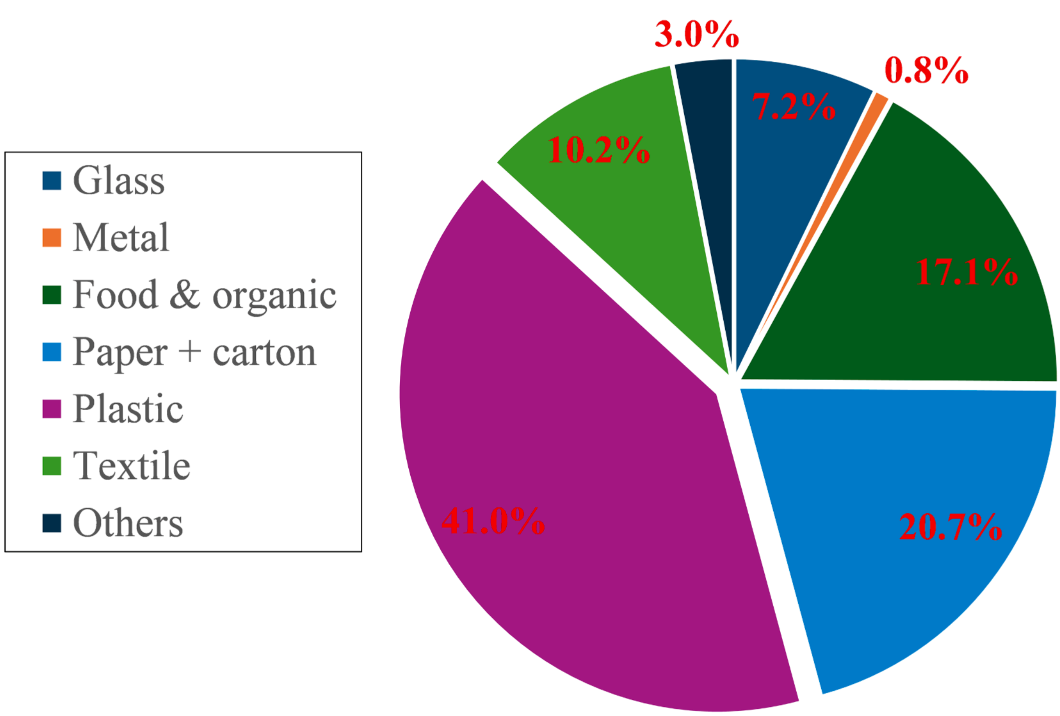

Fig. 3. Composition of MW in Türkiye.

While this study did not involve direct contact with vulnerable populations, the author recognizes the inherent occupational hazards associated with medical waste handling. The findings of this research, particularly the analysis of potential energy recovery through incineration and the associated emissions, indirectly highlight the importance of safe and regulated waste management practices to protect the health and well-being of waste workers. Future research that involves direct investigation of medical waste management processes on the ground, including interaction with waste workers, will necessitate stringent ethical protocols, including informed consent, full disclosure of risks, and measures to ensure the safety and anonymity of participants. This study serves as a foundational step that underscores the scale of medical waste generation in Türkiye, which can inform future research and policy aimed at improving the safety and sustainability of the entire medical waste management system, thereby indirectly benefiting those working within it.

3.2. Data handling and initial assessment

Regarding outlier handling, the raw data for MW generation between 2013 and 2020 (as presented in Fig. 2) did not exhibit any extreme values that were immediately identifiable as errors or anomalies requiring specific statistical outlier treatment. The data showed a relatively consistent increasing trend, and a visual inspection was conducted to ensure no single data point significantly deviated from the overall pattern. Concerning missing data imputation, the time-series data used for model development (2013–2020) was complete, with no missing values necessitating imputation techniques. The per capita MW generation was calculated directly from the reported total MW and population data for each year.

Regarding the alignment with best practices in time-series forecasting, standard practices often involve more formal outlier detection methods (e.g., interquartile range rule, Z-score) and various imputation techniques (e.g., linear interpolation, mean/median imputation, more sophisticated methods like Kalman filtering for time-series). While a visual inspection for outliers was performed, and no imputation was needed due to complete data, future research could benefit from a clearer articulation of these steps and the rationale behind the chosen approach. The robustness of the models was assessed through the goodness-of-fit metrics (which are explained at the end of this section), which indirectly reflect the overall adequacy of the model in capturing the underlying patterns in the observed data, given the initial scope of the study.

Regarding sensitivity analyses, no formal sensitivity analyses were conducted to explicitly test the impact of different outlier handling or imputation methods (since no imputation was necessary). This is a limitation of the current study. Future research should aim to include formal outlier detection methodologies and, if necessary, explore the impact of different imputation techniques on the forecasting results through sensitivity analyses, should longer and potentially less complete datasets become available.

3.3. *Methodology used for forecasting medical waste generation in Türkiye*

In this study, forecasting of MW generation in Türkiye is carried out using different population (per capita) based semi-empirical models and scenarios. Semi-empirical models generally deliver stout solutions to forecasting problems. In the view of this fact, first, Türkiye's average per capita MW generation between 2013 and 2020 is calculated using data given in Fig. 2 as 1.29 kg. This value is in good agreement with the per capita MW generation values of other countries such as Lebanon, Greece, and China, which were reported as 1.42, 0.70 and 0.7–1.5 kg (averaging above 1.0 kg) [36,37], respectively. Thus, the first model (Model 1) is generated by assuming a scenario that Türkiye's per capita MW generation would remain constant till 2040 by using Eq. (1).

$$MW(t) = MW_{pc,average} \times P(t) + \varepsilon(t) \quad (1)$$

In Eq. (1), $MW(t)$ is medical waste generation in year t, in thousand tons, $MW_{pc,average}$ is the average medical waste generation per capita between 2013 and 2020, which is taken as 1.29 kg, $P(t)$ is Türkiye's population at year t, in million people, $\varepsilon(t)$ is the random error term in year t, and t is year of interest which is $\geq$2013. Türkiye's population data and forecast between 2013 and 2040 are given in Table 3 [81,86]. Türkiye's MW generation forecast between 2013 and 2040 is calculated using Model 1 and shown in Fig. 4, which is given and elucidated in the results and discussion section.

The second model (Model 2) structured as Eq. (2) is generated based on an annual increase rate scenario for Türkiye's per capita MW generation between 2013 and 2020, which is estimated as nearly 8 % from data given in Fig. 2.

$$MW(t) = \left[MW_{pc}(t-1) \times \left(1 + MW_{pc,AIR}\right)\right] \times P(t) + \varepsilon(t) \quad (2)$$

In Eq. (2), $MW(t)$ is medical waste generation in year t, in thousand tons, $MW_{pc}(t-1)$ is per capita medical waste generation in the year before (*t-1)* in kg for reference and as a starting point $MW_{pc}(2013)$ is taken as 0.93 kg, $MW_{pc,AIR}$ is per capita medical waste generation annual increase rate, which is taken as 0.08 (or 8 %), $P(t)$ is Türkiye's population at year t, in million people, $\varepsilon(t)$ is the random error term in year t, and t is year of interest which is $\geq$2014. As an explanation, to estimate $MW_{pc}(2015)$ first $MW_{pc}(2014)$ must be calculated, then using $MW_{pc}(2015)$ value $MW_{pc}(2016)$ can be calculated by using Eq. (2). Thus, a stepwise analogy must be followed. Türkiye's MW generation forecast between 2013 and 2040 is calculated using Model 2 and presented in Fig. 4, which is given and interpreted in the results and discussion section.

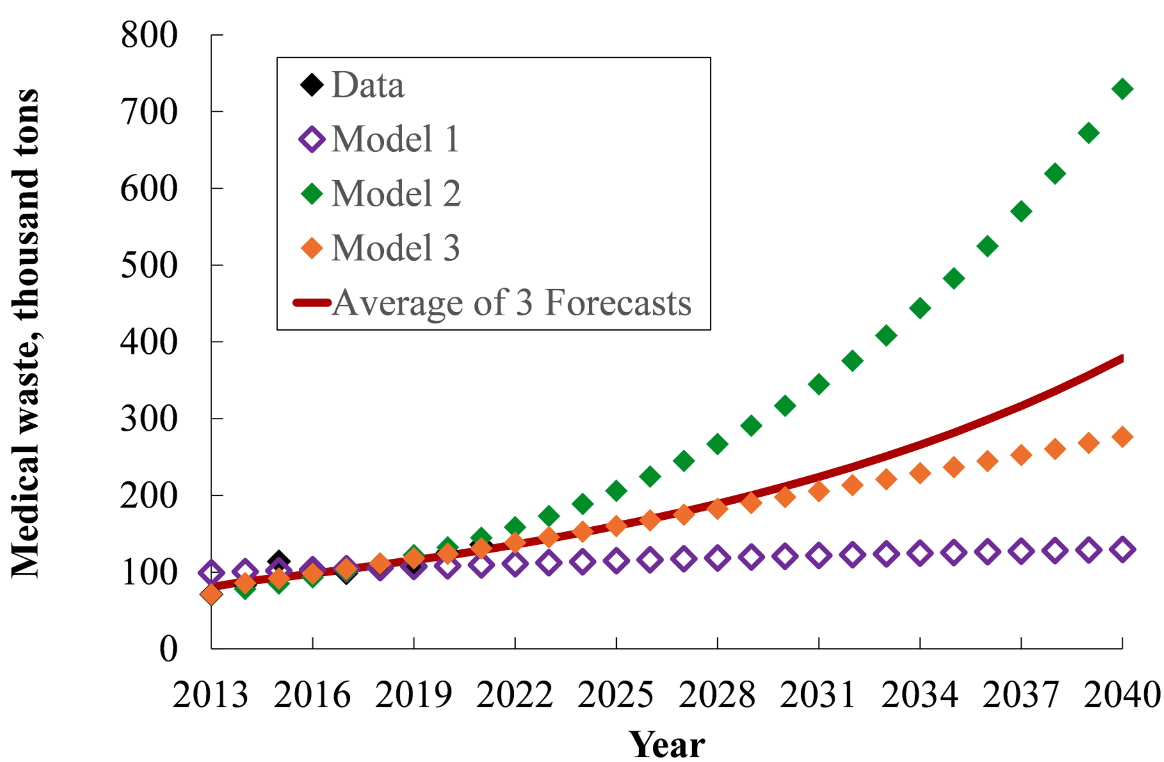

Fig. 4. MW generation data and forecasts for Türkiye between 2013 and 2040.

Türkiye's per capita MW generation between 2013 and 2020 might also follow a linear increasing mathematical trend as shown in Fig. 2. Therefore, the third model (Model 3) structured as Eq. (3) is generated based on a scenario that Türkiye's per capita MW generation would follow a linear increasing trend.

$$MW(t) = [C_1 \times t - C_2] \times P(t) + \varepsilon(t) \quad (3)$$

In Eq. (3), $MW(t)$ is medical waste generation in year t, in thousand tons, C_1 and C_2 are model constants, which are calculated using the data given in Fig. 2 using statistical functions and validated with the software Microsoft Excel as 0.064 and 127.0 using the methodology given elsewhere [87–90], $P(t)$ is Türkiye's population at year t, in million people, $\varepsilon(t)$ is the random error term in year t, and t is year of interest which is $\geq$2013. Türkiye's MW generation forecast between 2013 and 2040 is calculated using Model 3 and shown in Fig. 4, which is given and elucidated in the results and discussion section.

Models 1 to 3 provide a spectrum of data that covers potential stagnancy, exponential and linear rise scenarios of Türkiye's medical waste generation till 2040. Thus, it is beneficial to generate a fourth forecast, which is the average of these data. Results of these average forecasts are also illustrated in Fig. 4, which is given and interpreted in the results and discussion section.

Flexibility of models provides a higher predictive ability in studies focusing on MW generation [91]. Adaptable forecasting models can flawlessly address MW management tasks in different contexts and could aid future studies and practitioners dealing with new health problems [17]. The adaptability of forecasting models to material recycling, energy conversion, and resource recovery could play a key role in sustainability and waste management [92]. On the way to understand how socio-economic development and medical services affect the changes in MW production, a series of representative factors such as government health expenditure, population, the number of hospitalizations and visits, household consumption levels, the number of medical institutions and beds could be evaluated [37]. Detailed knowledge of MW forecasting can significantly improve MW management effectiveness [93].

The three forecasting models generated in this study are adaptable in the aforementioned aspects since they are per capita and population-based mathematical equations. This means that the effects of any significant economic or social change on the MW generation could be easily monitored/forecasted by changing the model parameters: $MW_{pc,average}$ value in Eq. (1) of Model 1, $MW_{pc}(t-1)$ and $MW_{pc,AIR}$ values in Eq. (2) of Model 2, and C_1, C_2 values in Eq. (3) of Model 3. These parameters can all be updated under different conditions, such as varying economic development levels, population structure changes, or advancements in medical technology since they are all per capita based average values. For example, if MW generation decreases to significant breakthrough in medicine then the effects of this on MW generation could be directly seen by simply calculating the new and smaller per capita $MW_{pc,average}$, $MW_{pc}(t-1)$ and $MW_{pc,AIR}$, and C_1, C_2 values in Models 1 to 3. Therefore, in the future if such drastic changes happen, new sound MW generation forecasts could be calculated based on the new paradigm due to the flexibility and adaptability of the proposed models.

3.4. Methodology used for forecasting the energy content of medical waste generation in Türkiye and estimating its natural gas equivalence

In this study energy generation from MW and associated GHG emissions are assessed based on a combustion/incineration route. Wastes with heating values greater than 10 MJ/kg could be combusted without addition of a secondary fuel [94]. In addition, MW can be co-combusted with MSW after pre-treatment, and also with hazardous waste with or without pretreatment. Co-incineration of MW in MSW incinerators is an essential disposal method for MW in small to medium-sized cities [95].

There is no or little information about the energy content of MW generated in Türkiye. Therefore, a global to local analysis is made and energy content/calorific value of different MW around the world were found from the literature and reported in Table 4 [84]. The composition of MW generated in Türkiye is similar to that of these countries (see Fig. 3). Therefore, the energy content of MW in Türkiye is assumed to be equal to the average value of 24.9 MJ/kg given in Table 4 and this value is used in the associated calculation below.

Regarding the significant variation in MW energy content across the countries presented in Table 4. Several key factors contribute to the significant differences in MW energy content reported across nations. Variations in healthcare practices and regulations regarding the use and disposal of materials like plastics, sharps, and textiles directly impact waste composition. A country's economic development and resource availability influence the sophistication and disposability of medical supplies. Furthermore, the success of waste segregation efforts at healthcare facilities determines the concentration of combustible materials. Discrepancies in data collection and reporting methodologies also contribute to the observed variations. Finally, even cultural and social norms can indirectly shape the generation and composition of medical waste, ultimately affecting its energy content.

These inherent differences in MW composition and energy content across countries have significant implications for the generalizability of Türkiye's energy recovery potential to other regions. The average energy content of 24.9 MJ/kg used in this study is derived from a global literature review, aiming to provide a reasonable estimate for Türkiye given the lack of specific local data. However, if another country or region has a significantly different MW composition (e.g., a lower proportion of plastics or a higher proportion of moisture-rich waste), the energy recovery potential based on the same mass of MW would likely be different. Therefore, while this study provides a valuable initial assessment for Türkiye, directly applying the estimated energy recovery potential to other regions without considering their specific MW characteristics would be inappropriate. Future studies focusing on energy recovery from MW in other countries should prioritize obtaining local data on MW composition and energy content to ensure more accurate and region-specific assessments.

MW generation in provinces of Türkiye in 2020 and their end-routes (landfilling or incineration) are given in Table 5 [77]. In 2020, nearly 9 % of Türkiye's MW was sent to incineration, whereas the remaining 91 % was sent to landfills after sterilization. Considering nearly 92 % of MW generated in Türkiye is combustible [84,85], there is a great potential for increasing the share of MW incineration. As a result, scenarios for incinerating 10–90 % (with 10 % increments) of Türkiye's MW are generated.

Calorific value of NG changes between 34.0 and 50.0 MJ/m^3, averaging around 42.0 MJ/m^3 [96–98]. This value is used in the associated calculations below. Thus, NG equivalent of Türkiye's MW is calculated

Table 4
Energy content of different MW around the world.

Country	MW type	Technology	Product	Energy content, MJ/kg
China	PVC MW	Hydrothermal carbonization	Hydrochar particles	24.2
Greece	Cotton MW	Torrefaction	Solid	20.1
Korea	Solid MW	Hydrothermal treatment	Pellets	28.3
Poland	Peat MW	Torrefaction	Solid	21.3
Spain	Plastic MW	Incineration	N/A	30.7
Average (calculated in this study)				24.9

Table 5
MW generation in Türkiye in 2020.

Provinces	Number of health institutions [(1)]	MW, tons	MW Disposed at landfills after sterilization, tons	% of total	MW sent to incineration plants, tons	% of total	Per capita MW, kg
Türkiye, total	1536	109,683	99,369	90.60 %	10,313	9.40 %	1.31
Adana	32	3245	3237	99.74 %	8	0.26 %	1.44
Adıyaman	12	748	748	100.00 %	0	0.00 %	1.18
Afyonkarahisar	22	772	772	100.00 %	0	0.00 %	1.05
Ağrı	9	487	487	100.00 %	0	0.00 %	0.91
Amasya	7	299	299	100.00 %	0	0.00 %	0.89
Ankara	84	8510	0	0.00 %	8510	100.00 %	1.50
Antalya	46	2934	2924	99.67 %	10	0.33 %	1.15
Artvin	8	168	168	100.00 %	0	0.00 %	0.99
Aydın	23	1444	1444	100.00 %	0	0.00 %	1.29
Balıkesir	25	1093	1093	100.00 %	0	0.00 %	0.88
Bilecik	8	171	171	100.00 %	0	0.00 %	0.78
Bingöl	8	209	209	100.00 %	0	0.00 %	0.74
Bitlis	8	320	320	100.00 %	0	0.00 %	0.91
Bolu	11	499	499	100.00 %	0	0.00 %	1.59
Burdur	8	191	191	100.00 %	0	0.00 %	0.71
Bursa	42	3985	3985	100.00 %	0	0.00 %	1.28
Çanakkale	14	513	513	100.00 %	0	0.00 %	0.95
Çankırı	9	181	181	100.00 %	0	0.00 %	0.94
Çorum	16	700	700	100.00 %	0	0.00 %	1.32
Denizli	23	1488	1488	100.00 %	0	0.00 %	1.43
Diyarbakır	28	2049	2049	100.00 %	0	0.00 %	1.15
Edirne	11	870	870	100.00 %	0	0.00 %	2.13
Elazığ	13	856	856	100.00 %	0	0.00 %	1.46
Erzincan	10	291	291	100.00 %	0	0.00 %	1.24
Erzurum	21	1115	1115	100.00 %	0	0.00 %	1.47
Eskişehir	15	1338	1338	100.00 %	0	0.00 %	1.51
Gaziantep	32	2658	2658	100.00 %	0	0.00 %	1.27
Giresun	17	614	614	100.00 %	0	0.00 %	1.37
Gümüşhane	6	139	139	100.00 %	0	0.00 %	0.98
Hakkari	4	207	207	100.00 %	0	0.00 %	0.74
Hatay	23	1831	1831	100.00 %	0	0.00 %	1.10
Isparta	15	905	905	100.00 %	0	0.00 %	2.05
Mersin	26	2484	2484	100.00 %	0	0.00 %	1.33
İstanbul	235	26,051	24,307	93.31 %	1744	6.69 %	1.68
İzmir	61	6386	6386	100.00 %	0	0.00 %	1.45
Kars	8	301	301	100.00 %	0	0.00 %	1.06
Kastamonu	18	472	472	100.00 %	0	0.00 %	1.25

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Table 5 (*continued*)

Provinces	Number of health institutions [(1)]	MW, tons	MW Disposed at landfills after sterilization, tons	% of total	MW sent to incineration plants, tons	% of total	Per capita MW, kg
Kayseri	27	1829	1829	100.00 %	0	0.00 %	1.29
Kırklareli	10	329	329	100.00 %	0	0.00 %	0.91
Kırşehir	6	194	194	100.00 %	0	0.00 %	0.80
Kocaeli	29	2554	2513	98.38 %	41	1.62 %	1.28
Konya	45	2745	2745	100.00 %	0	0.00 %	1.22
Kütahya	13	447	447	100.00 %	0	0.00 %	0.77
Malatya	19	1306	1306	100.00 %	0	0.00 %	1.62
Manisa	28	1782	1782	100.00 %	0	0.00 %	1.23
Kahramanmaraş	18	1248	1248	100.00 %	0	0.00 %	1.07
Mardin	12	650	650	100.00 %	0	0.00 %	0.76
Muğla	22	974	974	100.00 %	0	0.00 %	0.97
Muş	7	318	318	100.00 %	0	0.00 %	0.77
Nevşehir	10	237	237	100.00 %	0	0.00 %	0.78
Niğde	8	289	289	100.00 %	0	0.00 %	0.80
Ordu	17	949	949	100.00 %	0	0.00 %	1.25
Rize	11	507	507	100.00 %	0	0.00 %	1.47
Sakarya	18	1005	1005	100.00 %	0	0.00 %	0.96
Samsun	26	1911	1911	100.00 %	0	0.00 %	1.41
Siirt	8	213	213	100.00 %	0	0.00 %	0.64
Sinop	7	349	349	100.00 %	0	0.00 %	1.61
Sivas	19	1024	1024	100.00 %	0	0.00 %	1.61
Tekirdağ	19	1126	1126	100.00 %	0	0.00 %	1.04
Tokat	15	711	711	100.00 %	0	0.00 %	1.19
Trabzon	22	1205	1205	100.00 %	0	0.00 %	1.48
Tunceli	6	60	60	100.00 %	0	0.00 %	0.72
Şanlıurfa	19	2308	2308	100.00 %	0	0.00 %	1.09
Uşak	8	344	344	100.00 %	0	0.00 %	0.93
Van	14	1121	1121	100.00 %	0	0.00 %	0.98
Yozgat	15	546	546	100.00 %	0	0.00 %	1.30
Zonguldak	12	888	888	100.00 %	0	0.00 %	1.50
Aksaray	10	325	325	100.00 %	0	0.00 %	0.77
Bayburt	c	c	c	N/A	c	N/A	N/A
Karaman	6	248	248	100.00 %	0	0.00 %	0.97
Kırıkkale	7	296	296	100.00 %	0	0.00 %	1.06
Batman	13	415	415	100.00 %	0	0.00 %	0.67
Şırnak	8	379	379	100.00 %	0	0.00 %	0.70
Bartın	3	198	198	100.00 %	0	0.00 %	0.99
Ardahan	3	98	98	100.00 %	0	0.00 %	1.02

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Table 5 (*continued*)

Provinces	Number of health institutions (1)	MW, tons	MW Disposed at landfills after sterilization, tons	% of total	MW sent to incineration plants, tons	% of total	Per capita MW, kg
Iğdır	4	155	155	100.00 %	0	0.00 %	0.77
Yalova	7	240	240	100.00 %	0	0.00 %	0.87
Karabük	6	506	506	100.00 %	0	0.00 %	2.08
Kilis	c	c	c	N/A	c	N/A	N/A
Osmaniye	10	402	402	100.00 %	0	0.00 %	0.73
Düzce	8	401	401	100.00 %	0	0.00 %	1.01

(1) Includes university, maternity and general-purpose hospitals and their clinics.
0 True zero or magnitude less than half of the unit employed.
c Confidential data.
* Total does not add up due confidential data and round ups.

by using Eq. (4).

$$NG_{eqMW}(t) = MW(t) \times CV_{MW}/CV_{NG} \times AF_{comb} + \varepsilon(t) \quad (4)$$

In Eq. (4), $NG_{eqMW}(t)$ is natural gas equivalent of the energy content of medical waste generated in Türkiye in year t, in million m^3, $MW(t)$ is medical waste generation in year t, in thousand tons, which is the average of forecasts generated using Eqs. (1) to (3) and also given in Fig. 4 as "Average of 3 Forecasts", CV_{MW} and CV_{NG} are average calorific values of medical waste, which are taken as 24.9 MJ/kg and 42.0 MJ/m^3, respectively, AF_{comb} is the availability factor of MW for combustion/incineration, which changes between 10 % and 90 % with 10 % increments, $\varepsilon(t)$ is the random error term in year t, and t is year of interest which is $\geq$2013. NG equivalence of Türkiye's MW generation between 2022 and 2040 based on different increment scenarios are calculated by using Eq. (4) and reported as Fig. 5, which is given and elucidated in the results and discussion section.

In 2020, NG consumption in Türkiye was nearly 46.4 billion m^3 [99]. There is no large-scale natural gas fired power plants under construction in Türkiye. It is assumed that nearly 2.4 GW installed capacity will be put into operation by 2030 and an additional 10 GW NG combined cycle powerplants (NGCCPs) may be put into operation by 2035 to stabilize potential intermittencies associated with renewable energy plants for energy security [100]. Türkiye's natural gas demand till 2040 is forecasted using the highly cited linear model of the author [101]. Results of this forecast are given in Table 6 [101].

As stated above, 92 % of Türkiye's MW is combustible. Therefore, Türkiye's MW generation's ("Average of 3 Forecasts" in Fig. 4) percentile theoretic supply of NG between 2022 and 2040 is calculated by using Eq. (4), taking AF_{comb} as 0.92, and dividing it to NG forecast given in Table 6 in the associated year. Findings of this analysis are given in Table 7 and interpreted in the results and discussion section. The theoretic economic worth of this amount of NG is also calculated by taking the wholesale price of NG in Türkiye as 0.375 US$ per m^3 [102] and reported in Fig. 6, which is given in the results and discussion section.

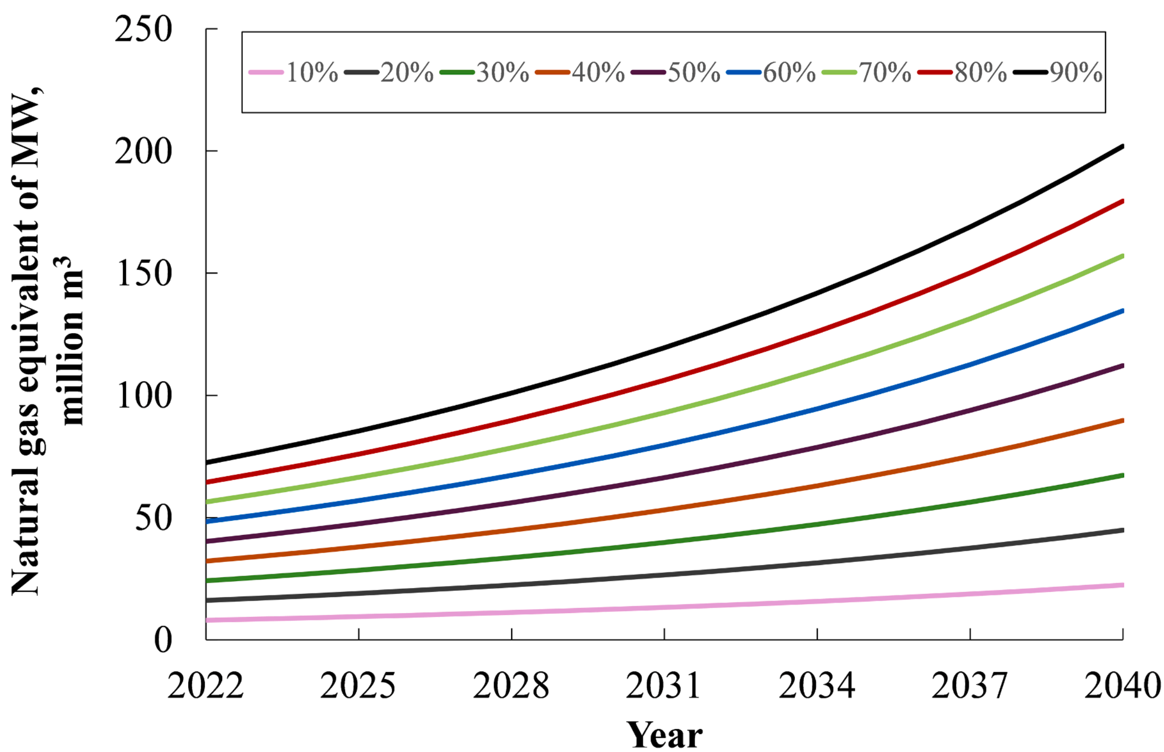

Fig. 5. NG equivalent of MW (Data: "Average of 3 Forecasts" and scenarios for AF_{comb}=10–90 % with 10 % increments) between 2022 and 2040.

Table 6
Türkiye's natural gas demand till 2040.

Year	Natural gas demand, billion m^3
2022	59.2
2023	61.3
2024	63.5
2025	65.7
2026	67.9
2027	70.1
2028	72.3
2029	74.6
2030	76.8
2031	79.0
2032	81.2
2033	83.4
2034	85.6
2035	87.8
2036	90.0
2037	92.2
2038	94.4
2039	96.6
2040	98.8

Table 7
Ratio of NG equivalence of all MW suitable for incineration to Türkiye's NG consumption between 2022 and 2040.

Year	NG equivalence of all MW suitable for incineration (Average of 3 Forecasts)/ Türkiye's NG consumption, %
2022	0.13 %
2023	0.13 %
2024	0.13 %
2025	0.13 %
2026	0.14 %
2027	0.14 %
2028	0.14 %
2029	0.15 %
2030	0.15 %
2031	0.15 %
2032	0.16 %
2033	0.16 %
2034	0.17 %
2035	0.18 %
2036	0.18 %
2037	0.19 %
2038	0.19 %
2039	0.20 %
2040	0.21 %

3.5. Greenhouse gas emissions from incineration of medical waste

Incineration of MW is beneficial for energy production, but the process also generates greenhouse gases. Yet, detailed information about this topic is limited in the literature. After a detailed analysis nitrogen oxide (NO_x), CO, and sulfur dioxide (SO_2) emissions from Tier 2 uncontrolled air and Tier 1 rotary kiln incineration of MW were found from the European Environment Agency (EEA) as nearly 1.8, 1.5, 1.1 and 2.6, 0.02, 0.32 kg/Mg MW, respectively [103]. These values are used to calculate theoretical associated NO_x, CO, and SO_2 emissions from incineration of MW in Türkiye by using the forecasts generated by Models 1 to 3 and given in Figs. 4& 5 and reported in the results and discussion section as Fig. 7.

3.6. Accuracy of the fit analysis

The accuracy of the forecasting models is compared with timeline series by calculating mean absolute percent error (MAPE) and root mean squared error (RMSE) values by using Eqs. (5) and (6), respectively [101]. In addition, the goodness of fit is measured via estimation of R^2.

$$\mathrm{MAPE} = \frac{1}{\mathrm{N}}\sum_{t=1}^{\mathrm{N}}\left|\frac{\widehat{y}_t - y_t}{y_t}\right| \times 100 \tag{5}$$

$$\mathrm{RMSE} = \sqrt{\sum_{t=1}^{\mathrm{N}}\frac{(\widehat{y}_t - y_t)^2}{\mathrm{N}}} \tag{6}$$

In Eqs. (5) and (6); $\widehat{y}_t$, y_t and N are estimated and actual values in year t and total number of years, respectively. The accuracy of estimations is appraised by error estimation. Therefore, smaller RMSE and MAPE values show better estimation [101].

Residual analysis is also made by calculating the ratio of absolute error to actual data by using Eq. (7) on timeline series and using the forecasts generated by Models 1 to 3.

$$\mathrm{RE}_t = \left|\frac{\widehat{y}_t - y_t}{y_t}\right| \times 100 \tag{7}$$

In Eq. (7), RE_t is the residual error in year t in %, $\widehat{y}_t$, y_t are explained in Eqs. (5) and (6), and t is the year of interest which changes between 2013 and 2021.

4. Results and discussion

4.1. Medical waste generation in Türkiye between 2011 and 2040

Timeline data [80] and forecasting results of Models 1 to 3 are shown in Fig. 4. The results clearly showed that data generated by the models fitted almost seamlessly to the timeline series between 2013 and 2021. In this period data generated by all models almost overlap. After 2022, the results of the models started to deviate from each. MW generation forecast generated by Model 2 increases more rapidly than the other forecasts, which is expected due to its exponential type of growth. It is estimated that Türkiye's MW generation in 2030 could be between 120.6 (Model 1) and 316.7 (Model 2), 211.7 (Average), thousand tons and this generation could increase to between 129.7 (Model 1) and 729.7 (Model 2), 378.6 (Average of 3 Forecasts) thousand tons in 2040.

Türkiye and Greece are neighboring countries with similar economies and healthcare systems, and England also has a similar healthcare system with Türkiye. In 2023, it has been reported that the National Health Service (NHS) providers in England produce nearly 156,000 tons of MW per annum [104]. As can be seen from Fig. 4, Türkiye's MW generation in 2023 was forecasted as nearly 143,500 tons (Average of 3 Forecasts). In 2018, Greek public hospitals produced 9500 tons of MW, and it is expected to reach 18,200 tons in 2025 and exceed 18,800 tons in 2030 [105]. The population of Greece in 2025 and 2030 were projected as nearly 10.4 and 10.3 million people [106]. On the other hand, Türkiye's population in 2025 and 2030 were projected as 88.8 and 93.3 million people, respectively (see Table 3). This means that Türkiye's population is nearly 9 times that of Greece in the same years. Türkiye's MW generation in 2025 and 2030 was projected as nearly 155,400 and 211,700 tons (see Average of 3 Forecasts data in Fig. 4). A simple linear extrapolation shows that if Greece have the same population as Türkiye, then its MW generation in 2025 and 2030 could be 160,500 and 170,300 tons. Therefore, the data and analysis given above clearly shows that the forecasts generated in this study are sound and highly compatible with MW generation data and forecasts of other countries with similar economies and healthcare systems like Türkiye.

Industrialization and urbanization have increased the quantity of waste generation especially MW generation in developed and developing countries like Türkiye and its neighbors [107]. It is also reported that there is a positive and significant influence of population size on MW generation, thus when the aging population grows MW generation consequently increases [39]. The results of the per capita forecasting studies and the analysis given in this study clearly showed that MW generation in Türkiye is going to increase in the years to come mainly

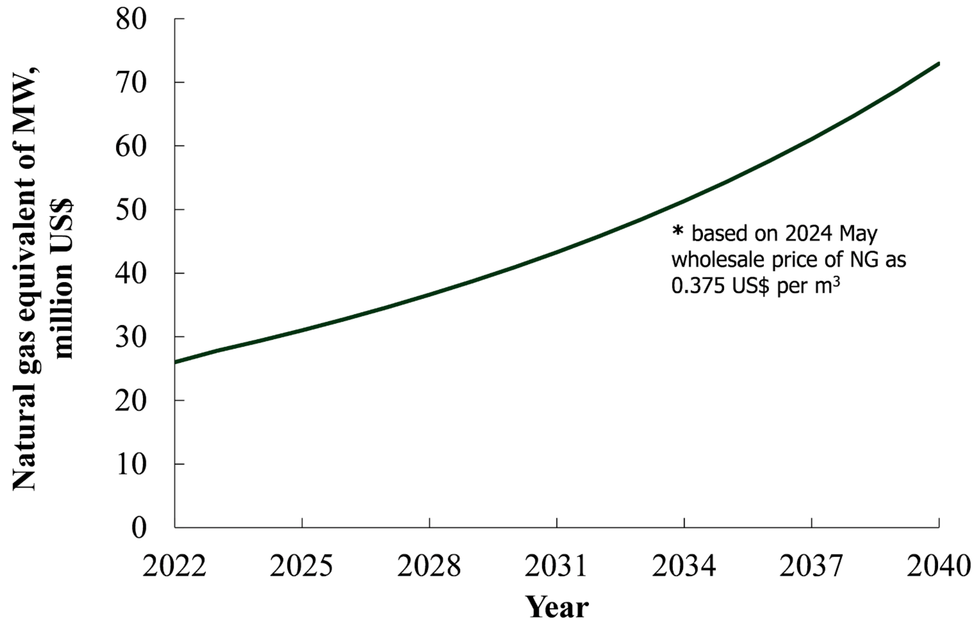

Fig. 6. Economic worth of NG (used for electricity generation) equivalent of combustible portion of MW (92 % of total) based on data: "Average of 3 Forecasts" between 2022 and 2040.

due to population increase and specifically rise in the share of aging population. It is estimated that in 2040 annual per capita MW generation in Türkiye could change between 1.29 and 7.27 kg, with an average of 2.75 kg. At these levels, Türkiye's annual per capita MW generation could be along with the highest in developed countries, exceeding that of China: 1.5 kg [37] and reaching that of South Korea: 7.2 kg [38].

Consequently, the novel findings of this study clearly shows that Türkiye must urgently find sustainable solution to its increasing MW problem. In that context, the result of the waste to energy calculations carried out in this study and elucidated in the following subsection could pave the way.

4.2. Natural gas equivalence of medical waste incineration in Türkiye between 2022 and 2040 and associated greenhouse gas emissions

The importance of alternative energy sources in Türkiye's energy portfolio increases as the instabilities around the globe enhanced by the 2019 pandemic raise issues about energy security while the energy demand continues to rise [108]. Combustion of MSW, biomass and alternative energy sources for power generation is considered as critical for Türkiye's energy sustainability and future [109,110]. As stated in the introduction section, MW is the main component of the hazardous portion of MSW in Türkiye. There is a growing interest in power generation from MSW in Türkiye in the last 10 years and combustion of MSW for power generation will become an important aspect of Türkiye's renewable energy policy in the next 10–15 years [49,111]. Therefore, innovative solutions around MW combustion and processing will become hot topics of the near future, which should also be supported by government policies.

NG equivalence of Türkiye's MW generation between 2022 and 2040 is estimated using Eq. (4) for different scenarios based on different AF_{comb} values and shown as in Fig. 5. As can be seen from this figure, in 2030 energy worth equal to the consumption of 12.5 million m^3 of NG could be produced if 10 % of MW is collected and combusted for heat and power generation. This value could increase to 206.5 million m^3 in 2040 if all the combustible portions of MW (92 %) are collected and incinerated for heat and power generation. These novel results clearly showed that there is a great economic potential for reutilization of MW in Türkiye for heat and power generation. Thus, Türkiye's national energy policy should be updated to include waste-to-energy schemes for sustainable reutilization of MW.

Novel to this study, energy content of MW suitable for incineration is compared to Türkiye's NG consumption based on equivalence analysis and the results of this are shown in Table 7. As can be seen from this table, MW in Türkiye could be reutilized to produce energy and this could generate energy worth equal to 0.13–0.21 % of Türkiye's annual NG consumption between 2022 and 2040. The economic worth of this NG equivalence is also calculated and reported in Fig. 6. As can be seen from this figure, if MW generation in Türkiye suitable for combustion is collected and used for power generation annually energy worth equal to the combustion NG worth 26.2–77.4 million US$ (based on 2024 May wholesale prices) could be generated between 2022 and 2040.

The results of this study clearly showed that there is a great economic potential for energy generation from MW in Türkiye via combustion. Yet, incineration of MW is no miracle solution, and it also has some drawbacks. The first drawback is the associated GHG emissions. Novel to this study, theoretical NO_x, CO, and SO_2 emissions from Tier 2 uncontrolled air and Tier 1 rotary kiln incineration of MW were calculated based on the conversion factors given in subSection 3.4 and the MW generation and incineration forecasts reported in Fig. 4. The results of these forecasts are shown in Fig. 7.

It is estimated that Tier 1 rotary kiln incineration of MW would generate the highest amounts of NO_x emissions and Tier 2 uncontrolled air combustion of MW would result in the highest amounts of CO, and SO_2 emissions. In 2030, if all the MW generated is collected and further processed for energy generation (combusted) theoretical NO_x, CO, and SO_2 emissions from Tier 2 uncontrolled air and Tier 1 rotary kiln incineration are estimated as nearly 380, 320, 230 and 550, 4, 70 tons, respectively. These values could increase to 680, 570, 420 and 980, 8, 120 tons in 2040, respectively.

Incineration of MW also results in the production of MW ash, which is nearly 5 % of the total original mass [112]. This ash is considered as a highly toxic material, which contains carbon components, dioxins, heavy metals, and leachable alkali chlorides [112]. As a solution, flue gases from MW incineration could utilize slaked lime for desulfurization calcium-rich medical waste incineration fly ash, which realizes the S/S of self-released Cl^- in magnesium potassium phosphate cement (MKPC) system containing abundant monopotassium phosphate (KH_2PO_4) [113]. Therefore, suitable and sustainable measures and routes must be found for the disposal of MW ash after incineration.

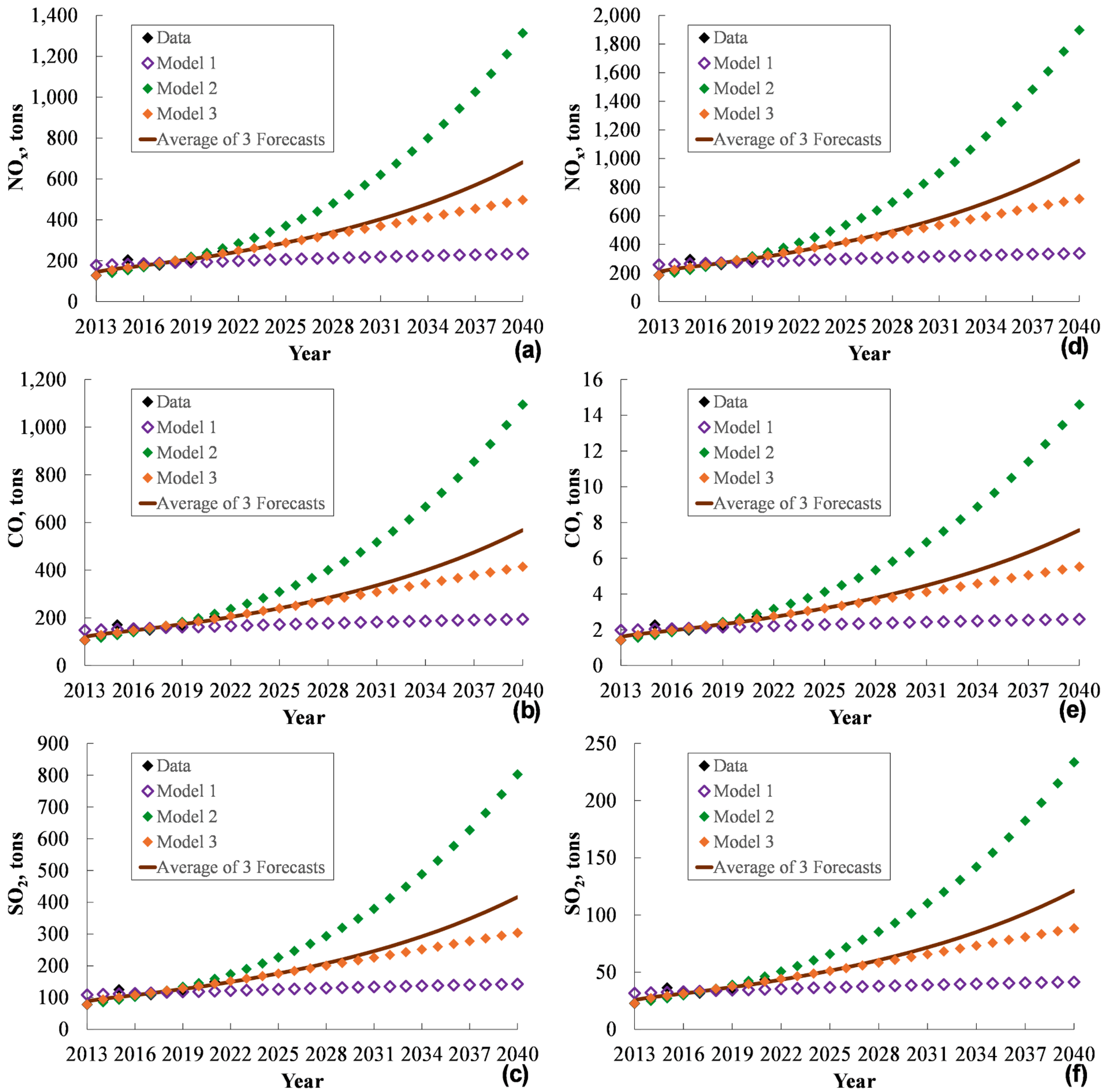

Fig. 7. NO_x, CO and SO_2 emissions from Tier 2 uncontrolled air (a), (b), (c) and Tier 1 rotary kiln (d), (e), (f) incineration based on MW generation data and forecasts for Türkiye between 2013 and 2040.

The paper's initial scope did not include a detailed evaluation of specific sustainable disposal routes for this ash. While current practices in Türkiye involve sending the majority of treated MW to landfills, which would consequently include incineration ash from the 9 % that is incinerated, this is not necessarily a sustainable long-term solution due to the potential for leaching of hazardous components and the need for dedicated landfill space. Sustainable disposal of MW incineration ash necessitates exploring various routes beyond conventional landfilling. Solidification/Stabilization (S/S), a common pre-treatment, involves binding agents like cement or lime to reduce the leachability of heavy metals, enhancing landfill safety. Incorporation into construction materials, such as cement, concrete, or asphalt, presents a potential beneficial reuse pathway, though rigorous testing is crucial [114]. Advanced thermal treatment technologies offer possibilities for further detoxification or material recovery. Finally, if other options are unsuitable, disposal in specialized hazardous waste landfills with engineered barriers provides a more environmentally controlled alternative to standard landfills [115]. Comparing the environmental impacts of these routes to current landfilling practices requires a detailed life cycle assessment for each option. Standard landfilling of untreated or unstabilized incineration ash carries risks of soil and groundwater contamination due to leaching of heavy metals and persistent organic pollutants [114,115]. Sustainable routes like S/S aim to mitigate this risk, while beneficial reuse in construction materials could reduce the need for virgin resources [114,115]. However, each alternative route would have its own set of environmental considerations that need careful evaluation.

It's crucial to clarify that the current study's techno-economic assessment, particularly the calculations of net present value (NPV) and potential economic worth (Fig. 6), adopted a simplified approach focusing primarily on the revenue potential from the NG equivalence of the energy content in the MW. The main components considered in the economic worth estimation were: Forecasted average MW generation in Türkiye, average calorific value of MW (based on literature), calorific value of NG. Wholesale price of natural gas in Türkiye (as of the specified date), combustible portion of MW (92 %). Specific cost components such as transportation, pre-treatment (beyond basic sterilization which is assumed to be a prerequisite regardless of disposal route), incineration facility capital and operational costs, ash disposal, regulatory compliance, and potential revenue from electricity generation were not explicitly included in this initial estimation of economic worth. The aim of this initial analysis was to provide a theoretical upper bound on the potential fuel value of the combustible portion of the projected MW generation across Türkiye.

It is important to recognize that the feasibility and costs associated with implementing MW-to-energy projects can vary significantly across different regions of Türkiye. Factors such as population density and distribution will directly influence the expenses related to medical waste collection and transportation. The existing waste management infrastructure in each region will dictate the necessity for new facilities and associated capital investments. Furthermore, local regulatory frameworks and the presence of regional incentives can substantially impact permitting processes and overall operational costs. The availability and cost of suitable land for constructing incineration plants will also be a crucial regional determinant. Finally, variations in energy demand and pricing across Türkiye could affect the potential revenue streams if electricity generation is considered as part of the MW valorization strategy.

The current study did not incorporate these regional variations due to the lack of detailed, spatially disaggregated data on MW generation, collection systems, and regional economic factors. Therefore, the economic worth presented should be interpreted as a national-level theoretical potential based on fuel equivalence, rather than a detailed project-level financial feasibility study. Therefore, future research should aim to incorporate a more comprehensive techno-economic assessment that includes these crucial cost components and considers the impact of regional variations across Türkiye to provide a more realistic evaluation of the feasibility of MW-to-energy projects.

4.3. Accuracy of fit analysis

Accuracy of the forecasting models is tested by calculating RMSE and MAPE (%) values, which are tabulated in Table 8. As can be seen from Table 8, according to the MAPE (%) and R^2 values all models generated good forecasts with high accuracies and goodness of fit. Moreover, amongst the three suggested models, the forecast generated by Model 3 given in Eq. (3) is considered a better fit. In addition to the error metrics used to validate forecasting models, a residual analysis is also made by calculating the ratio of absolute error to actual data by using Eq. (7) on the timeline series [80] and using the forecasts generated by Models 1 to 3 (see Fig. 4) between 2013 and 2021. The results of this residual analysis are shown in Table 9.

The RE_t values, %, of Model 3, which changes between 0–20 %, are smaller than those of Models 1 and 2 which change between 0–39 %. This suggests a better fit for Model 3, which also supports the claim above. RE_t values of the models are also found to be random. Thus, the residual analysis is believed to provide a more comprehensive evaluation of the model's performance and reliability.

The initial assessment of the forecasting models' accuracy focused on key metrics such as RMSE, MAPE (%), and R^2, alongside a residual error analysis RE_t that quantified the magnitude of the prediction errors. While these metrics offer valuable insights into the model's performance, a more in-depth statistical analysis of the residuals, including assessments of their distribution, potential autocorrelation, and heteroscedasticity, was not performed in this initial study. This limitation is partly due to the scope of the initial analysis and potentially influenced by the inherent challenges in obtaining long and consistently detailed time-series data for medical waste generation in Türkiye. To provide a more comprehensive validation, future research will prioritize a rigorous statistical analysis of the residuals, incorporating formal testing for their distribution (e.g., normality tests), autocorrelation (e.g., Durbin-Watson statistic, correlograms), and heteroscedasticity (e.g., Breusch-Pagan or White tests). Addressing these aspects in subsequent research will be crucial for a more robust confirmation of the models' reliability and predictive power.

Table 8
MAPE (%), RMSE and R^2 values of MW generation forecasting models.

Parameter	Model 1	Model 2	Model 3
RMSE	16.0	11.5	8.5
MAPE (%)	13.1 %	7.5 %	5.0 %
R^2	0.996	0.992	0.988

Table 9
Residual errors, %, between the models and timeline data of MW generation.

Year	Residual Errors, %		
	Model 1	Model 2	Model 3
2013	39 %	0 %	0 %
2014	21 %	6 %	3 %
2015	11 %	25 %	20 %
2016	5 %	5 %	0 %
2017	6 %	3 %	6 %
2018	1 %	4 %	3 %
2019	2 %	11 %	8 %
2020	14 %	5 %	1 %
2021	19 %	6 %	4 %

5. Conclusion

Three novel semi-empirical models generated in this study are used to forecast Türkiye's MW generation till 2040 based on different scenarios. RMSE, MAPE (%), R^2 and RE_t values of all models suggested high accuracy and goodness of fit. Yet, Model 3 is considered a better fit amongst others based on RMSE, MAPE (%), R^2 criteria and lower RE_t values. It is estimated that Türkiye's average annual per capita MW generation in 2040 could be 2.75 kg, which would be in alignment with the MW generation of other developed countries. Türkiye's MW generation in 2040 is estimated to change between nearly 130 and 730 thousand tons, where average of 3 forecasts is found as nearly 380 thousand tons. It is also estimated that in 2040 energy worth equal to the consumption of 206.5 million m^3 of NG could be produced if all the combustible portion of MW, which is 92 % of the total, is incinerated. Energy content of MW suitable for incineration is compared to Türkiye's NG consumption based on equivalence analysis and it is found that energy worth equal to 0.13–0.21 % of Türkiye's annual NG consumption between 2022 and 2040 could be supplied from incineration of MW. At these levels, annually energy worth equal to 26.2–77.4 million US$ of NG (based on 2024 May wholesale prices) could be generated from MW between 2022 and 2040. The main drawback of MW incineration would be greenhouse gas emissions and fly ash generation. It is estimated that Tier 1 rotary kiln incineration of MW would generate the highest amounts of NO_x emissions and Tier 2 uncontrolled air combustion of MW would result in the highest amounts of CO, and SO_2 emissions. In 2040, if all the MW generated is collected and further processed for energy generation theoretical NO_x, CO, and SO_2 emissions from Tier 2 uncontrolled air and Tier 1 rotary kiln incineration are estimated as nearly 680, 570, 420 and 980, 8, 120 tons in 2040, respectively. As a suggestion for future research, greenhouse gas emissions and fly ash generation from MW incineration should be analyzed in detail to find appropriate treatment and disposal routes for protecting the environment. In addition, for future comprehensive and comparable greenhouse gas emission analyses of MW incineration, employing specific metrics and established frameworks is crucial. Key emission metrics include reporting in carbon dioxide equivalent (CO_2e) for aggregated impact, detailing individual GHG emissions (kg/Mg MW) for specific pollutants, and using energy-specific emissions (kg CO_2e/kWh) when energy recovery is involved. Recommended frameworks encompass life cycle assessment (LCA) for a holistic "cradle-to-grave" evaluation, adherence to the Intergovernmental Panel on Climate Change (IPCC) Guidelines for National Greenhouse Gas Inventories for standardized reporting, the environmental impact assessment (EIA) framework for broader environmental impact mitigation, and the ISO 14,040 series on LCA for a rigorous and internationally recognized approach. Ultimately, the forecasting models and energy equivalence analysis presented in this study provide a valuable foundation for estimating MW generation and exploring waste-to-energy potentials, not only for Türkiye but also for other researchers in different countries.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) used DeepL, ChatGTP and Gemini in order to improve the language and readability. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

CRediT authorship contribution statement

Mehmet Melikoglu: Writing – original draft, Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization.

Declaration of competing interest

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

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I would like to dedicate this paper to my mother and father, Nebile Tülay Melikoğlu and Kazım Melikoğlu. I wish them health and goodness.

Data availability

Data will be made available on request.

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