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REVIEW

# Municipal solid waste incineration bottom ash: a competent raw material with new possibilities

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## Abstract

According to the economic feasibilities, municipal solid wastes (MSW) are being dumped or treated in different possible manners. Municipal solid waste incinerated ash (MSWIA) is one of the final products of MSW treatment plants after incineration. Due to less sustainable waste management options, MSWIA is produced in tons and dumped into landfills. Researchers in various developmental project suggest using MSWIA as an economical and eco-friendly mode of final disposal. The use of MSW incinerated bottom ash (MIBA) has an exceptional potential of supporting sustainability by conserving natural resources. The paper targets the possible benefits of MIBA in various construction and soil improvement projects by compensating the primary aggregates. The partial replacement of primary aggregates is a durable and cost-effective option for equal or improved strength. The addition of MSWIA is not new, but the studies available are limited in number. The presence of certain chemical compounds in MIBA is leading to advanced industrial-based applications. The residue can be a primary raw material for synthesizing new compounds, in land recovery and Hydrogen gas production. Some studies have favored its utilization in the most natural form, whereas some suggest avoiding the usage due to its various environmental and strength-based limitations. The article investigates significant studies and confirms the possible opportunities from waste residues for more competent raw material.

**Keywords** Sustainability · MSWIA · Waste management · Landfills · MIBA · Waste residue

## Abbreviations

| | |
|---|---|
| MSW | Municipal Solid Waste |
| MSWIA | Municipal solid waste incinerated ashes |
| MIBA | MSW incinerated bottom ash |
| MIFA | MSW incinerated fly ash |
| LCA | Life cycle analysis |
| WTE | Waste to energy |
| SEM | Scanning Electroscope Microscopy |
| LOI | Loss on ignition |
| TOC | Total organic carbon |
| PC | Portland cement |
| CFA | Coal fly ash |
| GGBS | Ground granulated blast furnace slag |
| LS | Limestone |
| Cd | Cadmium |
| Cu | Copper |
| Pb | Lead |
| Zn | Zinc |
| HCl | Hydrogen chloride |
| NaCl | Sodium chloride |
| PCDD | Polychlorinated dibenzo-p-dioxins |
| Ca | Calcium |
| Si | Silicon |
| Al | Aluminum |
| Ba | Barium |
| Cr | Chromium |
| Ni | Nickel |
| OPC | Ordinary Portland cement |
| C3S | Tricalcium silicate |
| VBA | Vitrified bottom ashes |
| PAH | Polycyclic aromatic hydrocarbon |
| PCDF | Polychlorinated dibenzodioxins |
| EOX | Extractable halogens inorganic bonding |
| BTX | Benzene–toluene–xylene |
| BTEX | Benzene-toluene-ethylbenzene-xylene |

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## Introduction

It is undeniable fact that human activities are the biggest generators of MSW, and studies have predicted an average production of 2.2 billion tons by the year 2025 [1]. Depending on different cultures, legislation, and various uses, the MSW sums up other constituents of which food, paper, plastics, metals, and glass are relatively common [2–4]. The reason behind the wide use of incineration practices for MSW is well known in the solid waste management sector. The reduction in volume by 90% and mass by at least 70% of initial values cannot be denied [5–7]. This fact favors it to be widely used in different countries as every country looks for more sound and cost-effective techniques to prevent the present overloading of landfill space.

It is also proved that incinerator plants contribute to greenhouse gases, but it can be controlled by changing the design and operation process. MIBA consists of 25% of the total initial waste fed to these incinerators in the form of raw MSW [8]. The latest innovations are now helping in contributing to the proper burning of MSW, and the heat produced is now a significant Waste to Energy (WTE) source for developing and developed economies [9–13]. The MIBA and the MSW incinerated fly ash (MIFA), which can be used for engineering projects, but both come with certain limitations [14–16].

The hazardous constituents of both MIFA and MIBA are a significant cause of concern for its environmental impacts. The leaching of these constituents due to rainwater exposure or direct contact to groundwater due to infiltration can adversely affect the water bodies and the exposed site's ecology [17–19]. Mass production of MIBA and MIFA demands safe treatment and scientific disposal for a sustainable future. Nowadays, many researchers and their research contributions have resolved this issue. The focus is on the treatment and disposal of these residues and utilizing these ashes as a major or minor component in various development projects [20] (Fig. 1).

Fly ash has smaller and smoother particles with a higher content of chlorides and hazardous compounds than MIBA, known for larger and coarser particles. Therefore, MIBA is a vital research interest for people looking for sustainable building solutions. The innovation requires public acceptance, for which it is necessary to evaluate the technical feasibility of MIBA infused materials considering ecotoxicity, LCA's, and leachability testing [21].

Certain European nations have laid their standards regarding recycling and reusing MIBA, keeping human and environmental safety in mind. Researchers are continuously searching for and developing eco-friendly and sustainable solutions to work with incinerated ashes [22–24]. The effective use of MIBA as an aggregate substitute in cement industry and also as a subgrade material in pavements has been studied by various researchers. Recent developments have shown the applicability of MIBA in other aspects as well. MIBA finds its applications commonly limited to an aggregate substitute in concrete, in cement production and also as subgrade material in pavements.

Typical applications of MIBA as a raw material in, and as a road construction material are well known, but there are specific innovative applications which needs to be addressed. This review paper is focused on the past and present works,

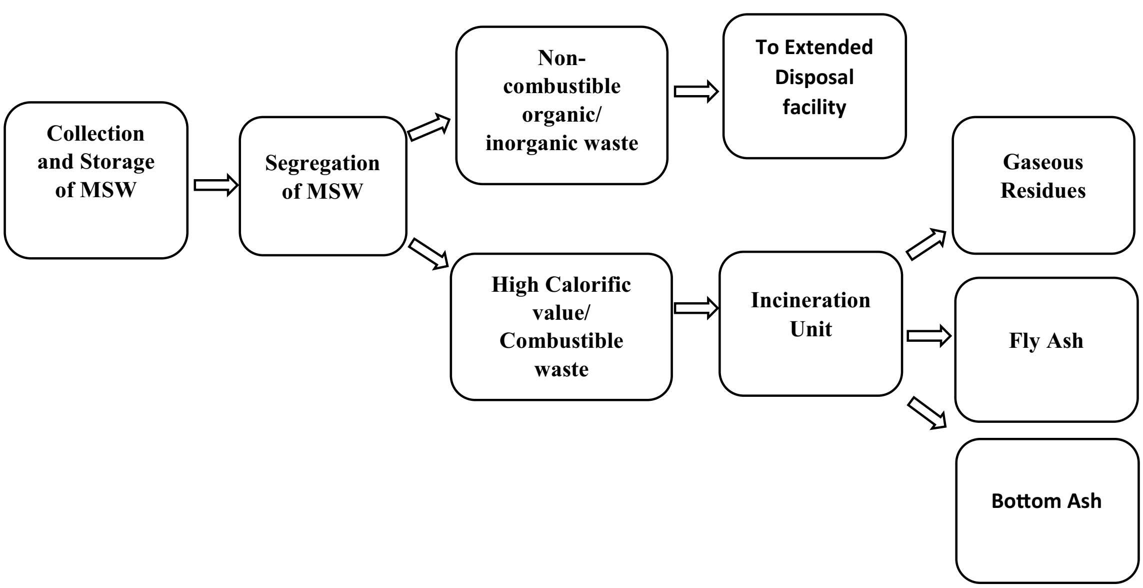



**Fig. 1** Basic Process of MSW incineration plant

which are milestone studies in MIBA recycling and reuse. It also discusses the various types of contaminants present in MIBA and multiple strategies to remove these hazardous components for safer and economically viable usage.

## Methodology

For this review, literature explicitly concerned to incinerated bottom ash applications was targeted. Hence a limited number of papers were included for a better understanding. Papers were selected based on the recent advances, better environmental and economic results, and future scope. As a significant number of publications were available, they were further narrowed down based on their relevance to the topic and the quality of results based on their recent cite scores. All these selected works were further bifurcated to respective applications and research areas related to MIBA as a raw material. It helped in a detailed examination of the works, including environmental impacts and the overview of cost comparisons and further recommendations regarding the MIBA usage (Fig. 2).

The presence of limited literature related to MSWI ashes for various applications allows more opportunities to study these residuals for a sustainable world. Certain chemical compounds in MIBA promise new industrial-based applications and a cheaper yet equally effective aggregate for specific geotechnical applications. The paper is divided into sections where the composition and properties of MIBA are described briefly, citing the available literature, and later the applications of MIBA are discussed. The review focuses explicitly on the recent works published in the last decade (Fig. 3).

In "Composition and Properties of MIBA" section, the basic properties and composition from various literature have been cited which the essential compounds present in MIBA. The section also discusses the physical and chemical nature and the average content present in weight percentage of these compounds. Further in "Standard incineration ash treatment techniques" section, the variety of techniques commonly used at waste incineration facilities are discussed briefly. The sections of "Common applications of MIBA" and "Advanced applications of MIBA" look into the standard and advanced possible uses of bottom ash from waste incineration facilities. The sections are further divided into

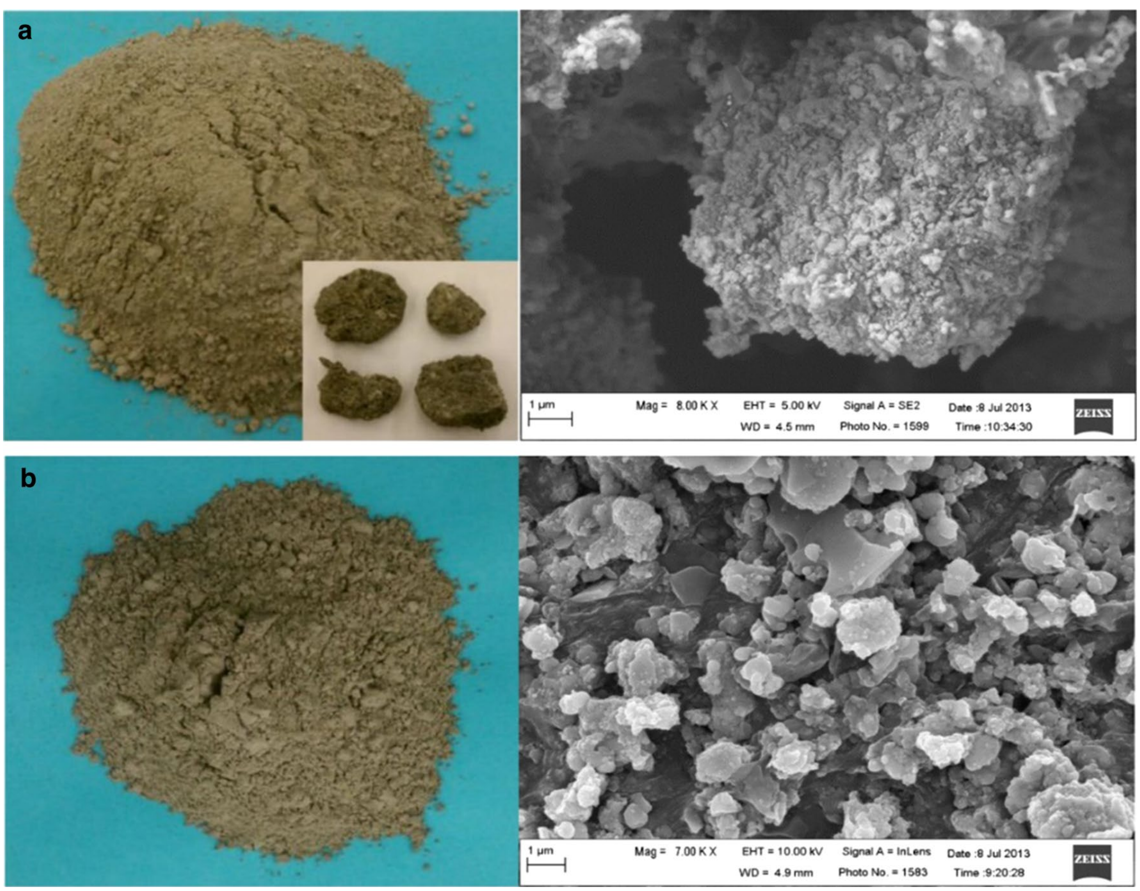



**Fig. 2** Types of MSWI ashes from WTE plant **a** bottom ash and **b** fly ash [25]

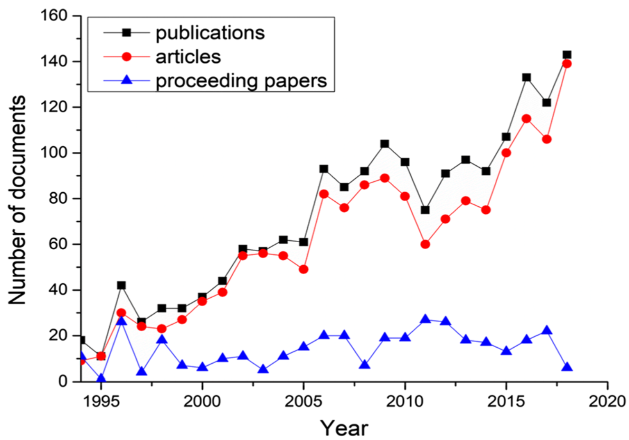



**Fig. 3** Trend of MSWIA related publications in 1994–2018 [26]

types of applications where MIBA can be absorbed significantly. These applications help in load minimization on landfills and reaping economic benefits. A short note on the economic viability of MIBA usage is also mentioned before making conclusions and recommendations at the end of this review.

This review confirms the considerable potential of incinerated bottom ash residues from WTE facilities. It is evident that the addition of MIBA as a soil stabilizer improves the geotechnical properties of soil. MIBA is a cost-effective and eco-friendly product that can be widely used in transportation engineering, structural engineering, and geoenvironmental engineering-based applications. It can be used as traditional fine aggregate material, but it also finds application in hydrogen gas production, landfill cover, land reclamation, and the synthesis of adsorbents. The concerns to leachability and groundwater contaminations are real, but with proper pre and post-treatment, these concerns can be minimized according to the required standards.

## Composition and properties of MIBA

Various factors like the composition of raw MSW, type of furnace in use, temperature, time of retention, and type of quenching process implemented, can be a reason to differ the type of MIBA generated, but the overall elemental composition remains the same [27]. Studies confirm coarse and porous nature of MIBA with a grayish appearance, primarily having components like minerals, ceramics, glass, and various non-ferrous materials in the unburnt form [27, 28]. Figure 4 depicts the precise SEM images of bottom incinerated ash which confirms the irregular structure of ash particles and presence of gypsum and calcite particles.

Carbonates, oxides, and hydroxides can easily be traced as these compounds are present in a considerable amount. $SiO_2$, CaO, $Fe_2O_3$, and $Al_2O_3$ are present in MIBA in higher concentrations (> 10 wt%), whereas $Na_2O$, $K_2O$, MgO, and $TiO_2$ are present in a very minimal concentration [30, 31]. The presence of such minerals is depicted using a ternary plot in Fig. 5. Studies confirm that $SiO_2$ accounts for almost 49% share in MIBA. Ranging between 2.4 and 15.0%, MIBA is considered a lightweight material with high water absorption capacity [22, 32]. LOI or loss on ignition of 5.8%, and the specific gravity was found in the range of 1.8 to 2.8, different study marks mean LOI in a diverse range of 1.9–6.3%, confirming the effectiveness of incineration.

MIBA has a pH in the range of 10.5 to 12.2, making it an essential chemical compound. This pH is the result of hydroxide presence. Aluminum is one of the concerned elements present in abundance, which causes the release of $H_2$ gas. This limitation can be overcome to a greater extent by implementing a grate shifting process [27, 34–36]. The leaching potential of MIBA is lower than fly ash, and hence it is considered a better material for constructional use. The formation of stable complex compounds after chemical reactions with water and carbon dioxide also reduces Hydrogen gas (Table 1).

## Standard incineration ash treatment techniques

The direct use of ash is always a concern for environmental degradation, and hence techniques are being used to control the contamination and to avoid environmental hazards. This can be achieved by either removing the hazardous compounds or stabilizing these compounds using various methods. The washing of ashes is a common treatment technique but the stabilization of MIBA is now an advanced trend for treatment [50, 51].

The effectiveness of washing techniques is considered highly effective in chloride and heavy metal removal [52, 53]. Chemical leaching involves using certain chemical compounds for the removal of heavy metals from the incinerated ash. The use of HCl and NaCl in a specific concentration gives excellent results for Zn, Cd, Cu, and Pb removal [54]. The concept of Bioleaching is very much related to chemical leaching in which microorganisms are used for the production of specific organic and inorganic acid, which serves the same purpose as chemical leaching. Bioleaching is considered a better and eco-friendly method of metal removal from incinerated ash [55–57]. Another popular and instant technique of heavy metal removal is Electrochemical treatment. Although the process is fast and reliable, high costs and low results make it the least popular [52, 58].

Stabilization of MIBA and MIFA can be done by adding cement-based materials in a definite ratio. It is considered an adequate measure of immobilization of heavy

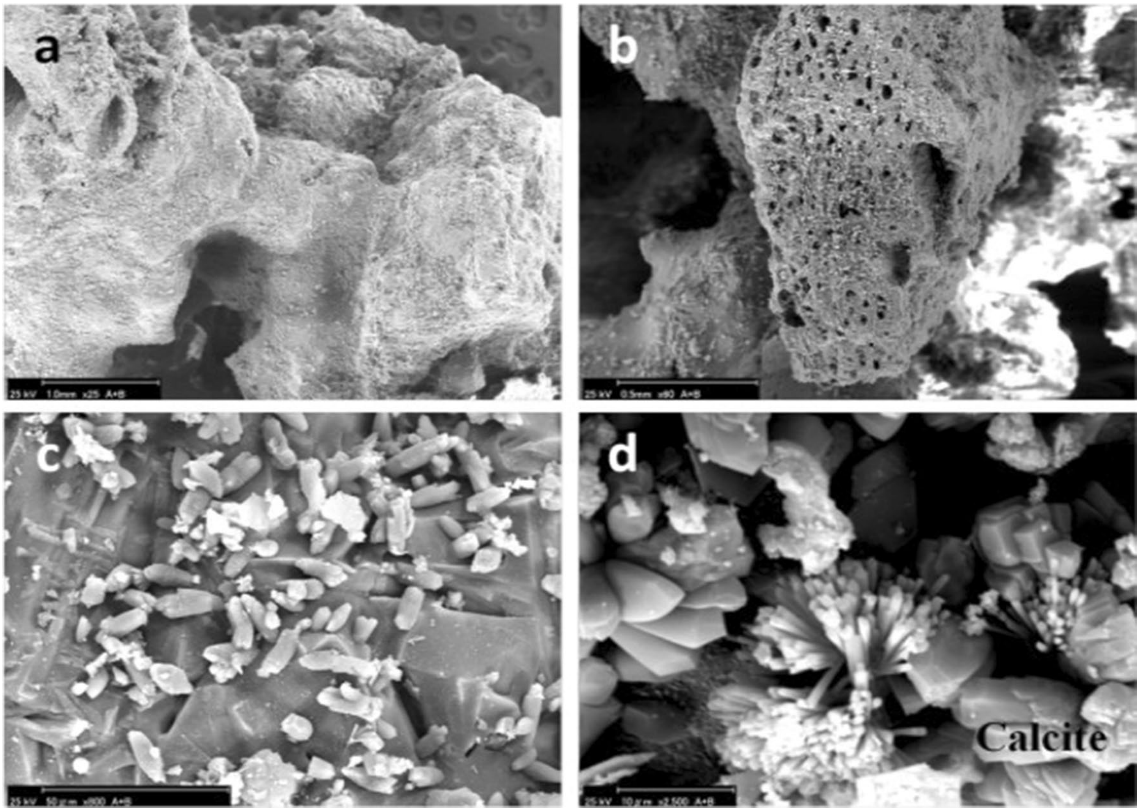
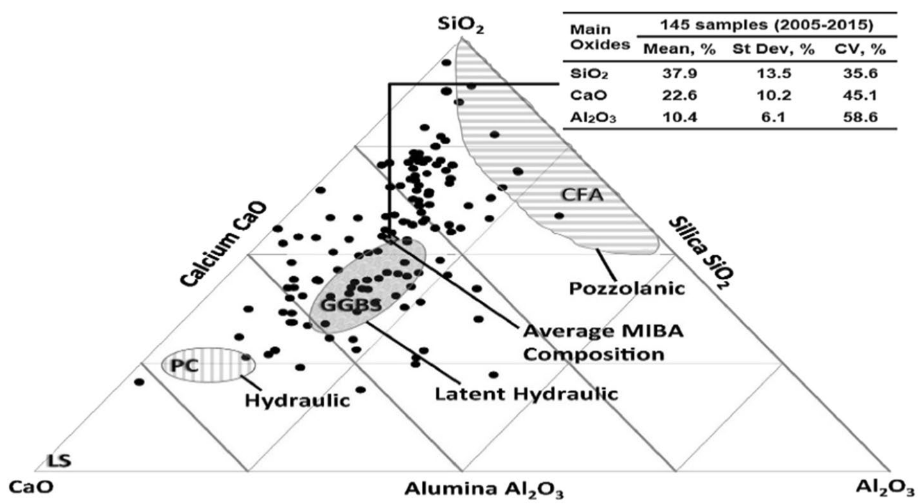



**Fig. 4** SEM images of MIBA: **a**, **b** shows irregular MIBA particles; **c** shows the presence of gypsum MIBA surface; **d** shows calcite crystals present in MIBA [29]

**Fig. 5** Ternary plot of three primary contents of MIBA [33]




PC = Portland cement, GGBS = ground granulated blastfurnace slag, CFA = coal fly ash, LS = limestone.

metals in cement matrices by using binding materials. The stabilization of MIBA depends on certain environmental factors as varying the pH, temperature, and humidity give different results [59, 60]. Fish bones in powdered form and specific other chemical stabilizers enhance the process of stabilization and yield better outcomes [61, 62]. Specific techniques like thermal and hydrothermal treatments of incineration ash treatments are also under consideration for metal removal. The latest studies have shown that effective microwave heating, when combined with hydrothermal

**Table 1** Composition of MIBA from different research studies

| Components (wt%) | Gao et al. [37] | Casanova et al. [38] | Flesoura et al. [39] | Singh and Kumar [40] | Zhang et al. [41] | Ashraf et al. [42] | Caprai et al. [43] | Yan et al. [44] | Saikia et al. [45] | Alam et al. [46] | Song et al. [47] | Nikravan et al. [48] | Biswal et al. [49] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $Al_2O_3$ | 12.037 | 5 | 10.8 | 9.20 | 14.18 | 10.57 | 7.09 | 7.28 | 9.09 | 11.7 | 8.57 | 4.26 | 4.38 |
| $SiO_2$ | 19.122 | 51.84 | 50.4 | 55.37 | 28.64 | 25.91 | 32.85 | 11.83 | 39.73 | 37.2 | 32.75 | 12.2 | 34.5 |
| $Fe_2O_3$ | 9.313 | 9.29 | 10.2 | 4.93 | 6.49 | 4.81 | 9.27 | 1.25 | 12.13 | 14.4 | 10.02 | 12 | 2.93 |
| CaO | 43.115 | 23.00 | 19.9 | 19.39 | 22.91 | 12.71 | 17.98 | 48.1 | 14.69 | 18.7 | 29.06 | 32.4 | 5.26 |
| MgO | 2.116 | 2.36 | 2.4 | 0.41 | 2.62 | 1.81 | 1.71 | 2.07 | 2.10 | 2.6 | 1.75 | 2.28 | 1.52 |
| $SO_3$ | 2.393 | 2.42 | 11.2 | 1.53 | – | – | 2.77 | 6.76 | – | 0.9 | 3.01 | 6.1 | 5.04 |
| $K_2O$ | 0.848 | 1.57 | – | 0.43 | 1.12 | 1.16 | 1.13 | 3.65 | 0.91 | 1.2 | 1.24 | 0.88 | 0.88 |
| $TiO_2$ | 2.48 | 0.34 | 1.3 | – | 2.88 | 2.17 | 1.17 | 0.34 | – | 1.3 | 1.57 | 1.17 | 1.12 |
| $Na_2O$ | 2.359 | – | 0.7 | 0.24 | 2.63 | 2.09 | – | 4.05 | 1.77 | – | – | 0.47 | 1.63 |
| $P_2O_5$ | 2.625 | 2.29 | – | 0.07 | 2.34 | 1.44 | 1.28 | 0.34 | – | 1.6 | 4.77 | 2.62 | 3.09 |

treatment, gives the best results for polychlorinated dibenzo-p-dioxins (PCDD) removal [63, 64].

## Common applications of MIBA

### Road construction

Countries like Belgium, Denmark, and the Netherlands allow the addition of MIBA for road construction as the implementation supports circular economy. If heavy metal leaching is controlled scientifically, MIBA can be used as well-graded sand or gravel for road construction [65]. A study by Lynn et al. suggests the use of MIBA can be considered for road construction. According to the study, the addition of MIBA can be done as bitumen-bound materials and unbound materials in pavement construction [22]. In colder regions, the concept of freezing and thawing of the final material should be considered before implementation at a mass level. Chelating agents for better solidification are considered more eco-friendly, but it permits lower resistance toward freezing and thawing [66, 67].

### Cement additive

Ca, Si, and Al's high content allows MIBA to act as good pozzolanic material [68]. To reduce OPC, MIBA can be used as the solid cementitious material in the cement blend [69, 70]. Several studies on partial cement replacement were considered to determine the leaching behavior of MIBA-based specimens. The concentrations of leached elements like Cd, Cu, Ba, Cr, Pb, Zn, and Ni were checked and compared between U.S limits and Chinese National standards. The results were within acceptable limits [3]. Thermal treatment of MIBA under the temperature of 800 °C or more causes dehydroxylation of $Ca(OH)_2$ [71]. Higher temperatures are responsible for converting $CaCO_3$ to CaO; hence the reactivity with cement increases [72]. It is noticed that due to specific alkali-aggregate reactions, both the flexural and compressive strengths of cement composites were reduced noticeably when incinerated ashes were used [73]. This issue can be solved either by decreasing the amount of alkali from the cement or using fibers or air-entraining admixtures [74]. Alkaline-treated MIBA, when used in concrete, gives higher 28 days compressive strength of 34.7 MPa and whereas the untreated MIBA gives 17.9 MPa [75].

### Lightweight aggregate

Fly ash and Bottom ashes are already being used as a lightweight aggregate in the construction industry. These materials are known for extraordinary properties such as high durability, lightweight, low water absorption, and adjustable thermal conductivity [76]. Higher content of CaO allows good water absorption, whereas the presence of $SiO_2$ allows vitrification at higher temperatures. The study compared the fly ash and MIBA derived from the fixed bed and mechanical bed incinerators to use lightweight aggregates [77]. The results confirm that lower calcium oxide content and higher contents of both ferric oxide and silica dioxide are necessary for better quality lightweight aggregates production. Another critical study suggests using recycled concrete slurry waste and finer quality MIBA to produce a new variety of cold bonded lightweight aggregates [78]. The results of the study confirm MIBA as a better version of lightweight aggregate when used with OPC [79, 80].

### Cement clinker production

Studies have estimated that the European Union annually generates 16–18 million metric tonnes of MIBA. This much-incinerated ash can fulfill the raw material requirement in cement production [33, 81]. The use of MIBA as a raw material can save natural resources and contribute to protecting the planet from environmental issues [82]. The amount of limestone in Portland cement production can be reduced using incinerated ashes as they have a high percentage of $SiO_2$, $Al_2O_3$, and CaO present in them. It also prevents $CO_2$ emissions from manufacturing units, which has a positive impact on the environment. MIBA can be used as raw feed for clinker manufacturing and can be substituted up to 40% of the raw feed [83]. The fly ash and MIBA should be fed in a limited percentage to protect the kiln from corrosion. If quenching is involved, pre-washing or any other treatment is not required for chloride removal in MIBA [84, 85]. The study has shown that up to 6% MIBA addition will not adhere to any adverse results on the clinker phase's compositions. Higher additions will only cause a significant drop in C3S values. Another study suggests removing Al and related species using alkaline treatment before consuming MIBA for cement production [86].

### Concrete production

Past studies suggest inclusion of incinerated ashes in concrete production for better results [87–89]. MIFA inclusions have given successful trail results for 10–40% of the total weight of the concrete. Comparing the slump values, the study has confirmed that MIBA can be used as a substitute for sand in a limited amount [90, 91]. When used as a coarse aggregate, the results for MIBA are more considerable due to lower surface area and better adsorption and water retention property. The properties can be further improved by washing or chemical treatment of MIBA so that the quantity of salts, metals and other organic components can be controlled. It has been suggested that the strength development in concrete is affected due to presence of Zn, Pb, Al ions and other salts which causes a serious delay [92–95]. These studies suggest inclusion of additional Si- or Al-rich cementitious materials to improve the pozzolanic reactions for better mechanical properties. It is also been proved that complete replacement of fine aggregates and coarse aggregates will give poor quality concrete, as the bond between cement and aggregates fails before the crushing of aggregates takes place [22, 33]. The significant results of MIBA replacement as both fine and coarse aggregate and respective compressive strengths are shown in Fig. 6.

## Advanced applications of MIBA

At present, MIBA is commonly used as a raw additive to applications mentioned above. In addition to it, there are some studies available that point out the futuristic applications of this incinerated byproduct as a valuable resource for further use. There are a limited number of publications available, and all these innovative applications require better pre-treatment of raw MIBA before considering for real-time industrial applications.

### Hydrogen gas production

Hydrogen gas is considered as the biggest flaw in the case of concrete production using MIBA. Higher pH values and Aluminum ion presence, is the reason behind the release of $H_2$ gas when MIBA comes in contact with $H_2O$ molecules. According to Saffarzadeh et al. [96], the process can be used for cleaner $H_2$ gas production. The process can further help in the removal of Al ions as they are dissolved in water and can be recovered hence making MIBA aluminum-free and fit for concrete production, and the gas collected can be stored and availed in cell fuel applications. According to a study, MIBA has an aeration capacity of about 1% of pure Al powder by mass. But the study limits this result to the specific source of bottom ash. It further explains that the reaction rate depends on the smaller particle size, molarity, and the reaction temperature of ash particles, and hence the amount of gas generation varies [47]. A further study of hydrogen gas production from MIBA seeks out the newer possibilities and suggests that better process design and controlled environment can yield better results [97].

### Land reclamation

Human existence needs land to develop its civilization, and for that land, reclamation is a need of the hour in countries with the highest population and limited land resources. Studies have been done to predict heavy metal leaching behavior when sea water comes in contact with MIBA due to land

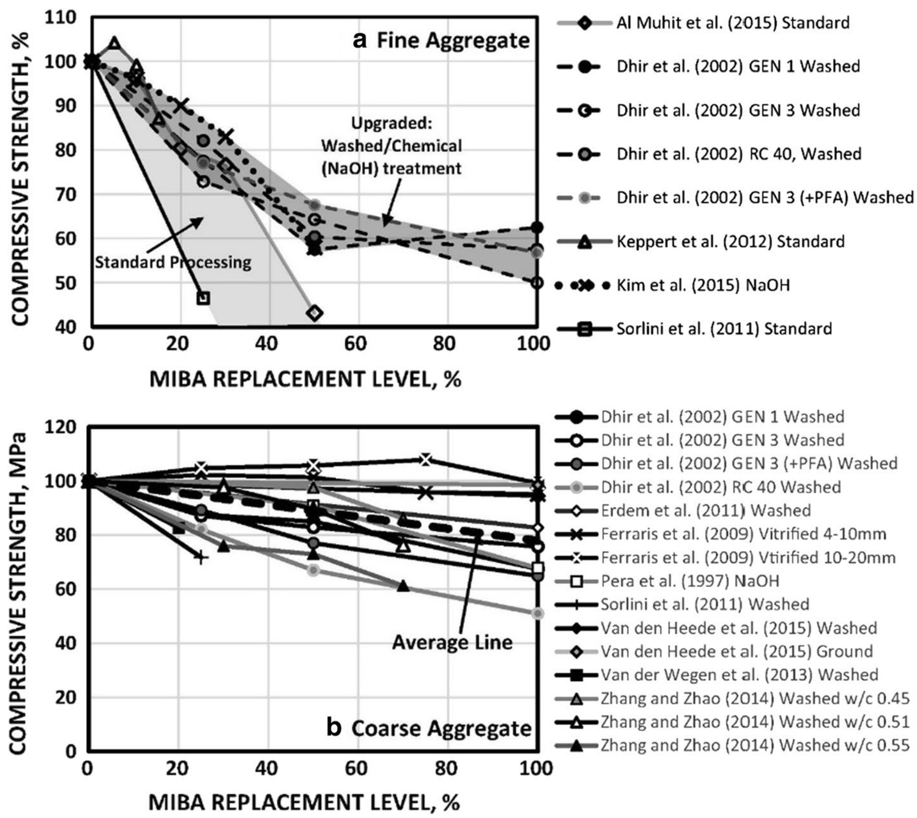



**Fig. 6** Graph showing MIBA replacement versus compressive strength of concrete (28 days) where **a** illustrates fine aggregate and **b** illustrates coarse aggregate components [22]

reclamation. Certain factors like the degree of disturbance in sea water, concentration gradients, and re-adsorption of heavy metals by MIBA were considered in such studies. These studies confirm a considerable potential in using MIBA for the land reclamation process [98]. Another research suggests that solidification/stabilization of marine clay using MIBA has given the desired results according to standards laid in Singapore [99, 100]. Stabilization of MIBA helps in controlling heavy metal leaching, and a pre-treatment with the alkaline medium is advised for better results [49].

## Landfill cover

MSWI ashes, both MIBA and MIFA, are most commonly disposed directly to landfills, and contamination control is often a concern due to direct disposal. This concern was challenged by a study published in 2017, which suggests the positive effect of MIBA on nitrogen compounds found in landfill sites [101]. In the same year, another study reported the adsorption behavior of MIBA toward nitrates, nitrites, and ammonia which are common in leachate. After a particular time, a varied trend in the leaching of Cr, Zn, and Cu from MIBA was noticed [102]. Not only MIBA but also MIFA has demonstrated successful adsorption of Hydrogen sulfite gas [103]. These studies suggest that both MIBA and fly ash can be used as landfill cover material, but incinerated ashes as a landfill liner need more studies and strict control.

## Synthesis of adsorbents and glass–ceramic materials

Ceramic-based materials are known for having low thermo-electrical conductivity and high durability with high thermochemical resistance. MIBA is generally used for glass–ceramic foams, ceramics, bricks, and tiles manufacturing as the higher temperatures are destroying dioxins and various other organic contaminants. A study shows the manufacturing of glass–ceramics from MIBA having 80% porosity and compressive strength of more than 6 MPa [104]. The recent research confirmed magnetite and hematite in porous products synthesized from VBA-based ceramics with high relative permittivity exceeding 50,000 (for a 20–200 Hz frequency range) and electrical conductivity of $0.9 \pm 0.1$ S/m. It confirms that VBA-based products have numerous new possible applications other than building materials [39].

Multiple studies have shown that the low silica content and large surface area of smaller MIBA particles enable higher removal efficiencies of heavy metals and organic dyes [105–107]. In the year 2017, the study demonstrated the conversion of MIBA to porous adsorbents, which can be used for gas and wastewater treatment [108]. A process was designed to convert the solid structure of MIBA to a porous microstructure under high alkaline conditions. The adsorbent proved significant toward Cu(II) ions, and a maximum adsorption capacity of 270.27 mg/g was observed. The results suggest the use of such adsorbents in the wastewater treatment process [109]. MIBA controls the leaching of metals, and adsorption of contaminants like 3-chloroaniline and triclosan was noted up to a greater extent (Table 2).

## The economic viability of MIBA applications

The incineration process is highly cost-driven and requires a considerable investment to keep it running for longer periods. As MSW's incineration is necessary to keep the volume of the waste being dumped into landfills in control, the applications of MIBA add individual profits to these incineration plants. In the year 2011, an LCA analysis confirmed that incineration leads to higher energy recoveries and the benefit to cost ratio was 6.5 times of that of landfill operations [111]. The studies have proved how economic and environmental benefits were achieved by utilizing MIBA in cement production (20 wt%) and brick production (10 wt%) [112]. In the USA, MIBA was used as 20% of MIBA in hot mix asphalt (HMA) and as 5% of clinker [113, 114]. Both of these studies suggest the economic feasibility of incorporating MIBA as a raw material at an industrial level (Table 3).

## Conclusions and recommendations

MIBA was once considered as a residue is now proving its potential as a significant construction material in various applications. The paper reviewed the current scenario of MIBA usage and its advantages on the environment and natural resources protection. The studies that happened over the years indicated that incinerated bottom ash could be successfully used in the construction sector. The review targeted the four critical sections: (1) Management of MIBA; (2) Composition and properties of MIBA; (3) Common and innovative applications of MIBA; and (4) Economic feasibility of MIBA applications.

The review makes the following conclusions fulfilling all these critical areas.

- Many constituents that are highly dependent on the feeding material and incineration facilities, limit the usage of MIBA as a raw material. The applications of MIBA are hence directly reliant on the type of constituents the bottom ash retains. Therefore, proper chemical characterization is a must for its application in concrete and other resource-based applications. The identification of heavy metals and soluble salts will help in selecting cost-effective pre-treatment techniques. It will ensure limited environmental setbacks and sustainable solutions for waste management.
- The review highlights, numerous advanced strategies to cut the adverse effects of bottom ash on the environment. Consumption in the construction sector, raw feeding to industries, hydrothermal treatment and removal of heavy metals before final landfill disposal are some of these which are cost effective. These applications can be further extended for the development of new technologies and various other value-added products.
- The solidification/stabilization of MIBA into cement or concrete composites is significant due to its cementation effect. The technique reduces the release of toxic compounds to a substantial amount and also results in structural benefits. The use of MIBA as a raw feed for solid cementitious materials, aggregate replacement, and cement clinkers has been proven useful by researchers in their works.
- From an engineering perspective, the application of MIBA in road construction and as a backfill material has suggested that MIBA is efficient as other construction or backfill materials. The only cause of concern is the contamination of ground and surface water sources from leachate interaction with runoff, rainfalls, and infiltration. In such a scenario, necessary preventive measures and design considerations can avoid the future contamination of resources.
- Although incineration is considered less eco-friendly, studies have shown that both MIBA and MIFA are being used since a decade. The incinerated ashes, when incorporated with cement production or any other facility where the incinerated ashes can be used directly, prove more environment friendly. It controls the carbon footprint of the industry and also favors the concept of a circular economy.
- Treatment of incinerated ashes according to the environmental rules and regulations is suggested. It is necessary to follow the standard protocols and a proper LCA of MIBA and its products are recommended before introducing the applications on an industrial level. There is an urgent need to establish guidelines, laws and regulations to give positive and controlled direction to MIBA generation and its utilization in developed countries. The regulations should follow the scientific evidences and address the need for a resource-efficient waste management action plan.

**Table 2** List of major MIBA applications allowed by the authorities and essential parameters required to be followed in European countries [110]

| Country | Number of working incineration facilities | Allowed applications of MIBA | Important components of regulations | Remarks |
|---|---|---|---|---|
| United Kingdom | 45 | Pipe bedding, road construction, structural platforms | No regulations hence depend on individual decision | MIBA is considered as non-hazardous waste, compliant to BS EN 13242:2013 |
| Sweden | 34 | Used as an unbound material | Ni, Pb, Zn, Cd, Cr, As, Cu, Hg, PAH (low–medium–high ring number) | No specific parameters available for MIBA usage |
| Netherlands | 12 | Construction material (bound and unbound | Toluene, xylene, benzene, ethylbenzene, benzo(a)pyrene, benzo(ghi)perylene, benzo(a)anthracene, benzo(k)fluoranthene, indeno(1,2,3-cd) pyrene, PAH, asbestos | No specific parameters available for MIBA usage |
| Italy | 39 | Construction of embankments, Foundations of road, cement raw material, environmental recoveries | No specific requirements | Considered as non-hazardous waste. Leachate studies are required |
| Germany | 68 | Foundation of road dams, bound top layer, base course, bound base course | Ni, PCDD/PCDF, Pb, Zn, TOC, Cd, Cr, Cu, EOX | More than 3 months of maturation period is required for final usage |
| Denmark | 24 | Open use in explicit construction applications, subbase layer | Ni, Pb, Zn, Cr (total), As, Cd, Cr (VI), Cu | No specific parameters are available for MIBA usage. Considered as non-hazardous waste |
| Belgium | 15 | Construction material (bound and unbound form) | Benzene, Pb, Zn, asbestos, ethylbenzene, styrene, As, Cd, Cr (total), Cu, Hg, Ni, toluene, xylene, chrysene, naphthalene, hexane, heptane, PCB benzo(a)anthracene, benzo(a) pyrene, benzo(ghi)perylene, benzo(b)fluoranthene, benzo(k)fluoranthene | Specific conditions: non-floating contaminants < 1 wt%<br>floating contaminants < 5 $cm^3$/kg Drying matter, and glass content < 2 wt% |
| Poland | 6 | Road construction: subbase layer | TOC, PCB, BTEX, PAH, hydrocarbons (sum of C10-40) | Considered as non-hazardous waste, non-hazardous waste, removal of light impurities, ferrous non-ferrous metals<br>Must compliant with PL EN 13242 and Technical requirement WT4 "Unbound mixes for national roads" (Republic of Poland, 2015) |
| Spain | 10 | Embankments, fillings, road subbase, and restoration of degradable areas and leveling of terrain | LOI, concentration of unburnt material | No specific parameters available for MIBA usage |
| Czech Republic | 4 | Application of MIBA on the soil surface | Ni, Pb, V, hydrocarbons (C10-40), As, Hg, PCB, Cd, Cr (total), BTX, EOX, PAH | No specific parameters available for MIBA usage |

**Table 3** Application based case studies exhibiting positive outcomes of MIBA inclusion

| Description of project | Country | Outcome | References |
|---|---|---|---|
| MIBA as an aggregate in base, sub base and filtration layer for an interim storage field | Finland | MIBA usage is recommended. Significant increase in stiffness was noticed | [115] |
| MIBA as unbound subbase (heavy traffic conditions) | Denmark | Good working condition and low rutting was observed in the year 2001 | [33] |
| MIBA as sand replacement liner at landfill | UK | Positive results were obtained regarding shear properties | [116] |
| MIBA as unbound subbase (urban road conditions) | France | Better results when tested for deflection, compaction and griding properties in the year 2001 | [117] |
| MIBA as unbound subbase for pavements | Sweden | Exhibited considerable performance and proper stiffness in the year 2006 | [118] |
| MIBA (20% with gravel) for road foundation | Italy | Exhibited usable performance in the year 2014 | [108] |
| MIBA as unbound subbase for asphalt road pavement | Sweden | Exhibited considerable performance and proper stiffness in the year 2006 | [119] |

**Declaration**

**Conflict of interest** Sanjeev Kumar and Davinder Singh confirm that there is no conflict of interest associated with the manuscript.

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