Published by
NIGERIAN SOCIETY OF PHYSICAL SCIENCES
Available online @ https://journal.nsps.org.ng/index.php/jnsps

J. Nig. Soc. Phys. Sci. 7 (2025) 2711

Journal of the Nigerian Society of Physical Sciences

Analysis of industrial solid waste for secure and eco-friendly disposal by incineration practices

Chinnarao Menda[a], Ch. Ramakrishna[b,*], V D N Kumar Abbaraju[c]

[a]*Sr.Manager- EHS, Raks Pharma private limited, JNPC, Parawada, Anakapalli District, PIN – 531019*
[b]*Department of Environmental Sciences, GITAM University, Visakhapatnam, Andhra Pradesh, INDIA – 45*
[c]*Department of Chemistry, GITAM University, Visakhapatnam, Andhra Pradesh, INDIA - 45*

Abstract

Solid waste management poses significant environmental challenges worldwide, particularly in developing nations like India, where unscientific disposal of industrial solid waste (ISW) leads to severe environmental and health concerns. With the increasing demand for energy, there is a growing emphasis on developing alternative fuels and optimizing waste management systems across all production stages. Among various methods, incineration has emerged as a sustainable alternative to landfilling, addressing issues such as soil, groundwater, and air pollution while generating energy. This study investigates 21 industrial waste samples from Visakhapatnam to evaluate their physical and chemical properties for secure and eco-friendly incineration. Key parameters analyzed include bulk density, pH, calorific value, and heavy metal concentrations. Bulk density values ranged from 0.23 to 1.48 g/cc, and pH levels varied from highly acidic (1.36) to slightly alkaline (11.74), with some falling outside the prescribed range of 4–12 for incinerable waste. Calorific values revealed substantial variation, with some exceeding the limit of 2500 Cal/gm, highlighting their potential for energy recovery. Heavy metal analysis demonstrated compliance with regulatory limits for most samples. Total zinc, copper, and chromium concentrations were within acceptable ranges, while cadmium concentrations (up to 8.5 mg/kg in certain samples) necessitate closer monitoring to mitigate potential environmental risks. Nickel concentrations were below the detection limit of 7.0 mg/kg, and lead levels remained well within permissible limits. The findings indicate that most waste samples are deemed suitable for incineration, posing minimal leaching risks. This study provides critical insights into optimizing waste-to-energy processes and reactor design, contributing to sustainable waste management practices and energy recovery solutions.

DOI:10.46481/jnsps.2025.2711

Keywords: Incineration, Heavy metals, Industrial waste, Calorific value, Bulk density

Article History :
Received: 24 February 2025
Received in revised form: 30 April 2025
Accepted for publication: 16 May 2025
Available online: 12 June 2025

Communicated by: B. J. Falaye

1. Introduction

Incineration is a widely used method for disposing of waste through combustion, allowing energy recovery and utilized directly or converted into electricity, gases, steam, and ash [1, 2]. The rapid growth of the global economy and urbanization has significantly increased waste generation, with cities producing approximately 1.2 kg of waste per capita daily and an estimated 1.3 billion tons annually. Of this total, around 15% undergoes incineration [3, 4]. A World Bank report [5] estimates that global municipal solid waste (MSW) generation currently stands at 2.01 billion tonnes annually, with projections suggest-

*Corresponding author Tel. No.: +91-988-514-4830.
Email address: rchintal@gitam.edu (Ch. Ramakrishna)

ing an increase to approximately 3.4 billion tonnes by 2050. This surge in MSW is driven by population growth, industrialization, improved living standards, and rapid urbanization [6–9]. Managing such vast quantities of waste presents significant challenges worldwide. Municipal solid waste incineration (MSWI) has gained prominence as an alternative to landfilling, particularly given the environmental challenges posed by landfills, including soil, groundwater, and air pollution caused by methane emissions during waste degradation [10–12]. Public opposition to landfills, coupled with high costs, limited land availability, and stricter regulations, has further emphasized the need for advanced waste management solutions. Landfilling, the most common method of MSW disposal, faces growing constraints due to limited land availability, environmental contamination, and stringent regulations. These issues have prompted environmental managers to explore alternative waste management strategies, including enhanced landfill bioreactors, composting, and thermal treatment processes [13, 14]. Among these, incineration has gained widespread acceptance due to its smaller land requirements, significant mass and volume reduction, and potential for energy recovery in the form of heat and electricity [2]. In MSWI, waste is combusted in furnaces at temperatures ranging from 800 to 1000°C. Heat produced during combustion is transferred via flue gases, which are cooled in high-pressure boilers to generate steam. This steam can then be used to produce electricity, offering a sustainable approach to energy recovery [15]. Researchers continue to explore and refine such technologies to address the growing challenges of municipal solid waste management. Incineration can reduce MSW mass and volume by 70–90%, making it a more efficient and space-saving option compared to sanitary landfills [16–18]. Consequently, this method is increasingly valued and implemented in both developed and developing countries as a practical solution for sustainable waste management. The efficiency of waste incineration technology is closely tied to the properties of the waste, such as moisture content and calorific value. Effective incineration requires high temperatures ranging from 800–1000°C, along with adequate air supply and thorough mixing of the gas stream. To minimize smoke release and prevent the formation of harmful emissions like dioxins and furans, a minimum temperature of 850°C is essential for burning carbonaceous waste. Optimal waste characteristics include a moisture content below 45% and a calorific value exceeding 1500 kcal/kg. Additionally, the incineration of chlorinated plastics should be avoided to reduce environmental hazards. Emission standards for such processes are regulated under the Solid Waste Management (SWM) Rules, 2016 [19]. Waste-to-Energy (WtE) technology leverages the energy potential of waste through high-temperature incineration and thermochemical or biochemical conversions to generate electricity and/or heat energy. This approach not only reduces waste volume but also mitigates the environmental impact of improper waste management [20–22]. Plastics and other non-biogenic materials are particularly advantageous for WtE processes, as they provide higher heat output compared to biogenic materials like paper. The increasing prevalence of plastic waste necessitates compositional analysis to optimize energy recovery [23]. Key parameters include calorific values exceeding 3500 kcal/kg, sulfur content below 2.5%, and chlorine content under 0.2%. Additionally, levels of heavy metals, polychlorinated biphenyls (PCBs), and other toxic substances must remain within permissible limits [10]. While AFs offer economic benefits over fossil fuels by utilizing waste materials, their use poses challenges such as uneven heat distribution, operational instabilities, emissions control, and limitations on clinker composition in cement manufacturing [24]. Understanding the chemical behaviour and composition of municipal solid waste (MSW) is critical for developing an effective waste management system. This knowledge is particularly important when MSW is intended for use as fuel or other applications, as it ensures compliance with safety and efficiency requirements [19]. In the present study, the focus was on analyzing various industrial waste samples from different locations to ensure their secure and eco-friendly disposal through incineration. By examining these samples, the research aims to evaluate their composition, leachability, and compliance with environmental standards for safe disposal, specifically focusing on the suitability of incineration as a disposal method.

2. Method and materials

The present research work was carried out at ‘Department of Environmental Sciences, GITAM School of Sciences, Gandhi Institute of Technology and Management (GITAM), Visakhapatnam during 2023-2024’. Twenty one samples from various locations, detailing various type of waste and waste management process. The details of each sample are presented in Table 1.

2.1. Sample collection

Collect a sufficient amount of material to ensure reliable analysis, typically around 1 kg for solid samples or an appropriate volume for liquid samples. Immediately secure samples in suitable containers to prevent contamination or deterioration. Solid samples should be placed in double-lined polyethylene bags or other appropriate containers to maintain integrity. Clearly marked each sample with essential details, including the sample identification number, collection date, and location. Thoroughly document the sampling process, noting any observations, environmental conditions, and potential hazards encountered during collection.

2.2. Analytical procedures

The characterization of waste and environmental samples requires specific methodologies to analyze various physical, chemical, and biological parameters. These methods provide insights into the composition, reactivity, and potential environmental impacts of the sample. Below is a detailed description of the parameters and the methodologies used for their analysis. Physical and Reactivity Analysis is performed by taking Physical State, Colour, and Texture, Reactivity in Air or Water, Toxic Gas Generation, Explosive Potential are measured. In addition to this Moisture, Density, and Combustion Properties like Paint

Table 1. Samples from various industrial waste collected at different locations.

Sample No.	Type of Waste	Location of sample collection	Report Date	Year
Sample -1	Organic Residue(distillation bottom residue)	JNPC, Parawada	29.04.22	2022-23
Sample -2	Process dried Sludge	JNPC, Parawada Visakhapatnam	22.05.22	2022-23
Sample -3	Organic Liquid Waste(spent solvent)	JNPC, Parawada, Visakhapatnam	09.06.22	2022-23
Sample -4	DMC residue	Allinagaram,Srikakulam	16.06.22	2022-23
Sample -5	Process residue	JNPC,Parawada	30.07.22	2022-23
Sample -6	Process organic residue	Atchutapuram, Visakhapatnam	10.08.22	2022-23
Sample -7	Manufacturing waste	Duvvada,Vizag	18.08.22	2022-23
Sample -8	Contaminated Glass Waste	Duvvada,Vizag	18.08.22	2022-23
Sample -9	Tank bottom sludge	JNPC,Parawada	29.08.22	2022-23
Sample -10	Organic residue	Nakkapalli, Visakhapatnam	29.08.22	2022-23
Sample -11	Methanol Containing hydrazine hydrate	JNPC, Parawada	11.09.22	2022-23
Sample -12	Chemical Containing Residue	Atchutapuram, Visakhapatnam	28.09.22	2022-23
Sample -13	WARP Sample	Pithapuram, Kakinada	22.10.22	2022-23
Sample -14	Chemical Incinerable Waste	JNPC,Parawada	24.10.22	2022-23
Sample -15	Paint Sludge	Atchutapuram, Visakhapatnam	28.10.22	2022-23
Sample - 16	organic Residue	JNPC,Parawada	25.01.23	2022-23
Sample – 17	Process Salt	JNPC,Parawada	27.01.23	2022-23
Sample – 18	off Specification product	Devunipalasa,Srikakulam	16.02.23	2022-23
Sample – 19	Date Expired Products	JNPC,Parawada	21.02.23	2022-23
Sample – 20	Discarded PPE	JNPC,Parawada	28.02.23	2022-23
Sample – 21	Paint Sludge	Kondapalli,Krishna	10.04.23	2023-24

Filter Liquid Test, Bulk Density, Moisture Content, Loss on Drying, Calorific Value. The parameter values are represented in Table 2 and 3.

2.3. Chemical composition

The pH value is measured at 25°C as per USEPA; 9045C (1995) to determine the acidity or alkalinity of the sample. This is a vital parameter influencing chemical reactions, leachate quality, and environmental compatibility. For Extractable Organics and In organics the concentrations of water-soluble organic and inorganic compounds are determined using USEPA-3540C and APHA 23rd Edition, 2540B & E, respectively. These analyses are critical for understanding potential leachate toxicity and environmental mobility. Reactive Cyanide and Reactive Sulfide: Tested using USEPA 9010B (1996) and 9030B/9034 (1996) methods, these analyses identify compounds that release hazardous gases like HCN and H_2S under certain conditions. Ammonical Nitrogenis measured as per APHA 4500 NH_3 (2017), this parameter indicates the presence of nitrogen in ammonium form, which can affect nutrient cycles and leachate properties.

2.4. Heavy metals analysis

Heavy metals are analyzed using USEPA-3050B (1996) in conjunction with AAS (7000B-2007) or specific methodologies for arsenic (APHA 3500 AsB). These methods quantify metals like zinc, copper, arsenic, cadmium, chromium, lead, and nickel. The analysis helps assess toxicity levels and compliance with regulatory standards. Along with Nitrogen, Carbon, Sulfur, Hydrogen, Chloride, Fluoride, Chloride as Cl^- (%), Fluoride as F (mg/L) measured as per APHA 4500 F-D, this test identifies fluoride levels, which are critical for assessing the sample's impact on water resources.

Table 2. Physical and chemical analysis of different industrial waste for secure incineration.

Parameter	Method	Std.for Secure incinarable waste	Sample - 1	Sample - 2	Sample - 3	Sample - 4	Sample - 5	Sample - 6	Sample - 7	Sample - 8
Bulk density (g/cc)	ASTM D5057-10.(2017)	.- - -	1.15	1.2	0.75	1.12	0.96	1.45	0.53	1.48
pH @ 26.2°C	USEPA:9045C.(1995)	4 to 12	5.82	11.74	1.36	5.22	8.4	1.1	7	6.34
Flash point (0C)	USPA:1020A(1992)	65.5	>65.5	40	55	65	62.5	48.5	35.8	35.6
Loss on drying at 105°C(%)	APHA23rd Edi.2540G (2017)	.- - -	30.04	8.27	91.12	10.01	68.19	52.36	14.23	6.38
Loss on drying at 550°C (Dry basis) (%)	APHA23rd Edi.2540G (2017)	< 20% non degradable > 5% Bio-degradable	95.24	89.64	94.12	99.93	91.31	99.29	97.28	49.78
Calorific value(Cal/gm)	IS:1350(Part-II),(Ref.2013)	< 2500	6527	8379	3070	5577	6505	2635	2657	2624
Extaractable Organics (%)	USEPA-3540C (1996)	> 4.0 w/W	< 1.0	< 1.2	< 1.0	< 1.1	< 1.0	< 1.5	< 1.0	< 0.5
Water soluble inorganics (%)	APHA23rd Edi.2540B&E (2017)	< 20% w/W	< 1.0	< 1.1	< 1.3	< 1.2	< 1.0	< 1.2	< 1.1	< 1.3
Water soluble organics(%)	APHA23rd Edi.2540B&E (2017)	< 10%	< 1.0	< 1.3	< 1.4	< 1,1	< 1.5	< 1.2	< 1.8	< 1.0
Reactive Cyanide(mg/Kg)	USEPA9010B (1996)& APHA23rd Ed:4500CN-E	250	< 1.2	< 1.1	< 1.5	< 1.0	< 1.0	< 0.5	< 1.8	< 1.3
Reactive Sulfide(mg/Kg)	USEPA9030B (1996)& 9034 (1996)	500	< 10.0	< 11.2	< 9.0	< 8.0	< 10.5	< 10.2	< 15.5	< 10.0
Ammonical nitrogen as NH3 (WLT) (mg/L)	APHA23rd Edition,2017:4500 NH3 B,C	< 1000.0	< 1.0	< 2.0	< 15.0	< 5.0	< 10.0	< 11.0	< 17.0	< 25.0
Zinc as Zn (Total) (mg/Kg)	USEPA -3050 B(1996) & 7000B-2007	.- - -	16.3	16.4	11.3	1.36	14.25	12.5	16.2	13.75
Zinc as Zn (TCLP) (mg/L)	USEPA 1311(1992), (Extraction) USEPA 7000B (2007), AAS	< 250	3.2	6.5	2.25	7.5	1.35	4.85	2.75	8.45
Zinc as Zn (WLT) (mg/L)	CPCB TSDF Protocal,(2010-11) & USEPA-7000B (2007)	< 10	3.6	3	5.3	4.5	4.2	3.5	2.5	4.8
Copper as Cu (Total) (mg/Kg)	USEPA -3050 B(1996) & 7000B-2007	.- - -	0.1	0.5	0.3	0.5	1.5	1.6	0.5	2.5
Copper as Cu (TCLP) (mg/L)	USEPA 1311(1992), (Extraction) USEPA 7000B (2007), AAS	< 25.0	1.5	1	2.1	1.8	0.9	0.5	0.4	1.5
Copper as Cu (WLT) (mg/L)	CPCB TSDF Protocal,(2010-11) & USEPA-7000B (2007)	< 10	< 10.0	< 10.5	< 10.5	< 10.2	< 1.90	< 1.50	< 0.45	< 1.42

Parameter	Method	Std.for Secure incinarable waste	Sample - 1	Sample - 2	Sample - 3	Sample - 4	Sample - 5	Sample - 6	Sample - 7	Sample - 8
Arsenic as As (Total) (mg/Kg)	USEPA -3050 B(1996) & 7000B-2007	.- - -	< 1.0	< 2.0	< 2.0	< 1.0	< 1.0	< 0.25	< 0.15	< 1.45
Arsenic as As (WLT) (mg/L)	CPCB TSDF Protocal,(2010-11) & USEPA-7000B (2007)	< 1.0	< 0.5	< 0.1	< 0.5	< 0.5	< 0.4	< 0.5	< 0.5	< 0.5
Cadmium as Cd (Total) (mg/Kg)	USEPA -3050 B(1996) & 7000B-2007	.- - -	8.5	4.5	2.5	3.5	5.5	4.5	2.5	1.5
Cadmium as Cd (TCLP) (mg/L)	USEPA 1311(1992), (Extraction) USEPA 7000B (2007), AAS	< 1.0	< 0.1	< 0.2	< 0.1	< 0.5	< 0.1	< 0.5	< 0.8	< 0.2
Cadmium as Cd (WLT) (mg/L)	CPCB TSDF Protocal,(2010-11) & USEPA-7000B (2007)	< 0.2	< 0.05	< 0.01	< 0.04	< 0.05	< 0.02	< 0.04	< 0.01	< 0.05
Chromium as Cr (Total) (mg/L)	USEPA 1311(1992), (Extraction) USEPA 7000B (2007), AAS	.- - -	< 0.1	< 0.5	< 0.5	< 0.4	< 0.5	< 0.5	< 0.5	< 0.2
Chromium as Cr (TCPL) (mg/L)	USEPA 1311(1992), (Extraction) USEPA 7000B (2007), AAS	< 5.0	< 1.0	< 1.0	< 0.25	< 0.15	< 1.45	< 0.75	< 10.5	< 0.25
Chromium as Cr (WLT) (mg/L)	CPCB TSDF Protocal,(2010-11) & USEPA-7000B (2007)	< 5.0	< 1.8	< 3.5	< 1.5	< 3.5	< 2.5	< 1.5	< 3.5	< 2.5
Nickel as Ni (Total) (mg/Kg)	USEPA -3050 B(1996) & 7000B-2007	.- - -	< 7.0	< 3.0	< 5.0	< 3.0	< 2.0	< 5.0	< 4.0	< 3.0
Nickel as Ni (TCLP) (mg/L)	USEPA 1311(1992), (Extraction) USEPA 7000B (2007), AAS	< 20.0	< 13.0	< 6.0	< 5.0	< 6.0	< 3.0	< 4.0	< 6.0	< 7.0
Nickel as Ni (WLT) (mg/L)	CPCB TSDF Protocal,(2010-11) & USEPA-7000B (2007)	< 3.0	< 1.5	< 2.5	< 1.5	< 2.0	< 2.5	< 1.5	< 3.5	< 2.5
Hexavalent chromium as Cr6+ (Total) (mg/Kg)	USEPA1998.SW846:7196A	.- - -	< 0.1	< 0.5	< 0.5	< 0.4	< 0.5	< 0.5	< 0.5	< 0.2
Hexavalent chromium as Cr6+ (WLT) (mg/L)	CPCB TSDF Protocal,(2010-11) & USEPA-7000B (2007)	< 0.5	< 0.2	< 0.4	< 0.3	< 0.22	< 0.18	< 0.16	< 0.24	< 0.25
Lead as Pb (Total) (mg/Kg)	USEPA -3050 B(1996) & 7000B-2007	.- - -	2.1	1.8	0.9	0.5	0.4	1.5	1.8	3.5
Lead as Pb (TCLP) (mg/L)	USEPA 1311(1992), (Extraction) USEPA 7000B (2007), AAS	< 5.0	2.25	1.5	1.35	4.85	2.75	2.45	1.35	3.45
Lead as Pb (WLT) (mg/L)	CPCB TSDF Protocal,(2010-11) & USEPA-7000B (2007)	< 2.0	< 0.5	< 0.1	< 0.5	< 0.5	< 0.4	< 0.5	< 0.5	< 0.5

Parameter	Method	Std.for Secure incinarable waste	Sample - 9	Sample - 10	Sample - 11	Sample - 12	Sample - 13	Sample - 14	Sample - 15
Physical state	Visual Method	.- - -	Solid	liquid	liquid	liquid	Sami Solid	Solid	Solid
Color	Visual Method	.- - -	Mixed Color	Black	Brown	Dark Brown	Brown	White	Mixed colours
Texture	Visual Method	.- - -	Plastic Pieces	liquid	liquid	liquid	Slurry	Powder	Lumps
Is there any violent chemical change (in air) (Normally unstable) (Yes/No)	Visual Method	.- - -	No	No	No	No	No	No	No
Reacts violent with water (Yes/No)	Visual Method	.- - -	No	No	No	No	No	No	No
Generation of toxic fumes with water/acid/basic (Yes/No)	Visual Method	.- - -	No	No	No	No	No	No	No
Forms potentiall explosive mixture with water (yes/No)	Visual Method	.- - -	No	No	No	No	No	No	No
Explosion when subjected to a strong initiating force (Yes/No)	Visual Method	.- - -	No	No	No	No	No	No	No
Explosion at normal temperature & pressure (Yes/No)	Visual Method	.- - -	No	No	No	No	No	No	No
Paint Filter Liquid Test	USEPA-9095A(1996)	pass	Fail	Fail	Fail	Fail	Fail	Fail	Fail
Bulk density (g/cc)	ASTM D5057-10.(2017)	.- - -	0.4	1.03	1.03	1.03	1.18	1.01	0.68
pH @ 26.2°C	USEPA:9045C.(1995)	4 to 12	7.74	1.15	8.82	2.9	8.62	5.69	6.14
Flash point(0C)	USPA:1020A(1992)	65.5	45.9	55.8	65.7	77.1	86.5	55.2	38.5
Loss on drying at 105°C(%)	APHA23rd Edi.2540G (2017)	.- - -	26.34	79.47	32.47	16.42	30.09	10.2	2.61

Table 3. Physical and chemical analysis of different industrial waste for secure incineration.

Parameter	Method	Std.for Secure incinarable waste	Sample - 16	Sample - 17	Sample - 18	Sample - 19	Sample - 20	Sample - 21
Physical state	Visual Method	.- - -	Solid	Solid	Solid	Solid	Solid	Solid
Color	Visual Method	.- - -	Black	Black	Mixed colours	Mixed colours	Mixed corours	Brick red
Texture	Visual Method	.- - -	Hard Lumps	Wet Lumps	Powder	Granules	Cloth& Polythene	Lumps
Is there any violent chemical change (in air) (Normally unstable) (Yes/No)	Visual Method	.- - -	No	No	No	No	No	No
Reacts violent with water (Yes/No)	Visual Method	.- - -	No	No	No	No	No	No
Generation of toxic fumes with water/acid/basic (Yes/No)	Visual Method	.- - -	No	No	No	No	No	No
Forms potentiall explosive mixture with water (yes/No)	Visual Method	.- - -	No	No	No	No	No	No
Explosion when subjected to a strong initiating force (Yes/No)	Visual Method	.- - -	No	No	No	No	No	No
Explosion at normal temperature & pressure (Yes/No)	Visual Method	.- - -	No	No	No	No	No	No
Paint Filter Liquid Test	USEPA- 9095A(1996)	pass	Fail	Fail	Fail	Fail	Fail	Fail
Bulk density(g/cc)	ASTM D5057-10.(2017)	.- - -	1.16	1.14	0.95	0.93	0.23	0.95
pH @ 26.20C	USEPA:9045C.(1995)	4 to 12	7.24	7.26	7.11	7.25	7.89	8.21
Flash point(0C)	USPA:1020A(1992)	65.5	65.8	39.5	65.2	49.5	75.1	52.8
Loss on drying at 1050C(%)	APHA23rd Edi.2540G (2017)	.- - -	1	23.69	7.35	4.26	1.22	24.27
Loss on drying at 550 0C (Dry basis) (%)	APHA23rd Edi.2540G (2017)	< 20% non degradable > 5% Bio-degradable	99.67	57.96	95.47	93.27	98.67	47.04
Calorific value (Cal/gm)	IS:1350(Part-II),(Ref.2013)	< 2500	8579	5436	6139	4474	5542	3184
Extaractable Organics(%)	USEPA-3540C (1996)	> 4.0 w/W	< 1.0	< 1.2	< 1.1	< 2.1	< 2.1	< 1.3
Water soluble organics(%)	APHA23rd Edi.2540B&E (2017)	< 10%	< 1.2	< 1.4	< 1.2	< 1.2	< 1.1	< 1.1

Parameter	Method	Std.for Secure incinarable waste	Sample - 16	Sample - 17	Sample - 18	Sample - 19	Sample - 20	Sample - 21
Reactive Cyanide(mg/Kg)	USEPA9010B (1996)& APHA23rd Ed:4500CN-E	250	< 1.1	< 1.0	< 1.8	< 1.4	< 1.0	< 1.6
Reactive Sulfide(mg/Kg)	USEPA9030B (1996)& 9034 (1996)	500	< 6.9	< 12.4	< 11.4	< 13.4	< 10.4	< 10.0
Ammonical nitrogen as NH_3 (WLT) (mg/L)	APHA23rd Edition,2017:4500 NH_3 B,C	< 1000.0	< 13.0	< 5.0	< 5.0	< 5.0	< 5.0	< 15.0
Zinc as Zn (Total) (mg/Kg)	USEPA -3050 B(1996) & 7000B-2007	.- - -	14.82	6.8	6.85	1.85	16	12.6
Zinc as Zn (TCLP) (mg/L)	USEPA 1311(1992), (Extraction) USEPA 7000B (2007), AAS	< 250	4.5	4.5	4.5	5.5	4.5	1.5
Zinc as Zn (WLT)) (mg/L)	CPCB TSDF Protocal,(2010-11) & USEPA-7000B (2007)	< 10	5.3	5.1	4.5	3.5	2.5	3.5
Copper as Cu (Total) (mg/Kg)	USEPA -3050 B(1996) & 7000B-2007	.- - -	0.4	0.5	0.6	0.8	0.9	9.9
Copper as Cu (TCLP) (mg/L)	USEPA 1311(1992), (Extraction) USEPA 7000B (2007), AAS	< 25.0	1.5	2.5	1.3	0.5	1.5	2.5
Copper as Cu (WLT)) (mg/L)	CPCB TSDF Protocal,(2010-11) & USEPA-7000B (2007)	< 10	< 2.5	< 1.5	< 1.5	< 1.0	< 2.5	< 1.5
Arsenic as As (Total) (mg/Kg)	USEPA -3050 B(1996) & 7000B-2007	.- - -	< 0.25	< 0.5	< 1.5	<0.25	< 0.5	< 10.5
Cadmium as Cd (Total) (mg/Kg)	USEPA -3050 B(1996) & 7000B-2007	.- - -	3.5	2.5	3.2	6.1	8.5	2.5
Cadmium as Cd (TCLP)) (mg/L)	USEPA 1311(1992), (Extraction) USEPA 7000B (2007), AAS	< 1.0	< 0.1	< 0.4	< 0.2	< 0.6	< 0.1	< 0.2
Cadmium as Cd (WLT)) (mg/L)	CPCB TSDF Protocal,(2010-11) & USEPA-7000B (2007)	< 0.2	< 0.02	< 0.1	< 0.05	< 0.03	< 0.02	< 0.05
Chromium as Cr (Total) (mg/L)	USEPA 1311(1992), (Extraction) USEPA 7000B (2007), AAS	.- - -	< 0.2	< 0.6	< 0.1	< 0.2	< 0.2	< 0.1

Parameter	Method	Std.for Secure incinarable waste	Sample - 16	Sample - 17	Sample - 18	Sample - 19	Sample - 20	Sample - 21
Chromium as Cr (TCPL) (mg/L)	USEPA 1311(1992), (Extraction) USEPA 7000B (2007), AAS	< 5.0	<0.25	< 0.5	< 0.3	< 0.1	< 0.1	< 0.4
Chromium as Cr (WLT) (mg/L)	CPCB TSDF Protocal,(2010-11) & USEPA-7000B (2007)	< 5.0	< 3.5	< 1.5	< 3.5	< 2.5	< 1.5	< 3.5
Nickel as Ni (Total) (mg/Kg)	USEPA -3050 B(1996) & 7000B-2007	.- - -	< 5.0	< 5.0	< 3.0	< 2.0	< 5.0	< 4.0
Nickel as Ni (TCLP)) (mg/L)	USEPA 1311(1992), (Extraction) USEPA 7000B (2007), AAS	< 20.0	< 4.0	< 5.0	< 6.0	< 3.0	< 4.0	< 6.0
Nickel as Ni (WLT)) (mg/L)	CPCB TSDF Protocal,(2010-11) & USEPA-7000B (2007)	< 3.0	< 1.5	<0.25	< 0.5	< 0.3	< 0.1	< 0.1
Hexavalent chromium as Cr6+ (Total) (mg/Kg)	USEPA1998.SW846:7196A	.- - -	< 0.8	< 0.8	< 4.0	< 0.18	< 0.16	< 0.24
Hexavalent chromium as Cr6+ (WLT) (mg/L)	CPCB TSDF Protocal,(2010-11) & USEPA-7000B (2007)	< 0.5	< 0.16	< 0.24	< 0.25	< 0.29	< 0.24	< 0.2
Lead as Pb (Total) (mg/Kg)	USEPA -3050 B(1996) & 7000B-2007	.- - -	1.3	0.5	1.5	2.5	2.5	1.5
Lead as Pb (TCLP)) (mg/L)	USEPA 1311(1992), (Extraction) USEPA 7000B (2007), AAS	< 5.0	3.1	2.5	1.5	2.5	1.3	2.5
Lead as Pb (WLT)) (mg/L)	CPCB TSDF Protocal,(2010-11) & USEPA-7000B (2007)	< 2.0	< 0.5	< 0.8	< 0.8	< 0.5	< 0.5	< 0.5

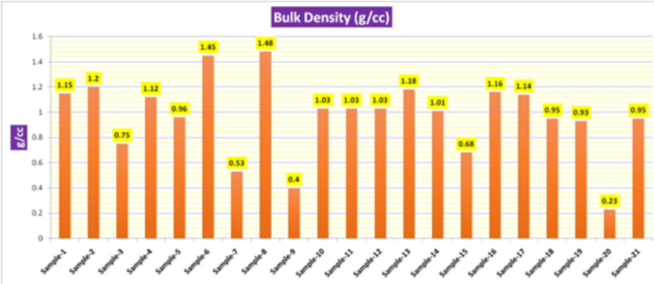

Figure 1. Bulk density of different samples collected at different locations.

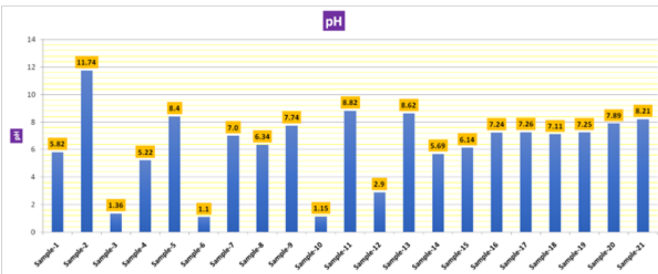

Figure 2. pH of different samples collected at different locations.

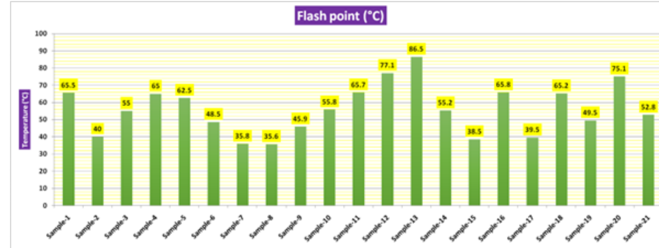

Figure 3. Flash point in °C of different samples collected at different locations.

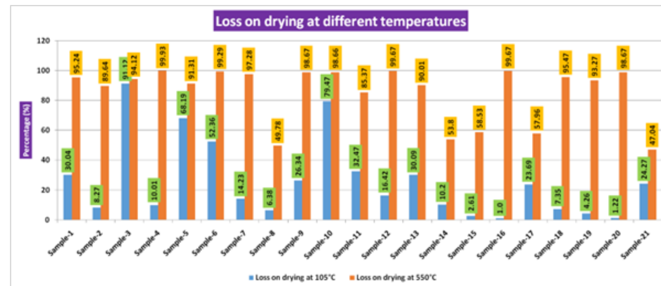

Figure 4. Loss on drying at 105°C & 550°C of different samples collected at different locations.

2.5. *Results and discussion*

This data represents the physical and chemical characteristics of 21 different samples, analyzed using various visual methods. Here's a summary of the key parameters like physical state, Color, Texture, Chemical Behavior, Paint Filter Liquid Test (USEPA-9095A, 1996), Physical State, Color, and Texture, Chemical Reactions (e.g., violent reactions, toxic fumes, explosive risks) are assessed and presented in Table 2.

2.6. *Bulk density*

Bulk density values range from 0.23 to 1.48 g/cc, which might indicate differences in the material composition or the moisture content of the samples. Generally, higher bulk density indicates a more compacted, possibly heavier material. This can impact handling and disposal (Table 2 and Figure 1).

3. pH

The pH values of analyzed samples ranged from highly acidic (1.36) to slightly alkaline (11.74), with many falling outside the acceptable range of 4–12 prescribed for secure incinerable waste. These extreme variations, particularly in the lower pH range, suggest the presence of high acid content, which can pose significant challenges for handling, treatment, and environmental safety. The significant variability in pH values across studies and regions underscores the influence of waste composition, site characteristics, and management practices. While well-managed sites exhibit pH within safe limits, leachates and effluents from industrial or poorly managed sites often show hazardous pH levels. To mitigate these risks, effective pH control through treatment methods like neutralization and the segregation of acidic or alkaline wastes is crucial. Furthermore, adopting site-specific waste management strategies can improve environmental safety and treatment efficiency, ensuring compliance with regulatory standards and reducing the hazardous implications of extreme pH levels. The values for different samples are represented in the Figure 2.

3.1. *Flash point*

Flash points are generally above the threshold of 65.5°C, with a few exceptions. Lower flash points could indicate a higher risk of combustion under certain conditions. For example, Sample 2 (40°C) is below the minimum, suggesting a need for caution in storage and disposal (Table 2 and Figure 3).

3.2. *Loss on drying*

The high values for loss on drying, especially for certain samples, indicate a significant amount of moisture or volatile matter, which may influence combustion efficiency or landfill stability. Losses higher than 30% could be due to organic content or moisture (Table 2 and Figure 4).

3.3. *Calorific value*

Calorific values range significantly, with some samples having values far exceeding the limit of 2500 Cal/gm (such as Samples 2, 10, 13). This indicates potential high energy content, which might influence how the waste is disposed of or incinerated (Table 2 and Figure 5).

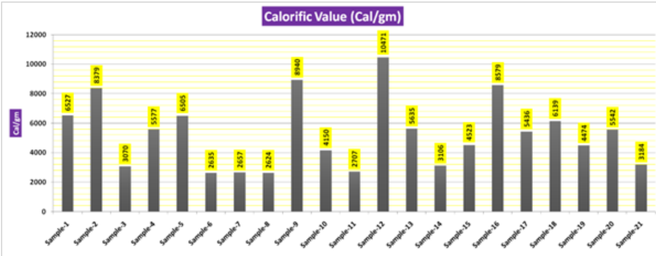

Figure 5. Calorific values (Cal/gm) of different samples collected at different locations.

3.4. Extractable organics

The organic content in the analyzed samples is notably low, falling below 1% in most cases. This observation suggests that the materials are predominantly inorganic or have undergone significant treatment to remove organic components, which is common in non-biodegradable waste. These findings underline the importance of detailed compositional analysis in determining appropriate waste management practices and minimizing environmental impact.

3.5. Water-soluble inorganics and organics:

Most samples show very low water-soluble content, indicating that they are either non-reactive or have limited interaction with water, which is favorable for disposal. However, if these exceed limits in specific cases, they may influence leachability or long term stability of the waste.

3.6. Reactive cyanide and sulfide:

All values for reactive cyanide and sulfide are below regulatory thresholds, which suggests that the samples do not pose significant risks related to toxic releases of these substances under typical disposal conditions.

3.7. Ammonical nitrogen:

The majority of the samples analyzed exhibit low ammoniacal nitrogen levels, indicating a limited potential for ammonia release, which is a significant concern in managing biological waste. Additionally, the seasonal variation observed in nitrite and nitrate concentrations, with increases noted during winter and summer, was attributed to agricultural activities surrounding the landfill. These trends emphasize the influence of external environmental factors and waste composition on nitrogen forms in landfill leachates. In comparison, the minimal ammoniacal nitrogen content in the current study's samples suggests a reduced risk of ammonia-related emissions or contamination. This suggests that the samples may be pre-treated or largely inorganic in nature. Consequently, these findings could inform waste management practices by highlighting the reduced necessity for stringent controls on ammonia emissions for the analyzed waste types.

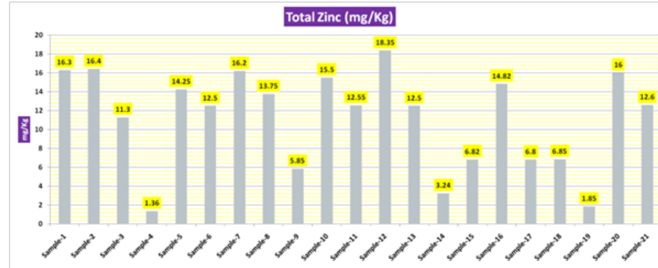

Figure 6. Total Zinc (mg/Kg) of different samples collected at different locations.

3.8. Zinc (Zn) analysis

The analysis of the dataset reveals that all samples meet the standards for secure incinerable waste for total Zinc, TCLP, and WLT values, indicating safe disposal conditions. Total Zinc concentrations in the samples range from 1.36 mg/kg (Sample-4) to 18.35 mg/kg (Sample-12), with all values significantly below the permissible limit of 250 mg/kg. This demonstrates that the overall Zinc content in the samples is well within safe levels for secure incineration (Table 2 and Figure 6). The TCLP values range from 1.35 mg/L (Sample-5) to 8.95 mg/L (Sample-14). All the TCLP values are below the permissible limit of 250 mg/L, ensuring that the Zinc in these samples has a minimal risk of leaching under standard disposal conditions. Samples with higher TCLP values, such as Sample-14, still remain well within the acceptable range, reflecting controlled leachability. Water Leaching Test (WLT) values range from 2.5 mg/L (Sample-7 and Sample-9) to 6.1 mg/L (Sample-12). All WLT values are below the permissible limit of 10 mg/L, confirming minimal water-soluble zinc content and reduced potential for environmental contamination via water leaching. In summary, the dataset shows that all samples comply with secure incinerable waste standards for total Zinc, TCLP, and WLT values. The results indicate safe disposal characteristics and low environmental risk across all samples.

In contrast, the lower zinc concentrations in the present study indicate minimal ecological risk from zinc contamination. These results, along with comparisons to other studies, underline the importance of context-specific assessments in understanding and managing zinc concentrations across different waste types and environmental settings.

3.9. Copper (Cu) analysis:

The dataset analysis for copper concentrations in the samples indicates compliance with secure incinerable waste standards, with all values well within permissible limits. Total copper concentrations in the samples range from 0.1 mg/kg (Sample-1) to 9.9 mg/kg (Sample-21), which is significantly below the allowable limit of 250 mg/kg. This highlights that the copper levels in the samples are low and pose minimal environmental risks when incinerated (Table 2 and Figure 7). The TCLP values range from 0.4 mg/L (Sample-7) to 6.5 mg/L (Sample-12). These values are substantially below the permissible threshold of 250 mg/L, ensuring that copper leachabil-

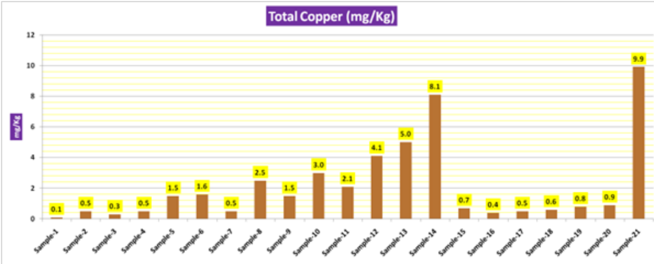

Figure 7. Total copper (mg/Kg) of different samples collected at different locations.

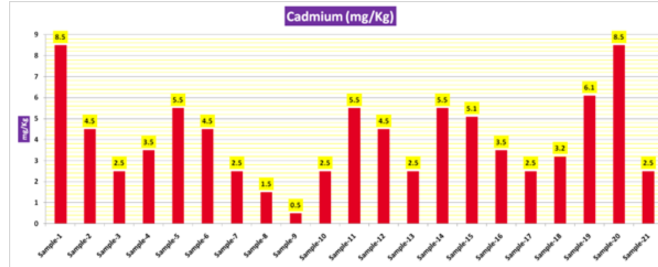

Figure 8. Total cadmium (mg/Kg) of different samples collected at different locations.

ity under toxicity characteristic leaching procedures is well-controlled. Even the highest value recorded (Sample-12) represents a minor risk of leaching. The WLT values across the samples are less than the acceptable limit of 10 mg/L. The majority of samples exhibit values below 2.5 mg/L, with several showing negligible leaching potential (<1.5 mg/L). This further confirms the low risk of water-soluble copper contamination from the samples. In conclusion, the dataset reflects that all samples adhere to the required standards for secure incinerable waste, with total copper concentrations, TCLP values, and WLT results demonstrating minimal environmental and health risks.

3.10. Arsenic (As) analysis:

The dataset analysis for arsenic concentrations in the samples demonstrates compliance with secure incinerable waste standards, with all water leaching test (WLT) values below the permissible limit of 1.0 mg/L. The total arsenic concentrations across samples are expressed as less-than values, indicating that arsenic is present at levels below the detection or quantification thresholds. The highest reported concentration is <10.5 mg/kg (Samples-10 and 21), while the lowest is <0.15 mg/kg (Sample-7). These values signify minimal arsenic content in the samples, suggesting low environmental risks. The WLT values range from <0.1 mg/L (Samples-2 and 10) to <0.8 mg/L (Samples-17 and 18), with all results falling well within the permissible standard of 1.0 mg/L. Most samples exhibit values at or below <0.5 mg/L, reflecting negligible leaching potential under water-soluble conditions. Overall, the data confirms that arsenic concentrations and leachability in these samples are significantly below hazardous thresholds, ensuring their safe disposal in compliance with regulatory standards. The minimal leaching potential underscores the environmental safety of these samples when managed as secure incinerable waste.

3.11. Cadmium (Cd) analysis:

The analysis of cadmium concentrations and leaching tests reveals that the total cadmium content across the 21 samples ranges from 0.5 mg/kg to 8.5 mg/kg, with the highest levels observed in Sample-1 and Sample-20. Despite the variation in total cadmium content, all samples demonstrate compliance with regulatory standards for secure incinerable waste disposal. The results of the Toxicity Characteristic Leaching Procedure (TCLP) indicate that cadmium leaching potential under acidic conditions is minimal, with values consistently below the permissible limit of 1.0 mg/L. The highest TCLP value recorded is <0.8 mg/L in Sample-7, while most samples show even lower values (Table 2 and Figure 8). Similarly, the Water Leaching Test (WLT) results confirm that cadmium mobility in water is negligible, with all values falling well below the standard of 0.2 mg/L. The highest WLT value observed is <0.1 mg/L in Samples-13 and 17, with the majority of the samples showing values below 0.05 mg/L. Even samples with relatively higher total cadmium concentrations, such as Sample-1 and Sample-20, exhibit low leachability in both tests, ensuring their suitability for safe disposal. Overall, the findings indicate that the cadmium content in all samples poses no significant environmental risk during disposal. The findings emphasize that the current waste samples are comparatively safer in terms of cadmium contamination, though consistent monitoring and appropriate management practices remain essential to ensure continued compliance and minimal environmental impact.

3.12. Chromium (Cr)

The analysis of chromium concentrations and leaching behavior in 21 samples demonstrates compliance with secure incinerable waste disposal standards. The total chromium content across all samples is below detection limits, indicating minimal presence in the waste. The Toxicity Characteristic Leaching Procedure (TCLP) results reveal chromium leachability under acidic conditions to be consistently within the permissible limit of 5.0 mg/L. The highest TCLP value recorded is <10.5 mg/L in Sample-7, while most samples exhibit significantly lower leachability. The Water Leaching Test (WLT) results indicate chromium mobility in water is also within acceptable limits, with all samples reporting values below the regulatory threshold of 5.0 mg/L. The highest WLT value observed is <4.5 mg/L in Samples-9 and 11, while other samples display lower concentrations. In conclusion, the negligible total chromium content, coupled with low leachability in both TCLP and WLT results, confirms that all samples meet the safety standards for secure disposal through incineration. These findings highlight the minimal environmental risk associated with chromium in the tested waste samples.

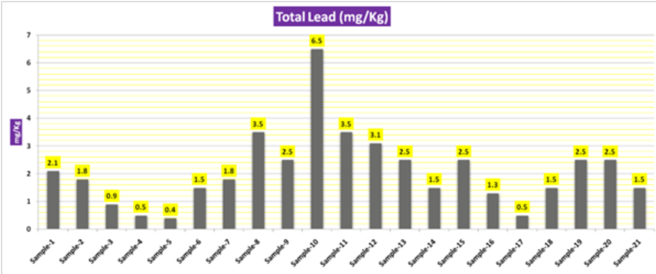

Figure 9. Total lead (mg/Kg) of different samples collected at different locations.

3.13. *Nickel (Ni)*

The data provided presents an analysis of Total Nickel concentrations along with the results of two leaching tests—Toxicity Characteristic Leaching Procedure (TCLP) and Water Leaching Test (WLT)—for a total of 21 samples. The results of the TCLP tests for all samples are also below 13.0 mg/L, with no sample exceeding the regulatory limit of 20.0 mg/L for secure incinerable waste. This indicates that the potential leachability of nickel from the samples into the environment, under conditions mimicking waste disposal or incineration, is within safe limits as per the standard. Similarly, the results from the Water Leaching Test (WLT) also show that the leachable nickel concentrations are well below the 3.0 mg/L threshold for secure disposal. The values for WLT range from less than 0.1 mg/L to a maximum of 3.5 mg/L, all of which are within the acceptable range for safe disposal and do not pose any significant risk to water quality.

In summary, the data demonstrates that all 21 samples conform to the environmental standards for secure incineration and disposal, as specified by the regulatory limits for Total Nickel content, TCLP, and WLT. The low concentrations observed for both Total Nickel and its leachability suggest that these samples are safe for disposal, posing minimal risk to the environment.

3.14. *Lead (Pb)*

The analysis of lead concentrations across the samples reveals compliance with secure disposal standards for most parameters. Total lead concentrations range from 0.4 mg/kg (Sample-5) to 6.5 mg/kg (Sample-10), with a mean value of 2.2 mg/kg, which is well below the permissible limit of 5.0 mg/kg for secure incinerable waste. This indicates that the overall lead content in the samples is within acceptable levels for disposal (Table 2 and Figure 9).

The results of the Toxicity Characteristic Leaching Procedure (TCLP) test show values ranging from 1.3 mg/L (Sample-20) to 5.5 mg/L (Samples-11 and 13). While the majority of the samples are within the permissible limit of 5.0 mg/L, Samples-11 and 13 exceed this threshold, suggesting potential leaching risks for these specific samples. These cases warrant additional attention or pre-treatment to mitigate the potential environmental impact.

Water Leaching Test (WLT) values for all samples are consistently low, ranging from <0.1 mg/L to <0.8 mg/L. These results are significantly below the permissible limit of 2.0 mg/L, indicating minimal water-soluble lead content and a low risk of contamination through water leaching.

In summary, while the total lead and WLT results demonstrate compliance with regulatory standards, the elevated TCLP values in two samples highlight the need for focused management strategies to address potential leaching concerns.

4. Summary

The analysis indicates that most samples tested for heavy metals are within regulatory disposal limits, posing no immediate risks of leaching harmful levels of zinc, copper, arsenic, or cadmium. However, a few samples with higher cadmium concentrations (e.g., 8.5 mg/kg) warrant closer monitoring during disposal processes to mitigate potential environmental impacts. While most tested samples exhibit safe heavy metal concentrations for disposal, insights from comparative studies emphasize the variability in contamination across industrial and municipal waste sources. Continual monitoring and adherence to regulatory limits are critical, particularly for elements like cadmium, arsenic, and zinc, which pose heightened environmental risks if concentrations exceed safe thresholds.

5. Conclusion

The overall quality of waste in terms of heavy metal contamination is compliant with most regulatory standards. Regular monitoring of nickel and lead levels (especially in the TCLP form) should be maintained, as some occasional spikes could cause issues. Cadmium, chromium, and nickel are consistently below the set thresholds, showing no significant environmental risks. The presence of lead near the upper limits for TCLP suggests that future disposal practices might need to ensure more stringent treatment or disposal methods if these levels increase further.

Data availability

The data used for this study is available on request from the corresponding author.

References

[1] A. H. Kanhar, S. Chen & F. Wang, "Incineration fly ash and its treatment to possible utilization: A review", Energies **13** (2020) 6681. https://doi.org/10.3390/en13246681.

[2] Y. Seo, "Current MSW management and waste-to-energy status in the Republic of Korea", Columbia University, New York, USA, 2013, pp. 49–58. https://wtert.org/wp-content/uploads/2020/10/YS-Thesis_final_Nov3.pdf.

[3] A. L. Fabricius, M. Renner, M. Voss, M. Funk, A. Perfoll, F. Gehring & L. Duester, "Municipal waste incineration fly ashes: from a multi-element approach to market potential evaluation", Environmental Sciences Europe **32** (2020) 88. https://doi.org/10.1186/s12302-020-00365-y.

[4] J. Hirvonen & R. Kosonen, "Waste incineration heat and seasonal thermal energy storage for promoting economically optimal net-zero energy districts in Finland", Buildings **10** (2020) 205. https://doi.org/10.3390/buildings10110205.

[5] S. Kaza, L. Yao, P. Bhada-Tata & F. Van Woerden, "What a waste 2.0: a global snapshot of solid waste management to 2050, Urban Development", World Bank Publications, 2018. [Online]. http://hdl.handle.net/10986/30317.

[6] T. Solheimslid, H. K. Harneshaug, N. Lümmen, "Calculation of first-law and second-law-efficiency of a Norwegian combined heat and power facility driven by municipal waste incineration–A case study", Energy Conversion and Management **95** (2015) 149. https://doi.org/10.1016/j.enconman.2015.02.026.

[7] M. Ni, D. Y. Leung, M. K. Leung & K. Sumathy, "An overview of hydrogen production from biomass", Fuel processing technology **87** (2006) 461. https://doi.org/10.1016/j.fuproc.2005.11.003.

[8] A. Patwa, D. Parde, D. Dohare, R. Vijay & R. Kumar, "Solid waste characterization and treatment technologies in rural areas: An Indian and international review", Environmental Technology & Innovation **20** (2020) 101066. https://doi.org/10.1016/j.eti.2020.101066.

[9] Z. Han, Y. Liu, M. Zhong, G. Shi, Q. Li, D. Zeng & Y. Xie, "Influencing factors of domestic waste characteristics in rural areas of developing countries", Waste management **72** (2018) 45. https://doi.org/10.1016/j.wasman.2017.11.039.

[10] S. T. Tan, H. Hashim, J. S. Lim, W. S. Ho, C. T. Lee & J. Yan, "Energy and emissions benefits of renewable energy derived from municipal solid waste: Analysis of a low carbon scenario in Malaysia", Applied Energy **136** (2014) 797. https://doi.org/10.1016/j.apenergy.2014.06.003

[11] F. S. Zhang, S. I. Yamasaki & M. Nanzyo, "Application of waste ashes to agricultural land—effect of incineration temperature on chemical characteristics", Science of the total environment **264** (2001) 205. https://doi.org/10.1016/S0048-9697(00)00715-4.

[12] V. K. Petropavlovskaya, A. N. Shishkov, S. A. Zamaraev, A. V. Goncharova & D. A. Zolnikov, "Considering different methods of thermal utilization of municipal solid waste", Earth and Environmental Science **990** (2022) 012067. https://doi.org/10.1088/1755-1315/990/1/012067.

[13] Z. Jing, X. Fan, L. Zhou, J. Fan, Y. Zhang, X. Pan & E. H. Ishida, "Hydrothermal solidification behavior of municipal solid waste incineration bottom ash without any additives", Waste management **33** (2013) 1182. https://doi.org/10.1016/j.wasman.2013.01.038.

[14] Z. Shareefdeen, A. Elkamel & S. Tse, "Review of current technologies used in municipal solid waste-to-energy facilities in Canada", Clean Technologies and Environmental Policy", **17** (2015) 1837. https://doi.org/10.1007/s10098-015-0904-2.

[15] E. I. Bureau, "Reference document on the best available techniques for waste incineration", European Union, Brussels, (2005). [Online]. https://op.europa.eu/en/publication-detail/-/publication/075477b7-329a-11ea-ba6e-01aa75ed71a1/language-en.

[16] S. D. Aurpa, S. Hossain & M. A. Islam, "Effect of plastic waste on volume consumption of landfill during the COVID-19 pandemic", Sustainability **14** (2022) 15974. https://doi.org/10.3390/su142315974.

[17] G. Mao, Y. Zhang, W. Wen & D. He, "Analysis of municipal solid waste treatment status and the feasibility of incineration in China", Sustainability **11** (2019) 1433. https://doi.org/10.3390/su11051433.

[18] E. Allegrini, C. Vadenbo, A. Boldrin & T. F. Astrup, "Life cycle assessment of resource recovery from municipal solid waste incineration bottom ash", Journal of Environmental management **151** (2015) 132. https://doi.org/10.1016/j.jenvman.2014.11.032.

[19] C. C. Wiles, "Municipal solid waste combustion ash: State-of-the-knowledge", Journal of hazardous materials **47** (1996) 325. https://doi.org/10.1016/0304-3894(95)00120-4.

[20] M. D. Meena, M. L. Dotaniya, B. L. Meena, P. K. Rai, R. S. Antil, H. S. Meena & R. B. Meena, "Municipal solid waste: Opportunities, challenges and management policies in India: A review", Waste Management Bulletin **1** (2023) 4. https://doi.org/10.1016/j.wmb.2023.04.001.

[21] H. Durak, "Comprehensive assessment of thermochemical processes for sustainable waste management and resource recovery", Processes **11** (2023) 2092. https://doi.org/10.3390/pr11072092.

[22] A. M. M. Hassan, M. Asif, M. A. Al-Mansur, M. R. Uddin, S. J. Alsufyani, F. Yasmin & M. U. Khandaker, "Characterization of municipal solid waste for effective utilization as an alternative source for clean energy production", Journal of Radiation Research and Applied Sciences **16** (2023) 100683. https://doi.org/10.1016/j.jrras.2023.100683.

[23] A. Karmakar, T. Daftari, K. Sivagami, M. R. Chandan, A. H. Shaik, B. Kiran, S. Chakraborty, "A comprehensive insight into Waste to Energy conversion strategies in India and its associated air pollution hazard", Environmental Technology & Innovation **29** (2023) 103017. https://doi.org/10.1016/j.eti.2023.103017.

[24] G.L Tihin, K.H. Mo, C.C. Onn, H.C. Ong, Y.H. Taufiq-Yap, H.V. Lee, "Overview of municipal solid wastes-derived refuse-derived fuels for cement co-processing", Alexandria Engineering Journal **84** (2023) 153. https://doi.org/10.1016/j.aej.2023.10.043.

[25] B. Karpan, A. A. A. Raman & M. K. T Aroua, "Waste-to-energy: Coal-like refuse derived fuel from hazardous waste and biomass mixture", Process Safety and Environmental Protection **149** (2021) 655. https://doi.org/10.1016/j.psep.2021.03.009.

[26] M. D. Meena, M. L. Dotaniya, B. L. Meena, P. K. Rai, R. S. Antil, H. S. Meena, L. K. Meena, C. K. Dotaniya, V. S. Meena, A. Ghosh, K. N. Meena, A. K. Singh, V. D. Meena, P. C. Moharana, S. K. Meena, Ch. Srinivasarao, A. L. Meena, S. Chatterjee, D. K. Meena, M. Prajapat & R. B. Meena, "Municipal solid waste: Opportunities, challenges and management policies in India: A review", Waste Management Bulletin **1** (2023) 4. https://doi.org/10.1016/j.wmb.2023.04.001.

[27] Environmental Protection Agency, "EPA 2021 in Review", 2021. [Online], https://www.epa.ie/publications/corporate/governance/epa-2021-in-review.php.