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Utilization of Medical Waste Ash as Planting Media: A Preliminary Review

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ABSTRAK

Ekspansi layanan kesehatan telah meningkatkan timbulan limbah medis secara signifikan, dengan insinerasi menjadi metode utama untuk reduksi volume dan inaktivasi patogen. Proses ini menghasilkan abu limbah medis (medical waste ash/MWA) yang dikategorikan sebagai limbah berbahaya karena bersifat sangat alkalis dan mengandung logam berat berpotensi toksik (potentially toxic metals/PTM). Meskipun karakteristik fisikokimia MWA telah banyak dilaporkan, sintesis kritis mengenai potensi pemanfaatannya sebagai media tanam, khususnya dalam integrasi dengan bahan organik, masih terbatas. Tinjauan naratif ini menganalisis literatur multidisipliner periode 2000–2025 untuk menilai kelayakan teknis serta implikasi lingkungan dari pemanfaatan tersebut. Dalam berbagai konteks geografis dan teknologi insinerasi, MWA secara konsisten menunjukkan sifat sangat alkalis (pH > 10) dan didominasi oleh CaO (10–62% berat) serta SiO_2 (1–58% berat). Keberadaan oksida hara seperti K_2O, MgO, SO_3, dan P_2O_5 mengindikasikan potensi fungsi agronomis, khususnya pada sistem budidaya nonpangan. Namun demikian, PTM seperti Zn, Pb, Cr, Cu, Ni, Cd, dan Hg terdeteksi secara konsisten, dengan mobilitas yang dipengaruhi oleh kondisi pembakaran, komposisi limbah, dan fraksionasi abu. Sintesis literatur mengindikasikan bahwa pencampuran MWA dengan bahan organik berpotensi menstabilkan pH, meningkatkan ketersediaan hara, serta memfasilitasi imobilisasi PTM melalui mekanisme khelasi. Dalam kerangka ekonomi sirkular, pemanfaatan kembali MWA berpotensi mengurangi volume pembuangan, kebutuhan transportasi, serta beban lingkungan jangka panjang akibat penimbunan di landfill. Meskipun demikian, tinjauan ini menegaskan perlunya validasi eksperimental, pengujian toksisitas yang terstandar, dan uji lapangan skala besar untuk memastikan kinerja agronomis serta keamanan lingkungan jangka panjang sebelum penerapan skala luas.

Kata kunci: abu limbah medis; sisa pembakaran; media tanam; logam beracun potensial; pupuk organik

ABSTRACT

The expansion of healthcare services has significantly increased medical waste generation, with incineration serving as the primary method for volume reduction and pathogen inactivation. This process produces medical waste ash (MWA), classified as hazardous due to its strong alkalinity and the presence of potentially toxic metals (PTMs). Although the physicochemical characteristics of MWA have been widely reported, a critical synthesis of its potential utilization as planting media, particularly in integration with organic amendments, remains limited. This narrative review analyzes multidisciplinary literature published between 2000 and 2025 to assess the technical feasibility and environmental implications of such utilization. Across diverse geographical contexts and incineration technologies, MWA consistently exhibits high alkalinity (pH >10) and is predominantly composed of CaO (10–62 wt.%) and SiO_2 (1–58 wt.%). The presence of nutrient-related oxides, including K_2O, MgO, SO_3, and P_2O_5, indicates potential agronomic functionality, particularly for non-food cultivation systems. However, PTMs such as Zn, Pb, Cr, Cu, Ni, Cd, and Hg are consistently detected, with mobility influenced by combustion conditions, waste composition, and ash fractionation. Literature synthesis suggests that blending MWA with organic amendments may stabilize pH, enhance nutrient availability, and facilitate PTM immobilization through chelation mechanisms. From a circular economic perspective, MWA valorization may reduce disposal volumes, transportation demand, and long-term environmental burdens associated with landfilling. Nevertheless, the existing body of research remains largely laboratory based. Rigorous experimental validation, standardized toxicity assessment, and large-scale field trials are therefore required to ensure agronomic performance and long-term environmental safety before broad implementation.

Keywords: medical waste ash; incineration residue; planting media; potentially toxic metals; organic fertilizer

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1. INTRODUCTION

In incineration technology, medical waste is treated in high-temperature combustion chambers, undergoing sequential processes including drying, gasification, and combustion. These processes convert waste materials into flue gases and solid ash residues (Chen *et al.*, 2012). A substantial proportion of potentially toxic metals (PTMs) released during combustion is retained in the resulting ash, while a fraction may be emitted to the atmosphere through flue gas discharge (Dalkılıç and Dursun, 2020). Consequently, incinerator ash—both fly ash and bottom ash—commonly contains elevated concentrations of PTMs.

Conversely, numerous studies have demonstrated that medical waste incinerator ash (MWA) also contains mineral components with potential agronomic value. The ash is predominantly composed of calcium oxide (CaO) and silicon dioxide (SiO_2) (Akyıldız et al., 2017; Bakkali et al., 2013; Darmayanti et al., 2012; Kumar et al., 2021; Liu et al., 2013; Miao et al., 2022; Tsakalou et al., 2018; Wang et al., 2017). These compounds have been shown to improve soil physical properties and pH buffering capacity when applied as soil ameliorants (Dariah et al., 2021; Ram & Masto, 2014). The presence of nutrients and soil amendments indicates that incinerator ash has the potential to be used as a planting medium.

However, MWA cannot be applied directly without appropriate treatment, as PTMs are persistent, non-biodegradable inorganic constituents with densities exceeding 5 g cm^{-3} (Kosakivska *et al.*, 2021). Uncontrolled applications may therefore pose environmental and health risks. The full potential of MWA as a planting medium remains insufficiently explored, particularly in relation to strategies that simultaneously enhance agronomic performance and mitigate PTM-related risks.

Previous studies have indicated that various types of ash with physicochemical properties comparable to MWA can function as planting media under controlled conditions. MWA has been reported to be applicable in agricultural contexts (El-Amaireh *et al.*, 2023; Ghazali *et al.*, 2022), and biomedical waste ash has been explored as a fertilizer source(Goswami-Giri, 2007). Nevertheless, adverse plant responses, such as stunted growth and abnormal leaf coloration, have been observed in the absence of additional organic amendments, highlighting the necessity of complementary treatments. Similarly, bottom ash from municipal solid waste incineration applied at concentrations below 20% showed limited improvement compared with conventional planting media (Sormunen *et al.*, 2016). In contrast, the combined use of coal ash, organic matter, and mineral fertilizers has successfully substituted topsoil and supported plant growth in several studies(Sriningsih *et al.*, 2022; Suhartini *et al.*, 2022).

Special liquid organic fertilizer is an organic amendment rich in amino acids derived from readily degradable organic waste, including food waste, vegetables, and fruits (Abidin *et al.*, 2024b, 2025). When integrated with MWA, this fertilizer serves a dual function: enhancing nutrient availability and acting as a chelating agent for PTMs. Organic amino acids, particularly proteinogenic amino acids, are recognized as effective natural chelators for metal ions (Dolev *et al.*, 2020). Metal chelation by organic compounds has been shown to accelerate PTM dissolution and increase metal uptake by plants, including hyperaccumulator species (Hidayati, 2005; Kim *et al.*, 2013). Consequently, MWA amended with amino-acid-based organic fertilizer may be suitable for use as a planting medium for hyperaccumulator plants, cover crops, or ornamental vegetation, thereby reducing the potential release of PTMs into the environment.

In addition to environmental considerations, the utilization of MWA has economic implications. In the absence of reuse options, incinerator ash is typically transported to licensed hazardous waste landfills, incurring substantial disposal costs. These costs represent a significant financial burden for waste generators (Pasaribu and Sukandar, 2017). Reuse-oriented management strategies therefore offer potential economic benefits by reducing disposal volumes and associated costs.

Despite growing interest in waste-derived planting media, there remains a limited integrated synthesis addressing how medical waste incinerator ash, when combined with organic fertilizers, can function as a safe and effective planting medium while balancing agronomic performance, environmental risk, and economic feasibility. This narrative review seeks to address this gap by synthesizing multidisciplinary evidence on MWA utilization.

Accordingly, this study aims to:

(1) synthesize the physicochemical characteristics of MWA reported across different countries,

(2) analyze the variability of PTM concentrations and the factors controlling their distribution, and

(3) evaluate the potential and limitations of MWA–organic fertilizer systems as sustainable planting media.

This review proposes a conceptual MWA–POCI framework linking chemical buffering, biological regulation, phytoremediation pathways, and economic value creation.

2. METHODHOLOGY

This study adopts a structured narrative review approach to synthesize multidisciplinary literature related to the utilization of medical waste incinerator ash (MWA) as planting media. A narrative review was selected to accommodate the heterogeneity of study designs, analytical methods, and disciplinary perspectives (environmental engineering, agronomy, waste management, and environmental economics) inherent in the existing literature. The review process follows a transparent and sequential workflow commonly applied in high-quality narrative reviews Sarkar & Bhatia (2021), as illustrated in Figure 1.

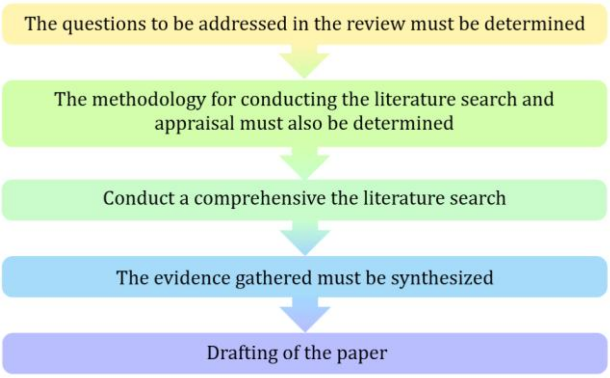

Figure 1. Steps of Writing a Narrative Review

The literature search was conducted between November 2024 and January 2026 using major scientific databases, including Scopus, ScienceDirect, and Google Scholar. Additional references were identified through backward citation tracking of key review and experimental papers. The search covered publications published between 2000 and 2025, reflecting the period during which research on medical waste incineration and ash characterization, treatment, and reuse has substantially developed. The search strategy employed combinations of the following keywords: *"medical waste ash," "medical waste incinerator bottom ash," "medical waste fly ash," "incineration residue," "planting media," "soil amendment," "phytoremediation," "potentially toxic metals," "leaching behavior," "chelation,"* and *"organic fertilizer."*

The inclusion criteria comprised: i) Peer-reviewed journal articles, conference proceedings, and selected technical reports; ii) Studies published in English and Indonesian; iii) Research addressing at least one of the following aspects: physicochemical characteristics of MWA, potentially toxic metal (PTM) content and leaching behavior, treatment or stabilization strategies, agronomic performance, phytoremediation potential, or environmental and economic implications of MWA reuse. Studies focusing exclusively on non-medical waste ash (e.g., municipal solid waste ash, coal fly ash, biomass ash) or unrelated waste streams were excluded to maintain thematic relevance and avoid conceptual overlap.

The initial database search yielded approximately 210 publications. After removing duplicates and screening titles and abstracts based on the predefined inclusion and exclusion criteria, 185 articles were retained for further evaluation. Full-text screening was subsequently conducted to assess data relevance, methodological clarity, and contribution to the study objectives. Based on this process, 171 publications were ultimately retained and synthesized in the present manuscript, corresponding to the references cited in the reference list. These studies collectively provide experimental data, comparative analyses, and conceptual insights relevant to MWA reuse as planting media.

The selected literature was analyzed using a thematic qualitative synthesis approach. Rather than listing individual study outcomes, findings were critically compared across studies to identify patterns, variability, and explanatory factors. This process resulted in the identification of five main analytical dimensions:

1. Physical and chemical characteristics of MWA,
2. Potentially toxic metal content and leaching behavior,
3. The role of organic amendments and chelation mechanisms,
4. Agronomic performance and phytoremediation potential,
5. Environmental and economic implications of MWA utilization.

This methodological framework enables an integrative and critical assessment of MWA as a potential planting medium while ensuring transparency, reproducibility, and coherence with the interdisciplinary nature of the topic.

3. RESULT AND DISCUSSION

3.1. Physicochemical Characteristics of Medical Waste Incinerator Ash (MWA)

The incineration of medical waste produces two primary types of ash: bottom ash (MWBA) and fly ash (MWFA). The classification of these materials is determined by the specific combustion process and the stage of ash collection. According to Appendix IX of Government Regulation of the Republic of Indonesia No. 22/2021, both MWBA and MWFA derived from medical waste incineration are categorized as hazardous and toxic waste from specific sources, with waste codes A347-2 and A347-1, respectively (KLHK, 2021). Despite this regulatory classification, the physicochemical properties of medical waste incinerator ash (MWA) vary substantially across countries and facilities, indicating that MWA cannot be treated as a homogeneous material.

The physical appearance of MWA ranges from light gray to dark gray or black, primarily reflecting the amount of unburned carbon remaining after combustion. Lighter-colored ash is generally indicative of more complete combustion and lower residual carbon content, whereas darker ash suggests incomplete oxidation (Akyıldız *et al.*, 2017; Rathoure, 2019; Tsakalou *et al.*, 2018).

A comparison of relevant studies indicates that the distribution of particle sizes is significantly impacted by the design of incinerators and the temperature at which they operate. MWBA, produced by rotary kilns or controlled-air incinerators, is characterized by its coarser particles and higher porosity. This property of MWBA may enhance aeration and drainage when incorporated into planting media. According to Ni et al. (2013), reported MWBA particle sizes frequently exceed 0.5 µm. In Greece, where medical waste was treated in a rotary kiln operating at 1100–1200 °C, approximately 85% of MWBA particles exceeded 250 µm (Tsakalou *et al.*, 2018). A similar outcome was observed in a study conducted in Morocco, where incineration at temperatures ranging from 800 to 1200 degrees Celsius resulted in the production of MWBA, characterized by a particle size distribution ranging from 0.25 to 1.00 millimeters. This distribution indicates that the ash is relatively coarse and structurally stable (Bakkali *et al.*, 2013).

In contrast, MWFA manifests a considerably more refined particle size distribution, indicative of the occurrence of volatilization–condensation processes during the process of flue gas cooling. SEM analyses indicate that MWFA is composed of ultrafine polycrystalline plate-like particles with a diameter of less than 0.5 µm. These particles agglomerate into spherical structures measuring 20–100 µm (Ni *et al.*, 2013). A substantial body of research has documented that the predominant proportion of MWFA particles exhibit a diameter less than 100 µm, with some particles measuring below 56 µm (Tsakalou *et al.*, 2018; Vavva *et al.*, 2017) These finer fractions are more prone to compaction and reduced permeability, particularly when applied directly without blending, highlighting the need for controlled incorporation into planting media.

Although nutrients are reported (Table 1) in oxide form (e.g., K_2O, P_2O_5, MgO, and SO_3), plants absorb these elements as soluble ionic species. Therefore, the presence of these oxides in MWA indicates nutrient potential. CaO and SiO_2 are the predominant oxide components of MWA, yet their relative proportions exhibit significant variation across different countries and incineration systems. This variability is not random but rather reflects systematic differences in incineration temperature, waste composition, and incinerator configuration.

Ash produced in high-temperature incineration systems (>900–1200 °C) generally exhibits elevated concentrations of calcium oxide (CaO). This phenomenon is evident in MWBA samples from China (MWBA-1 to MWBA-3; CaO 53–62%), Greece (MWFA CaO ≈62%), and Turkey (MWBA CaO ≈39%). The enrichment of CaO is attributed to the thermal decomposition of calcium-bearing medical materials, such as medical plasters, pharmaceutical residues, and calcium-based additives, as well as the transformation of carbonate minerals into oxide phases at elevated temperatures.

Conversely, higher SiO_2 contents are more frequently observed in ash generated by lower-temperature incinerators or facilities with mixed or poorly segregated waste streams. For instance, MWBA from Greece exhibits SiO2 contents that surpass 57%, and numerous samples from Morocco and Indonesia also manifest SiO2-dominant compositions. Elevated levels of silicon dioxide (SiO_2) are typically associated with the presence of silicate-based materials, including glass containers, laboratory ware, and packaging materials, which are not fully decomposed during the process of combustion. These findings underscore the pivotal function of waste segregation efficiency prior to incineration in regulating ash mineralogy.

The design of the incinerator has been identified as a factor that further influences chemical homogeneity. It has been demonstrated that rotary kiln systems and dual-chamber incinerators generally produce ash with more uniform oxide compositions than older or small-scale systems. Furthermore, the presence of MWFA indicates the presence of Na_2O, K_2O, and Cl, which are byproducts of the volatilization of alkali metals and salts during the combustion process. While these components can contribute to alkalinity, they may also introduce salinity risks if MWA is applied without proper conditioning.

The pH of MWA typically ranges from moderately to strongly alkaline (approximately 7.9–11.3), with systematic differences observed across facilities. MWBA generally exhibits higher pH values (8.6–10.7) than MWFA, reflecting its higher CaO content and lower concentration of volatile acidic compounds (Ni *et al.*, 2013; Zhao *et al.*, 2010). A comparative analysis of the available data indicates that the ash produced in centralized and well-controlled incineration facilities tends to exhibit more stable and predictable pH values. In contrast, the ash from older or decentralized incinerators demonstrates wider fluctuations in pH due to variable combustion efficiency and inconsistent waste inputs. These differences carry important agronomic implications, as excessively alkaline ash has been shown to reduce micronutrient availability, while moderately alkaline ash can provide beneficial liming effects when applied to acidic soils.

Across many countries and incinerator types, MWA almost always contains a mixture of Zn, Pb, Cr, Cu, Ni, Cd, Hg and other metals (Fe, Ti, Ba, Mn, Ag, As, Co, Sb, Sn, Sr). Zinc (Zn) is very common and often among the highest concentrations. Lead (Pb) frequent and toxic, usually high relative to other metals. Chromium (Cr) is linked to needles, syringes, and plastics. Copper (Cu) – from electrical parts, pigments, devices. Nickel (Ni) – present but often at moderate levels. Cadmium (Cd) – sometimes detected in bottom ash, more often concentrated in fly ash. Mercury (Hg) – can be present, but often volatilizes and is detected more in fly ash or emissions (Bolan *et al.*, 2021; Debrah and Dinis, 2023; Kadhem *et al.*, 2024; Valavanidis *et al.*, 2008; Zhao *et al.*, 2010), as demonstrated in Table 2.

The organic content of MWBA ranges from 21.57 to 30.14%, depending on the typical medical waste destroyed (Zhao *et al.*, 2010a). Another study showed that the total organic carbon was around 1.77 - 13.2% (Kumar *et al.*, 2021).

Table 1. MWA Chemical Composition

MWA Type	Country	Incinerator Specification	SiO_2	CaO	MgO	K_2O	SO_3	P_2O_5	References
			%						
MWFA	China	Gyration kiln	17.13	24.42	1.80	2.80	6.37	-	(Liu et al., 2013)
MWBA-1		Furnace, grate, and arch	10.45	62.18	7.54	1.30	0.86	1.70	(Miao *et al.*, 2022)
MWBA-2		CC 1: 600-800 °C	15.35	53.62	8.89	1.41	0.71	1.78	
MWBA-3		CC 2: 900-1200 °C	13.20	55.87	9.47	1.26	0.74	1.90	
MWFA-1		Rotary kiln	9.06	5.37	3.48	1.64	1.03	-	(Wang et al., 2017)
MWBA-1		in max. 1200 °C	30.94	10.63	2.64	1.01	0.25	-	
MWFA-2		Medium-scale	10.84	17.02	2.10	1.19	0.47	-	
MWBA-2		850 – 1050 °C	24.64	25.58	1.34	0.76	0.75	-	
MWFA	Greece	Rotary kiln	1.30	62.02	1.80	0.82	-	-	(Tsakalou *et al.*, 2018)
MWBA		1100–1200 °C	57.52	19.34	1.83	0.92	0.03	-	
MWBA	Turkey	Rotary kiln CC 2: 1000-1200 ˚C	7.96	38.53	2.29	3.29	1.57	-	(Akyıldız *et al.*, 2017)
MWBA	India	Double Chamber >800 - 1050±50 °C	14	39	4	1	7	-	(Kumar *et al.*, 2021)
MWBA-1	Morocco	I1 =1200°C	17	14	3	3	10	18	(Bakkali *et al.*, 2013)
MWBA-2		I2 = 800°C	23	20	3	1	6	2	
MWBA	Indonesia	Unknown	16.21	15.36	1.91	1.12	-	5.37	(Darmayanti *et al.*, 2012)

Note: CC = Combustion Chambers. I = Incinerator

Table 2. PTM Concentration of MWA

MWA Type	Country	Specification	PTM (ppm)							References
			Cd	Cu	Cr	Ni	Pb	Zn	Hg	
MWBA-1	China	Small fixed grate furnaces 700-800°C	ND	1.160	895,37	667,31	0,33	8.430	-	(Zhao *et al.*, 2010)
MWBA-2			ND	1.450	515,19	500,49	0,07	12.700	-	
MWBA-3			ND	1.260	916,50	519,32	0,24	13.720	-	
MWBA-1	Morocco	I1 =1.200°C	0,75	-	316,07	138,35	1.043	3.638	-	(Bakkali *et al.*, 2013)
MWBA-2		I2 = 800°C	3,81	-	185,15	31,14	862,60	8.236	-	
MWFA	Greece	Rotary kiln 800-1.000°C	ND	2.397	178	198	1	8.234	-	(Valavanidis *et al.*, 2008)
MWBA			5,9	1.100	84	62	2.050	5.650	-	
MWFA		Rotary kiln 1.100–1.200°C	3,3	138,2	-	22,4	135,5	1.103	1,8	(Tsakalou *et al.*, 2018)
MWBA			3,2	1.287	-	124	18	52,7	1,3	
MWFA	Turkey	Rotary kiln CC 2: 1.000-1.200 ˚C	-	2.840	810	150	320	2.030	-	(Akyıldız *et al.*, 2017)
MWBA	Jordan	CC 1: 800-900°C CC 2: 900-1.200°C	ND	2.385	3.900	1.248	3.250	3.534	-	(Allawzi *et al.*, 2018)
MWFA	Japan	Fixed grate incinerator	13,56	320,22	12,65	19,96	439,74	1831,5	6,18	(Sukandar *et al.*, 2009)
MWBA	India	Double Chamber >800 - 1050±50 °C, residence time: 2 s	0,6 – 30,9	41,2 – 486,7	45,8 - 486,7	7,5 – 290,4	159 – 5792,8	1.145,6 – 1.853,7	-	(Kumar *et al.*, 2021)
MWBA	Indonesia	Rotary kiln in average 900˚C	4,11	267,71	1.378,9	-	5.209,4	6.355,3	ND	(Girsang and Herumurti, 2013)
MWBA		Average 900˚C	-	76,18	30,31	-	102,06	6.046,27	-	(Saragih and Herumurti, 2013)

Note: CC = Combustion Chamber. ND = Not Detected

A comprehensive review of the extant comparative evidence clearly demonstrates that MWA properties are strongly controlled by operational parameters of incineration systems, including temperature, waste composition, and incinerator design. The suitability of MWA as a planting medium is directly influenced by variations in $CaO–SiO_2$ dominance, pH, particle size, and PTM concentrations. Consequently, the reuse of MWA necessitates prior physicochemical characterization and controlled blending with organic amendments to balance alkalinity, enhance physical structure, and mitigate environmental risks. This underscores the imperative for integrating ash reuse strategies with considerations of chemical composition and the comprehensive operational framework of medical waste incineration.

3.2. Modification of MWA Properties through Organic Amendments (POCI)

The incorporation of amino-acid-based liquid organic fertilizer (hereafter referred to as special liquid organic fertilizer, POCI) represents a key strategy for modifying the physicochemical and biological limitations of medical waste incinerator ash (MWA) when used as a planting medium. In its untreated form, MWA is predominantly mineral, alkaline, low in organic carbon and nitrogen, and biologically inert due to high-temperature incineration. The addition of POCI therefore functions not merely as a nutrient supplement, but as an integrated amendment that alters multiple interacting properties of MWA-based media.

POCI is a liquid organic fertilizer produced using MASARO technology, in which readily degradable organic wastes—such as food residues, vegetables, and fruits—are processed in a controlled bioreactor system with the aid of a MASARO catalyst (Abidin *et al.*, 2024a, 2025). Approximately 1 kg of organic waste can yield up to 10 L of liquid fertilizer. From a chemical standpoint, POCI complies with the minimum nutrient requirements stipulated in the Indonesian Minister of Agriculture Decree No. 261/KPTS/SR.310/M/4/2019 and contains substantial concentrations of organic carbon (14.25% w/v), organic nitrogen (9.53% w/v), and combined NPK (2.77% w/v), along with essential micronutrients such as Fe, Mn, Cu, Zn, B, and Mo (Abidin et al., 2024). When blended with MWA, these inputs directly address nutrient deficiencies and enhance the fertility of an otherwise nutrient-poor ash matrix, while simultaneously increasing organic matter content and buffering extreme alkalinity.

Beyond basic nutrient enrichment, a defining mechanism by which POCI modifies MWA properties lies in its high amino acid content. Food-waste-derived liquid organic fertilizers have been reported to contain total amino acid concentrations ranging from approximately 1,027 to 4,965 mg/L (Gao *et al.*, 2021). Detailed compositional analyses reveal the presence of proteinogenic amino acids such as glycine, alanine, arginine, aspartic acid, glutamic acid, methionine, proline, serine, and tyrosine (Abidin *et al.*, 2024b). In MWA-based systems, these compounds perform a dual function: they serve as readily available organic nitrogen sources and act as natural chelating agents capable of modifying metal speciation and mobility.

Chelation involves the formation of stable complexes between metal ions and organic molecules containing multiple functional binding sites, effectively encapsulating metal ions and altering their chemical behavior (Jacob et al., 2024; Ram et al., 2024), as illustrated in Figure 1. In contrast to synthetic chelators such as EDTA, amino-acid-based chelators are biodegradable and exhibit greater environmental compatibility (Ram et al., 2024). Studies have shown that amino acid–metal complexes can match or exceed the effectiveness of EDTA in enhancing metal mobility and uptake, while avoiding long-term persistence in soil systems (Ghasemi *et al.*, 2014; Jie *et al.*, 2008).

Organic amino acids are recognized as effective chelating agents for potentially toxic metals (PTMs), with chelation efficiency governed by molecular weight, functional groups, and side-chain structure (Dolev *et al.*, 2020). Amino acids with molecular weights in the range of 150–200 g/mol and reactive functional groups (e.g., carboxyl, amino, and thiol groups) exhibit particularly strong metal-binding capacity (Ram et al., 2024). Empirical studies demonstrate that fermented food-waste liquids can chelate Cd, Cu, and Zn (Dai et al., 2017). while specific proteinogenic amino acids such as Asp, His, Thr, and Cys show high affinity for Cd, Cu, Ni, and Zn (Dolev et al., 2020). Importantly, unlike EDTA, amino acids exhibit relatively low affinity for Ca, allowing the structural and liming benefits of Ca-rich MWA to be preserved while selectively moderating PTM mobility. This selective chelation is particularly advantageous in MWA-based planting media, where excessive immobilization of essential base cations could otherwise compromise soil structure and plant nutrition.

Incineration is an effective technology in eliminating pathogens from medical waste (Kanemitsu *et al.*, 2005; Smith *et al.*, 2002; Suprihatin, 2018). Kanemitsu et al. (2005) reported that *B. stearothermophilus* spores (ATCC 7953), the spores of which are considered to be the most heat-resistant of the potentially infectious agents, could be completely eradicated at temperatures of 300, 500, and 1100°C. The application of POCI reintroduces biological components by supplying diverse microbial groups, including rhizobacteria, nitrogen-fixing bacteria, phosphorus-solubilizing bacteria, and fungi. Although trace levels of pathogenic bacteria such as *Salmonella* sp. and *E. coli* have been detected in POCI, reported concentrations remain below regulatory limits (Abidin *et al.*, 2024b).

Overall, the incorporation of POCI functions as a property-modifying amendment that alters the intrinsic chemical, biological, and buffering characteristics of MWA, transforming it from a biologically inert and nutrient-limited residue into a chemically conditioned and biologically active planting medium. These property-level modifications establish the foundational conditions under which the physical, chemical, and biological performance of MWA–POCI-based planting media can be systematically evaluated in the subsequent section.

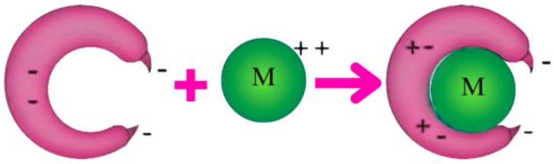

Figure 1. Chelation of Metal Ions by Chelating Agents

3.3. Physical, Chemical, and Biological Performance of MWA–POCI-Based Planting Media

The physicochemical and biological modifications induced by POCI, as discussed in Section 3.2, directly translate into changes in the functional performance of MWA-based planting media. These performance outcomes are reflected in enhanced physical structure, improved nutrient availability and buffering capacity, and the establishment of biologically active systems that collectively support plant growth while mitigating environmental risks.

The performance of planting media is fundamentally governed by the interaction between physical structure, chemical fertility, and biological activity. Together, these properties determine the ability of the media to provide mechanical support for roots, regulate water and air balance, supply essential nutrients in available forms, and sustain biological processes necessary for healthy plant development. Accordingly, planting media characteristics are commonly categorized into physical properties (e.g., porosity, aeration, and water-holding capacity), chemical properties (e.g., fertility, pH, and cation exchange capacity), and biological properties (e.g., microbial abundance and activity)(Abad et al., 2002; Bilderback et al., 2005; Michel, 2009).

3.3.1. Physical Performance of MWA–POCI-Based Planting Media

The primary physical functions of planting media include providing mechanical support for plant anchorage, regulating water retention and drainage, ensuring adequate gaseous exchange for root respiration, and facilitating nutrient transport to the root surface (Dumroese et al., 2008). The effectiveness with which these functions are performed is largely controlled by particle size distribution and bulk density, as these parameters govern pore structure and, consequently, water–air dynamics and root–media interactions (Bilderback *et al.*, 2005; Verdonck and Demeyer, 2004).

An effective planting medium must exhibit sufficient total porosity to simultaneously retain plant-available water and maintain oxygen diffusion within the root zone. Water is predominantly stored within micropores, where capillary forces counteract gravitational drainage and ensure moisture availability for plant uptake. In contrast, gaseous exchange occurs primarily through macropores, which drain freely following irrigation or rainfall and provide a continuous oxygen supply required for root respiration (Bilderback *et al.*, 2005; Raviv and Lieth, 2008). Accordingly, the water-holding capacity of a growing medium is defined as the proportion of total pore space that remains water-filled following gravitational drainage, reflecting its capacity to supply water without inducing hypoxic conditions. An ideal planting medium therefore maintains a high proportion of micropores to ensure sufficient water retention while preserving adequate macroporosity to facilitate excess water drainage, prevent oversaturation, and avoid anaerobic stress on plant roots (Bilderback *et al.*, 2005; Caron and Michel, 2021).

In MWA–POCI-based systems, physical performance is strongly influenced by media composition. Materials with contrasting particle sizes, shapes, and surface characteristics contribute differently to pore continuity, bulk density, and moisture retention behavior (Graceson *et al.*, 2013). Ash-based materials have attracted particular attention due to their capacity to modify these key physical parameters. Previous studies indicate that ash incorporation can reduce bulk density, increase total porosity, and enhance water retention, especially when combined with fine-textured soils or clay-rich substrates (Farhain *et al.*, 2022; Takoutsing *et al.*, 2016). These improvements are attributed to the heterogeneous particle size distribution of ash, which promotes the formation of both macro- and micropores when properly blended.

Particle size distribution represents a critical determinant of physical performance, directly influencing water availability, aeration efficiency, and nutrient transport to plant roots (Hunduma & Gezahagn, 2020). Standard particle size classes range from clay (<0.002 mm) and silt (0.002–0.05 mm) to fine, medium, and coarse sand fractions up to very coarse sand (1.00–2.00 mm) (Rathoure, 2019). Medical waste incinerator ash exhibits a wide particle size spectrum depending on ash type and incineration conditions.

Medical waste fly ash (MWFA), produced predominantly at high combustion temperatures (800–1200 °C), is characterized by extremely fine particles ranging from approximately 0.15 to 100 μm, with about 90% (w/w) below 56 μm—closely resembling silt-sized fractions (Tsakalou *et al.*, 2018). While such fine particles contribute to high water-holding capacity and increased reactive surface area, their dominance may also lead to compaction, reduced permeability, and limited aeration when MWFA is applied alone.

In contrast, medical waste bottom ash (MWBA) generally consists of coarser particles, with most fractions exceeding 225 μm and extending up to 1 mm, although a smaller proportion of finer particles (down to approximately 2.2 μm) is also present (Bakkali *et al.*, 2013; Miao *et al.*, 2022; Ni *et al.*, 2013; Tsakalou *et al.*, 2018). It means that MWBA spans a wider particle size range from clay-sized to coarse sand-sized fractions, providing improved structural stability and enhanced macroporosity relative to MWFA. This heterogeneity suggests that MWBA can play a complementary role in blended media formulations by improving drainage and aeration performance.

The physical limitations associated with fine ash fractions can be further mitigated through the incorporation of organic amendments and composting processes. Previous studies have demonstrated that the addition of organic matter, such as cow dung, and the application of vermicomposting techniques to MWA improve texture, promote particle aggregation, and enhance overall physical quality, resulting in planting media that meet established structural standards (Sohal *et al.*, 2021). These findings highlight the importance of controlled blending strategies in optimizing the physical performance of MWA-based planting media by balancing water retention, aeration, and mechanical stability.

The beneficial effects of organic amendments are closely linked to reductions in bulk density. Numerous studies have reported a negative correlation between organic matter content and bulk density, whereby increased organic matter leads to higher porosity and reduced compaction (Crnobrna *et al.*, 2022; Federer *et al.*, 1993; Hossain *et al.*, 2015; Huerta-Pujol *et al.*, 2010; Ruehlmann and Körschens, 2009). The accumulation of organic matter enhances the development of soil aggregates and mesoscale structural features by providing energy sources for soil organisms, ultimately lowering bulk density and improving pore connectivity (Martinez *et al.*, 2023).

Beyond the direct contribution of organic matter, biological activity introduced via POCI also contributes to physical performance enhancement. Various microbial groups present in POCI contribute to soil aggregation through the production of extracellular polymeric substances (EPS). These EPS—composed primarily of polysaccharides, proteins, and extracellular DNA—function as natural binding agents that promote the adhesion of individual soil particles into stable aggregates. Through this mechanism, microorganisms enhance interparticle cohesion across different textural fractions, including sand, silt, and clay. The resulting aggregation improves the structural stability of the growing medium, influencing pore continuity, water retention, and aeration by modifying the spatial arrangement and interaction of mineral particles (Bettermann *et al.*, 2021; Cania *et al.*, 2020; Mager and Thomas, 2011).

3.3.2. Chemical Performance of MWA-Based Planting Media

3.3.2.1. Nutrient Availability and Fertility

Fertility can be defined as the ability to supply nutrients as plant nutrients in a readily available form, in sufficient quantities required for normal plant growth and reproduction, and without toxic substances. There are seventeen chemical elements, Carbon (C), Hydrogen (H), Oxygen (O), Nitrogen (N), Phosphorus (P), Sulfur (S), Potassium (K), Calcium (Ca), Magnesium (Mg), Iron (Fe), Manganese (Mn), Copper (Cu), Molybdenum (Mo), Boron (B), Zinc (Zn), Chlorine (Cl), and Nickel (Ni), which have so far been recognized as essential elements for plants. Without these nutrients, plants cannot complete their life cycle and perform normal physiological functions. In addition, there are several other elements, such as sodium (Na), silicon (Si), vanadium (V), iodine (I), and cobalt (Co), which are considered beneficial for the growth of plants and certain microorganisms (Osman, 2013). According to Mengel & Kirkby (2007), plant nutrient elements can be divided into three categories based on their quantitative requirements: macronutrients, micronutrients, and toxic or waste elements.

Macro-nutrients are elements that plants need in relatively large amounts (>0.1% of dry mass) (Maathuis, 2009; Mengel and Kirkby, 2007). The nutrients included in macro-nutrients are C, H, O, N, P, K, Ca, Mg, and S. Plant organic matter is indeed composed of three main elements, namely C, H, O, and additional elements of N, S, and P (Mengel and Kirkby, 2007), but the elements C, H, and O can be taken by plants naturally. Carbon is absorbed as CO_2 gas from the atmosphere and soil solution, while H and O are usually absorbed through water molecules (H_2O) (Reid, 2006). Since C, H, and O are naturally available, indicators of these three components in the planting media are often overlooked and rarely discussed in the context of fertilization. As for other macro elements, Ca, Mg, and S are often referred to as secondary nutrients because attention to these three elements is given after the main elements (Sufardi, 2019).

Medical waste incinerator ash (MWA) contains a range of macro- and micronutrients; however, it is notably deficient in N and organic carbon (OC) due to the high-temperature incineration process (Goswami-Giri, 2007). Nitrogen present in waste materials is typically volatilized at relatively low temperatures, commonly below 1000 °C, resulting in substantial N losses during incineration (Xie *et al.*, 2009). The limited carbon content is greatly influenced by the type of incinerator and combustion temperature, with higher temperatures promoting more complete oxidation (Rubli *et al.*, 2000).

The incorporation of liquid organic fertilizer derived from food waste provides an effective means to address these chemical limitations. Such fertilizers are rich in essential macronutrients, particularly N, P, and K (Wu *et al.*, 2023). Abidin et al. (2024) reported that POCI contains approximately 9.53% (w/v) organic nitrogen and 2.77% (w/v) NPK, indicating its strong potential to enrich N, P, K, and organic carbon pools when applied to MWA-based planting media.

Beyond absolute nutrient concentrations, the enrichment of OC and N directly influences the carbon-to-nitrogen ratio (C/N) of the planting media. The C/N ratio is a key indicator of nutrient availability for microorganisms and plays a central role in regulating microbial activity, organic matter decomposition, and nutrient mineralization processes (Lucitawati *et al.*, 2018; Madusari, 2015). In this context, the addition of liquid organic fertilizer not only compensates for nutrient deficiencies in MWA but also optimizes the C/N balance, thereby enhancing microbial functionality and overall biological performance of the planting media.

POCI further contributes to increasing plant-available phosphorus in planting media through both its intrinsic phosphorus content and the activity of phosphate-solubilizing microorganisms contained within the fertilizer. Phosphate-solubilizing bacteria are capable of hydrolyzing insoluble inorganic phosphorus compounds—such as calcium phosphate, aluminum phosphate, and iron phosphate—into soluble inorganic forms, primarily orthophosphate ions ($H_2PO_4^-$ and HPO_4^{2-}), which can be readily absorbed by plants (Kundan *et al.*, 2015). This microbial mechanism is particularly relevant in MWA-based media, where phosphorus may be present in chemically stable but poorly available mineral forms.

In addition to nitrogen and phosphorus, sulfur (S) dynamics in MWA-based planting media are also influenced by biological processes stimulated by POCI. Solid sulfur present in incinerator ash can undergo microbial oxidation to sulfate (SO_4^{2-}), a plant-available form of sulfur. Sulfur oxidation involves the transformation of elemental sulfur, hydrogen sulfide (H_2S), and sulfide (S^{2-}) into sulfate by sulfur-oxidizing microorganisms (Chaudhary et al., 2023; Vidyalakshmi et al., 2009). Higher availability of solid sulfur substrates promotes greater sulfate production, thereby increasing sulfate concentrations in the planting media. Several microbial taxa commonly associated with organic fertilizers, including *Bacillus, Pseudomonas*, and fungi such as *Trichoderma* spp., possess the ability to oxidize sulfur into sulfate forms usable by plants (Chaudhary & Goyal, 2019; Grayston et al., 1986; Vidyalakshmi et al., 2009). Moreover, POCI contributes to sulfur availability through the mineralization of organic sulfur compounds, particularly sulfur-containing amino acids such as methionine and cystine. Microorganisms present in POCI can also assimilate inorganic and organic sulfur compounds into their biomass, which are subsequently released into the planting media following cell lysis. Previous studies have demonstrated that bacteria and fungi can store substantial amounts of sulfur within their cells, making it available to plants and other organisms upon microbial turnover (Jha & Subramanian, 2016; Meena et al., 2015).

3.3.2.2. Potential of Hydrogen (pH) Regulation and Nutrient Balance

Potential of Hydrogen (pH) is a fundamental chemical property of planting media because it governs nutrient solubility, ionic speciation, microbial activity, and ultimately plant growth performance. Most plants thrive within a pH range of 5.5 to 6.5 (Strawn *et al.*, 2020), although certain species can tolerate conditions that are either more acidic or more alkaline. *Pennisetum purpureum cv Mott*, for example, has a high tolerance and can adapt to planting media with a pH range of 4.5-8.2 (Sirait, 2018).

According to Penn & Camberato (2019), pH significantly influences plants' capacity to regulate nutrient availability and microbial community structure in the rhizosphere. Nitrogen availability is particularly sensitive to pH, as acidic conditions favor ammonium (NH_4^+) dominance, while alkaline conditions promote nitrate (NO_3^-) accumulation (Zhang et al., 2022). Although nitrogen uptake can occur over a wide pH range, excessively high pH has been shown to inhibit nitrogen uptake efficiency and suppress plant growth (Zou *et al.*, 2016). Phosphorus availability also exhibits a strong pH dependency, with maximum availability generally occurring around pH 5.5 and decreasing near neutral to alkaline conditions due to fixation with Ca, Fe, or Al compounds (Barrow *et al.*, 2020). Similarly, potassium availability declines under extreme acidity due to enhanced leaching losses (Kucher, 2019), while micronutrients such as Mn, Zn, Cu, Fe, and B show decreasing solubility with increasing pH and calcium carbonate content (Sharma et al., 2011; Sufardi, 2019)

MWA, particularly MWBA, is typically characterized by alkaline pH values resulting from high concentrations of calcium-rich mineral phases. Kumar et al. (2021) reported MWBA pH values ranging from 7.89 to 11.29, consistent with earlier findings of pH 8.6–10.7 (Zhao et al., 2010). In contrast, medical waste fly ash (MWFA) often exhibits slightly acidic to near-neutral pH values (6.33–6.95), reflecting differences in mineral composition and condensation processes during incineration (Wang et al., 2017). While alkalinity may confer liming potential, excessively high pH in MWBA can severely restrict nutrient availability and disrupt nutrient balance when used directly as a planting media.

The incorporation of organic amendments has been widely reported as an effective strategy to regulate pH in ash-based media. Previous studies demonstrated that the addition of organic matter and composting processes significantly reduce the pH of MWA, as observed in cow-dung-amended and vermicomposted ash systems (Sohal *et al.*, 2021). In this context, the application of POCI is expected to contribute to pH moderation through multiple interacting mechanisms. Microbial metabolism associated with POCI can produce organic acids during the decomposition of organic substrates, leading to localized proton release and gradual pH reduction. In addition, nitrification processes driven by introduced microorganisms generate hydrogen ions, further contributing to pH buffering in alkaline media. One of the strains of microorganisms contained in POCI is Lactobacillus sp. These microorganisms have been reported to be capable of reducing the pH of the environment (Zhu et al., 2022).

Beyond pH adjustment, POCI plays a critical role in maintaining nutrient balance under regulated pH conditions. By moderating alkalinity, POCI enhances the solubility and plant availability of phosphorus, potassium, and micronutrients that are otherwise immobilized in high-pH ash matrices. Simultaneously, the buffering capacity provided by organic functional groups helps stabilize pH fluctuations, creating a chemically balanced environment that supports sustained nutrient uptake and microbial activity. Consequently, pH regulation mediated by POCI is closely linked to improved nutrient balance, transforming chemically extreme MWA into a more agronomically functional planting medium.

In addition to regulating nutrient availability, pH exerts a decisive control over the solubility, speciation, and mobility of PTMs such as Pb, Cd, and Zn in ash-based planting media.

In highly alkaline conditions, these metals are commonly immobilized through precipitation as hydroxides, carbonates, or complex calcium-associated phases, which significantly limits their bioavailability but may also constrain their geochemical stability under changing environmental conditions (Chen et al., 2023; El-eswed, 2020). Conversely, excessive acidification can markedly increase PTM solubility, elevating the risk of metal leaching and phytotoxicity (Lewińska and Karczewska, 2025; Martínez and Motto, 2000). Overall, precipitation as hydroxides, carbonates, and Ca-associated phases in alkaline environments substantially reduces metal bioavailability, but the resulting phases are not universally permanent; their stability is sensitive to later shifts in pH, redox, salinity, and mineral weathering.

A moderate and controlled reduction in pH—rather than extreme acidification—can therefore induce *selective mobilization* of PTMs, in which weakly bound metal fractions become more chemically dynamic without triggering uncontrolled release. Such conditions favor the transformation of metals from strongly mineral-bound forms into organically complexed or microbially associated species, which are generally less bioavailable and more environmentally stable (Ding *et al.*, 2024; Kicińska *et al.*, 2022; Li *et al.*, 2022; Liapun and Motola, 2023; Xu *et al.*, 2018). This *controlled immobilization* mechanism is particularly relevant in MWA–POCI systems, where organic ligands and microbial metabolites introduced by POCI interact with pH-driven processes to stabilize PTMs through complexation, biosorption, and secondary mineral formation. By maintaining pH within a moderately acidic to near-neutral range, the MWA–POCI planting media can thus achieve a dual function: enhancing nutrient balance while simultaneously regulating PTM behavior.

Within MWA–POCI systems, this pH-mediated regulation is particularly important, as the buffering effect of organic amendments enables controlled adjustment of PTM solubility while maintaining overall chemical stability of the planting media. Thus, pH regulation functions as a primary chemical control that governs PTM behavior and sets the boundary conditions for subsequent biological interactions discussed in Section 3.3.3.

3.3.2.3. Cation Exchange Capacity (CEC) and Nutrient Retention

The exchange capacity of positively charged ions, such as Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, NH_4^{+}, is referred to as CEC. Cation exchange capacity is the ability to absorb and exchange cations from and into the growing media layer. This ability will be affected by soil texture, clay mineral type, organic matter content, and pH value (Takoutsing *et al.*, 2016). Cation exchange coefficient is a chemical property of planting media that is closely related to fertility. Media with high CEC are able to absorb and provide nutrients better than media with low CEC (Sasmita and Haryanto, 2021). Saturated CEC values decrease in proportion to pH, as the load for clay minerals is quite stable below pH 6.0. The load on mineral colloids increases beyond pH 6.0 due to the enormous hydrogen ionization of activated hydroxyl groups at the crystal periphery. The effect of cation exchange is important because it affects the physicochemical properties of soil (Inamuddin *et al.*, 2021). MWA composting using special liquid organic fertilizer is thought to reduce pH, so it can increase CEC.

3.3.3. Biological Performance of MWA–POCI-Based Planting Media

The biological performance of planting media plays a critical role in regulating nutrient cycling, plant health, and the environmental behavior of PTMs. In the case of MWA, high-temperature incineration eliminates all indigenous microorganisms, rendering the material biologically inert despite its mineral richness (Kanemitsu *et al.*, 2005). Consequently, biological functionality in MWA-based planting media depends entirely on external biological inputs. The application of POCI introduces diverse and functionally active microbial communities, including rhizobacteria, nitrogen-fixing bacteria, phosphorus-solubilizing bacteria, and fungi (Abidin *et al.*, 2024b). These microbial communities contribute to nutrient cycling, plant growth promotion, and suppression of soil-borne pathogens (Ait-Kaki *et al.*, 2014; Amira *et al.*, 2015; Hussein and Joo, 2018; Sharma *et al.*, 2011; Sturz and Christie, 2003). Rhizobacteria such as *Azotobacter*, *Pseudomonas*, *Bacillus*, and *Lactobacillus* spp. contribute to nitrogen availability, phytohormone production, and disease resistance, while phosphorus-solubilizing bacteria improve P and K availability through mineral dissolution and organic acid production. Fungi such as *Trichoderma* spp. further enhance biological resilience by acting as biocontrol agents against phytopathogens.

Beyond nutrient cycling and plant health, microbial activity introduced via POCI plays a decisive role in regulating PTM behavior within the MWA–POCI-based planting media. These microorganisms contribute to PTM stabilization through multiple, interrelated mechanisms, including biosorption, bioaccumulation, biocomplexation, and biomineralization (Bolan *et al.*, 2021). Together, these processes regulate metal mobility, bioavailability, and long-term environmental stability.

Biosorption represents the first line of microbial metal immobilization and is a passive, metabolism-independent process in which metal ions are bound to microbial cell surfaces through ion exchange, surface complexation, and electrostatic interactions. This process results in the sequestration of metals external to the cell structure, primarily via binding to extracellular polymeric substances (EPS) composed of polysaccharides, proteins, and other functional groups (Khan *et al.*, 2025; Momin *et al.*, 2024; Njoku *et al.*, 2020; Pande *et al.*, 2022). By immobilizing metal ions at the cell surface, biosorption effectively reduces PTM mobility and bioavailability in the planting media and has been widely documented in bacterial genera such as *Azotobacter* and *Pseudomonas* (Xu *et al.*, 2020; Yin *et al.*, 2019).

In contrast to biosorption, bioaccumulation is an energy-dependent process that occurs exclusively in metabolically active cells and involves the active transport of PTM ions across cellular membranes. Once internalized, metals are sequestered within intracellular compartments or bound to specific biomolecules, thereby reducing their reactivity and toxicity (Danouche *et al.*, 2021). This mechanism has been reported for various PTMs in microorganisms such as *Pseudomonas* spp. and *Bacillus* spp., highlighting its importance in long-term metal stabilization under biologically active conditions (Naik et al., 2012; Sharma & Shukla, 2021; Sharma et al., 2006).

Following surface binding and intracellular sequestration, additional stabilization may occur through biocomplexation and biomineralization processes. In biocomplexation, absorbed PTM ions form stable complexes with microbial organic ligands, including proteins, organic acids, and polysaccharides, resulting in metal–chelate species with reduced toxicity and bioavailability (Shan *et al.*, 2021). Concurrently, biomineralization transforms soluble PTMs into stable inorganic mineral phases, further limiting their mobility within the growing medium. Phosphate-solubilizing bacteria play a critical role in this process by promoting the formation of metal–phosphate minerals (George and Wan, 2023; Lin *et al.*, 2016; Park *et al.*, 2011; Zhu *et al.*, 2019), while fungi such as *Trichoderma asperellum* have demonstrated measurable removal of PTMs through mineralization-driven pathways (Sun *et al.*, 2018).

3.4. Agronomic and Environmental Implications

The integration of MWA with POCI not only improves the intrinsic properties of planting media but also determines its practical agronomic applicability and environmental safety. The implications of this system extend to soil amelioration, phytoremediation-oriented cultivation, and mitigation of environmental risks associated with potentially toxic metals (PTMs).

3.4.1. Soil Amelioration Potential

The MWA–POCI system exhibits significant potential as a soil ameliorant, particularly for degraded or nutrient-poor substrates. The inherently alkaline nature of MWA contributes to liming effects, improving soil pH and calcium availability, while the addition of POCI supplies organic carbon, nitrogen, and biologically active compounds that enhance soil structure and fertility. Organic inputs derived from POCI contribute to improved soil texture through reductions in bulk density, increases in total porosity and moisture retention, and enrichment of fine-grained mineral fractions (Shen *et al.*, 2008). These physical improvements are accompanied by enhanced biological activity (Kumpiene *et al.*, 2007) reduced nutrient leaching losses (Sajwan *et al.*, 2003); and overall improvements in vegetation establishment and growth (Rautaray *et al.*, 2003).

Beyond these general organic matter effects, amino acid–metal complexes introduced via POCI play a specific role in ameliorating alkaline and saline conditions. Long-term applications of amino acid–based chelates have been shown to improve soil chemical balance and nutrient availability in saline and calcareous soils, producing effects comparable to those of organic acids and humic substances, while simultaneously supporting plant growth and nutrient uptake (Fahimi *et al.*, 2016; Sánchez *et al.*, 2005; Souri, 2016).

Moreover, microbial activity stimulated by POCI accelerates organic matter decomposition and nutrient mineralization processes, promoting sustained nutrient release rather than short-term nutrient pulses. Through the combined action of physicochemical improvement and biologically mediated nutrient cycling, MWA–POCI formulations can therefore function as engineered soil conditioners suitable for non-food agricultural applications, reclamation of marginal or degraded lands, and landscape restoration initiatives.

However, given the presence of potentially toxic metals in MWA, the soil amelioration function of MWA–POCI systems is most appropriately targeted toward non-food applications, such as land reclamation, bioenergy crop production, and landscape rehabilitation.

3.4.2. Compatibility with Hyperaccumulator and Non-Food Crops

The agronomic application of MWA–POCI-based planting media is most suited for non-food crops, such as ornamental plants, bioenergy crops, and hyperaccumulator species, due to the residual PTMs in MWA. In comparison to nonaccumulator plants growing in comparable conditions, hyperaccumulators can accumulate PTM at least 100 times more (Reeves, 2024). Each element has a different threshold concentration, with acceptable minimum values above 100 mg/kg for Cd, 1,000 mg/kg for As, Co, Cr, Cu, Ni, Pb, and Se, and 10,000 mg/kg for Mn and Zn (Reeves, 2024; Ucer *et al.*, 2013).

This capacity is governed by distinct physiological and biochemical mechanisms, including enhanced metal uptake, translocation, sequestration, and detoxification pathways (Liu et al., 2024). Such traits make hyperaccumulators particularly compatible with MWA–POCI systems, where controlled PTM mobility and sustained nutrient supply coexist.

Several grass species commonly employed in land reclamation and soil stabilization have demonstrated both high biomass production and phytoextraction potential. These include vetiver (*Vetiveria zizanioides*), Bermuda grass (*Cynodon dactylon*), dwarf napier grass (*Pennisetum purpureum* cv. Mott), humidicola grass (*Brachiaria decumbens* cv. Humidicola), atratum grass (*Paspalum atratum*), and Guinea grass (*Panicum maximum*) (Anda *et al.*, 2022; Hanping, 2003; Harmini *et al.*, 2022). Previous studies have classified several of these species as effective hyperaccumulators or phytoextractors for metals such as Pb, Cd, and Zn, particularly under amended soil conditions (Boonmeerati & Sampanpanish, 2021; Chen et al., 2012; Coulibaly et al., 2021; Daniel et al., 2024; Song et al., 2022; Zhang et al., 2010).

The application of amino acid–based liquid organic fertilizers, such as POCI, further enhances the phytoextraction potential of hyperaccumulator plants. Amino acid amendments have been shown to increase plant biomass, photosynthetic activity, and antioxidant enzyme responses, while simultaneously promoting PTM uptake and accumulation. For example, amino acid fertilizers enhanced Cd and Pb extraction by *Solanum nigrum* (He *et al.*, 2019) and significantly increased Cd uptake and biomass production in *Nasturtium officinale* under contaminated conditions (Zhang et al., 2010).These findings suggest that POCI not only supports plant growth in MWA-based media but also facilitates controlled PTM uptake through chelation and improved root–metal interactions.

Ornamental plants represent a particularly attractive category of non-food crops for MWA–POCI systems, as they combine phytoremediation functionality with aesthetic and economic value. Several ornamental species, including *Calendula officinalis*, *Chlorophytum comosum*, *Helianthus annuus*, and *Miscanthus sinensis*, have demonstrated high tolerance to and accumulation capacity for PTMs such as Cd, Pb, Cu, and Zn (Abdullahi *et al.*, 2021; Liu *et al.*, 2008; Shao *et al.*, 2019; Wei *et al.*, 2008; Yu and Zhou, 2009). The use of ornamental hyperaccumulators has been widely recognized as a sustainable and socially acceptable phytoremediation strategy, as it enhances landscape quality, reduces soil erosion, and contributes to ecosystem restoration without compromising food safety (Herlina *et al.*, 2020; Rocha *et al.*, 2022).

Overall, the compatibility of MWA–POCI-based planting media with hyperaccumulator and non-food crop species underscores its suitability for phytoremediation-driven land use, including revegetation of degraded sites, urban landscaping, and bioenergy crop production. By aligning plant selection with the physicochemical and biological properties of the amended media, MWA–POCI systems can simultaneously support vegetation establishment, facilitate PTM management, and mitigate environmental risks associated with ash reuse.

3.4.3. Phytoremediation Potential and Environmental Risk Mitigation

The integration of MWA with POCI creates a planting media system that is not only agronomically functional but also strategically suited for phytoremediation-oriented environmental management. Phytoremediation relies on the combined action of plants, microorganisms, and soil physicochemical processes to remove, stabilize, or transform potentially toxic metals (PTMs) into less mobile and less hazardous forms (Mahar *et al.*, 2016). Within this framework, the MWA–POCI system provides a chemically buffered and biologically active matrix capable of regulating PTM behavior while maintaining favorable conditions for plant establishment and sustained growth.

The phytoremediation potential of MWA–POCI-based planting media arises from the complementary operation of phytoextraction and phytostabilization mechanisms. On one hand, hyperaccumulator species and high-biomass non-food crops cultivated in this medium can absorb PTMs from the rhizosphere and translocate them to aboveground tissues, enabling gradual contaminant removal through controlled harvesting (Sadasivam and Jawaharlal, 2022; Ucer *et al.*, 2013). Effective phytoextraction requires that metals be present in bioavailable forms, including free metal ions and soluble metal complexes in the soil solution or weakly adsorbed to exchangeable sites on mineral surfaces (Ouyang, 2002). The moderated chemical environment of the MWA–POCI system supports this requirement without inducing excessive metal solubilization.

In practice, the effectiveness of phytoextraction in MWA–POCI systems is closely linked to plant physiological capacity. Ornamental and bioenergy grasses such as *Triarrhena sacchariflora, Helianthus annuus*, and *Miscanthus sinensis* have been reported to accumulate multiple PTMs through physiological mechanisms involving antioxidant defense systems, glutathione metabolism, and ATP-binding cassette (ABC) transporter pathways (Abdullahi *et al.*, 2021; Adesodun *et al.*, 2010; Nie *et al.*, 2021; Tian *et al.*, 2013). These traits enable such species to tolerate elevated metal concentrations while sustaining high biomass production, making them particularly suitable for controlled phytoremediation using MWA–POCI-based planting media.

In parallel, phytostabilization plays an equally important role in limiting PTM mobility and reducing environmental exposure risks. The presence of calcium-rich ash constituents, organic ligands, and biologically derived metabolites promotes PTM retention within the root–media interface, particularly in the rhizosphere zone (Kumpiene *et al.*, 2007). These interactions favor the formation of less mobile metal phases through adsorption, complexation, and incorporation into secondary mineral forms, thereby restricting downward migration and off-site transport.

From a chemical perspective, chelation plays a critical role in regulating both nutrient and PTM behavior in the MWA–POCI system. Chelating agents derived from organic amendments improve nutrient and metal mobility by maintaining cations in soluble, plant-available forms while preventing undesirable precipitation reactions (Datir *et al.*, 2012). Chelated metals and nutrients are more readily absorbed by plant roots due to their neutral or weakly charged complexes, exhibit enhanced translocation within plant tissues, and reduce losses through leaching (Ram et al., 2024).

A key advantage of the MWA–POCI system lies in its capacity to mitigate environmental risks associated with PTM leaching. Ash-derived media often exhibit high alkalinity and elevated ionic strength, conditions that can immobilize metals but may become unstable under fluctuating pH or moisture regimes (Martinez *et al.*, 2023). The addition of POCI moderates these conditions by introducing organic carbon and biologically driven buffering processes, thereby reducing the likelihood of abrupt changes in PTM solubility. Previous studies have shown that organic amendments significantly decrease metal leaching by promoting adsorption, complexation, and incorporation into secondary mineral phases (Kumpiene *et al.*, 2007; Park *et al.*, 2011; Sajwan *et al.*, 2003).

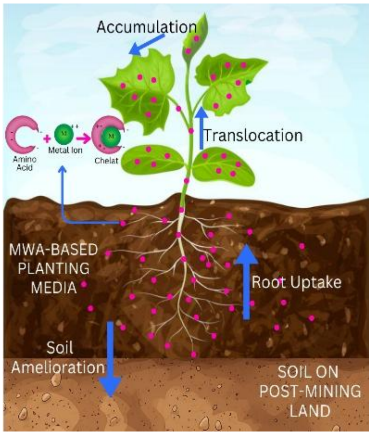

Figure 2. Conceptual Framework Illustrating the Multifunctional Role of MWA–POCI Systems as (i) Engineered Planting Media and Soil Ameliorants, and (ii) Facilitators of Phytoremediation Through Regulated PTM Uptake, Translocation, and Accumulation in Hyperaccumulator Cover Crops. The System Integrates Physicochemical Modification, Biological Activation, and Controlled Metal Dynamics.

As illustrated in Figure 2, the combination of MWA and POCI functions not merely as a planting medium, but as an integrated system in which soil amelioration processes and phytoremediation pathways operate simultaneously. Organic ligands and microbial metabolites derived from POCI regulate PTM behavior, enabling controlled plant uptake while maintaining environmental stability.

3.5. Economic and Sustainability Considerations of MWA Reuse

Within the framework of the waste management hierarchy and circular economy principles, the utilization of MWA as a secondary resource represents a strategic alternative to conventional disposal pathways (Awino and Apitz, 2024; Murillo *et al.*, 2025). As a processing residue, MWA offers a direct opportunity to reduce the overall volume of hazardous waste requiring final disposal, thereby lowering transportation demand and landfill-related costs (Darmawan *et al.*, 2022). In contrast, inadequate ash management practices—such as direct landfilling or uncontrolled dumping—are associated with elevated ecotoxicity, risks to groundwater quality, and additional indirect environmental burdens arising from remediation activities and extended transport chains (Bolan *et al.*, 2023; Ghazali *et al.*, 2022; Jaber *et al.*, 2021), posing significant risks to human health and the environment (Kadhem *et al.*, 2024; Salih, 2023).

From a financial perspective, the reuse of MWA as a component of planting media, particularly when combined with POCI, represents a practical strategy to mitigate these impacts by diverting a portion of hazardous residues away from final disposal. Such diversion translates into avoided landfill tipping fees, reduced transportation requirements, and a lower dependence on engineered hazardous waste repositories. The magnitude of disposal-related costs can be illustrated by evidence from large-scale urban waste management systems. In a megacity network model for Istanbul, Balci et al. (2022) estimated that annual landfill-related expenditures for medical waste incineration residues could reach approximately €62.45 million, equivalent to about IDR 1.03 trillion per year at current exchange rates. Although cost structures differ across countries, comparable economic pressures are evident in Indonesia, where hazardous medical waste disposal costs have been reported at approximately IDR 2.5 million per drum (Sitompul, 2021). While these figures are not directly comparable due to differences in regulatory frameworks, scale, and accounting methods, they collectively demonstrate that disposal constitutes a major economic burden.

Beyond direct economic savings, MWA–POCI reuse yields substantial avoided environmental and social externalities. Reduced transport demand lowers greenhouse gas emissions associated with fuel combustion and fleet operations, while also decreasing the probability of traffic accidents involving hazardous waste shipments. Minimizing the amount of MWA sent to landfills mitigates long-term environmental risks such as metal leaching, groundwater contamination, and the potential need for costly remediation measures (Ghazali *et al.*, 2022; Hong *et al.*, 2018; Jaber *et al.*, 2021; Kadhem *et al.*, 2024; Salih, 2023). These avoided impacts represent deferred future costs that are often excluded from conventional financial accounting but are critical from a sustainability and life-cycle perspective (Chen & Yu, 2023; Ding et al., 2025). Consequently, MWA reuse contributes to lowering hidden environmental liabilities and health-related risks borne by surrounding communities and public authorities.

In addition to cost avoidance, the MWA–POCI system creates positive economic value through functional substitution and ecosystem service provision. When incorporated into planting media, MWA partially replaces virgin materials such as lime or engineered soil conditioners, thereby conserving natural resources and reducing upstream extraction costs. Simultaneously, its application in non-food cropping systems and phytoremediation-oriented land management contributes indirect value through land rehabilitation, contaminant stabilization, and improved environmental quality. In this context, the reuse of MWA aligns with the core advantages of hazardous waste utilization as articulated by Ferreira et al. (2003), namely the use of low- or no-cost raw materials, conservation of natural resources, and reduction of waste requiring final disposal. Moreover, the use of POCI—produced from readily degradable organic waste—extends this value creation by diverting organic residues from landfills, thereby reinforcing circular resource flows across multiple waste streams.

Taken together, the economic performance of MWA reuse in combination with POCI should not be interpreted solely as a waste disposal cost-reduction strategy, but rather as an integrated value-generation pathway. By simultaneously delivering direct cost savings, avoided environmental externalities, and newly created functional value, the MWA–POCI system demonstrates how hazardous waste reuse can contribute to economic efficiency, environmental risk mitigation, and long-term sustainability objectives within a circular economy framework, aligning with the waste management hierarchy principles (Awino and Apitz, 2024; Murillo *et al.*, 2025).

4. CONCLUSION

This review synthesizes current knowledge on the potential utilization of MWA as a planting media component, with particular emphasis on its integration with POCI. The analysis demonstrates that MWA is characterized by alkaline properties and high CaO content, accompanied by variable concentrations of SiO_2 and macro-nutrient oxides (e.g., MgO, K_2O, P_2O_5, and SO_3), while also containing potentially toxic metals (PTMs) such as Zn, Pb, Cr, Cu, Ni, Cd, and Hg. These characteristics indicate that MWA exhibits both agronomic potential and environmental risk, necessitating careful management when considered for reuse.

The reviewed studies indicate that, when appropriately conditioned and combined with organic amendments such as POCI, MWA-based planting media can support plant establishment while moderating PTM mobility through physicochemical buffering, complexation, and biologically mediated processes. The complementary operation of phytoextraction and phytostabilization mechanisms provides a conceptual basis for using MWA–POCI systems in non-food cropping and phytoremediation-oriented applications. However, the variability in ash composition across countries, incinerator designs, and operating temperatures highlights that MWA reuse cannot be generalized and must be evaluated on a case-by-case basis.

From an economic and sustainability perspective, the reuse of MWA has the potential to reduce disposal-related costs, transportation demand, and landfill dependency, while avoiding environmental and social externalities associated with uncontrolled ash management. The reviewed evidence suggests that these benefits extend beyond direct cost savings and include avoided long-term liabilities related to groundwater contamination, remediation needs, and public health risks. Nevertheless, most existing economic assessments remain qualitative or context-specific, underscoring the need for more robust and comparable economic evaluations.

Despite its promising potential, the reuse of MWA as planting media remains constrained by several knowledge gaps. Experimental validation under controlled conditions is required to quantify nutrient availability, PTM bioavailability, and plant uptake dynamics in MWA–POCI systems. Comprehensive toxicity testing, including leaching behavior and ecotoxicological assessments, is necessary to ensure environmental safety. Furthermore, field-scale trials are needed to evaluate long-term performance, stability, and risk under realistic environmental conditions.

Overall, this review highlights that the integration of MWA with organic amendments such as POCI represents a technically plausible and potentially sustainable reuse pathway, provided that environmental risks are adequately managed. Future research should focus on experimental and field-based validation, standardized assessment protocols, and integrated environmental–economic evaluations to support evidence-based decision-making for the safe and responsible reuse of medical waste incinerator ash.

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