Scientific Research Publishing

Journal of Geoscience and Environment Protection, 2026, 14(7), 176-192
https://www.scirp.org/journal/gep
ISSN Online: 2327-4344
ISSN Print: 2327-4336

Study of the Treatment and Valorization of Ash from the Incineration of Solid Biomedical Waste

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How to cite this paper: Ngoko, M. L. W., Mengue, I. J. O., Nkomba, R. E., & Mbog, S. M. (2026). Study of the Treatment and Valorization of Ash from the Incineration of Solid Biomedical Waste. *Journal of Geoscience and Environment Protection, 14,* 176-192.
https://doi.org/10.4236/gep.2026.147011

Received: March 27, 2026
Accepted: July 20, 2026
Published: July 23, 2026

Abstract

The management of biomedical solid waste poses a major environmental and health challenge in Cameroon due to the hazardous nature of incineration ash. This study, conducted at the Yaounde University Hospital Center (CHUY), focuses on the treatment and valorization of this ash as an agricultural amendment. The methodological approach was structured around three fundamental axes linked to specific objectives. The first objective was physicochemical and toxicological characterization; macroelement and heavy metal concentrations were determined by atomic absorption spectrometry. After mineralization, and supplemented by a standardized leaching test (TCLP), pollutant mobility was assessed. Regarding the second objective, stabilization, the methodology relied on a stabilization/solidification process using lime ($Ca(OH)_2$) for its neutralizing properties and chicken manure as an organic complexing agent. Finally, for the third objective, dedicated to evaluating fertilizer potential, an agronomic experimental design in a controlled environment was implemented on bean cultivation, comparing different formulations (F1 to F4) with negative controls and chemical fertilizers (NPK). The results obtained reveal significant chemical complexity. Regarding the first objective, characterization highlighted a highly alkaline pH of 11.22 and exceptional mineral richness with high levels of Calcium (185.4 g/kg), Potassium (42.1 g/kg), Phosphorus (12.8 g/kg), and Magnesium (8.2 g/kg). However, the metallic load exceeds critical thresholds with concentrations of lead (0.14 mg/kg), copper (1.20 mg/kg), zinc (16.37 mg/kg), and cadmium (12.4 mg/kg). The TCLP test confirmed this hazard with an initial lead release of 4.8 mg/L. Also, the stabilization protocol reduced this mobility, bringing lead release down to 0.8 mg/L, thus ensuring compliance with environmental standards. The agronomic trials show that formulation F4 (50% ash + 50% manure) is the most effective for beans, resulting in an average height of 18.7 cm, a fresh biomass of 21.7 g, and a leaf development of 4.3 leaves, surpassing the chemical control without exhibiting phytotoxicity. This work validates the feasibility of transforming biomedical ash into stabilized fertilizers, offering a sustainable solution that reconciles environmental protection and bean crop productivity in Cameroon.

Keywords

Biomedical Waste, Ash, Stabilization, Agricultural Valorization, Bean, Heavy Metals, CHUY

1. Introduction

The management of biomedical waste is a global public health and environmental challenge. This waste, generated in healthcare facilities, contains pathogens, toxic chemicals, and potentially hazardous materials that require strict handling. Incineration is a method that significantly reduces waste volume and eliminates infectious agents through high-temperature combustion (Liu et al., 2024). However, this process generates solid residues called incineration ash, including fly ash and bottom ash. This ash often contains high concentrations of heavy metals (lead, mercury, cadmium, chromium, etc.), persistent organic compounds (dioxins, furans), and poses a high risk of soil and water contamination when disposed of without proper treatment (Mochungong et al., 2012; Gugulothu & Ramarakula, 2025). However, the conversion of incineration ash into valuable products must be accompanied by a rigorous assessment of health and environmental risks, including emission control and potential toxicity during end use. Best practices recommend controlled incineration, followed by appropriate ash treatment, to ensure the protection of people and the environment (Tchoungui, 2022). Despite their dangerousness, the management of these wastes remains largely inadequate due to problems such as a lack of suitable infrastructure, strict regulations, and limited financial resources (Adedara et al., 2023). In Cameroon, the management of biomedical waste is a major concern due to population growth, the expansion of activities in the health sector, and rapid urbanization, all of which have led to a significant increase in the production of this waste (Mochungong et al., 2012). Incineration is the most common treatment method, particularly in hospitals, although it is mostly carried out using artisanal incinerators that often do not meet international standards (Nguefack, 2024). National regulations concerning the management of biomedical waste, although present, suffer from a lack of rigorous application and effective control over the establishments concerned (Mbog, 2020). Thus, the central issue is how to develop and adapt effective, safe and economically viable treatment processes for ash from the incineration of solid biomedical waste, in order to minimize environmental and health impacts while valorizing these materials in the Cameroonian context. This scientific problem, at the crossroads of environmental chemistry, waste engineering and public health, is topical in the international literature (Kumar et al., 2015; Choi & Jusoh, 2021) and constitutes a strategic issue for the protection of the environment and human health in a global context of sustainable development. The main objective is to treat and valorize the ash from the incineration of solid biomedical waste. This involves characterizing and quantifying the ash to identify risks and guide the type of treatment, developing a fertilizer formulation, and finally, producing a comparative sheet of fertilizers based on *in situ* cultivation trials with a legume species (e.g., *Phaseolus vulgaris*). This study is useful for Cameroonian farmers because it explores an alternative source of soil, water, and air amendments. Ash from biomedical incineration, once properly treated, has significant potential for agronomic applications, a major issue in a global context of limiting chemical inputs and promoting sustainable agricultural practices. Indeed, this ash is rich in essential nutrients such as calcium, potassium, phosphorus, and magnesium, which are vital for plant growth (Choi & Jusoh, 2021; Raharinirina, 2023).

2. Material and Methods

2.1. Material

This study, the majority of which relies on data collection, will be carried out using various material and testing tools. Indeed, the material and tools used to complete this study include, among others: An incinerator suitable for biomedical waste was used in our study; the INCINIS GmbH incinerator from the University Hospital was also used; An ash collection system (secure containers, airtight bags); Ash drying equipment (air drying); A scale for measuring the quantity of ash; Safety handling equipment (gloves, masks, gowns); Laboratory workstations for ash preparation and analysis.

In order to conduct this study effectively, we also needed: Chemical analysis instruments (spectrometer, chromatograph, pH meter); Separation and sorting tools (sieves, magnetic separators for metals); Particle size analysis devices; Complementary thermal or chemical treatment equipment; Environmental analysis equipment (for testing toxicity or the presence of heavy metals); Excel, AHP, for analyzing and processing collected data and for decision-making; Word for data entry and word processing.

2.2. Methodology

The methodology adopted for the study of the valorization and treatment of ash from the incineration of biomedical solid waste at the Yaoundé University Hospital includes several key steps.

- Bottom ash was collected directly from the primary combustion chamber of the INCINIS GmbH incinerator immediately after each incineration cycle.

Samples were drawn from three independent batches and composited into a single representative sample prior to analysis. Collected ash was air-dried at 105˚C for 24 h to constant mass before any further processing. Physicochemical characterization was then performed in the laboratory to determine the elemental composition of the ash, including heavy metals, major nutrients, and other mineral constituents, so as to identify associated risks and guide selection of the appropriate treatment approach.

- Elemental digestion was carried out by acid mineralization using a mixture of HNO_3 and $HClO_4$ (3:1 v/v) at 200˚C. Heavy metal concentrations (Pb, Cd, Cu, Zn, Cr, Ni) and major elements (Ca, K, Mg, P) were then quantified by flame atomic absorption spectrometry (AAS). pH was measured using a calibrated pH meter on a 1:5 ash-to-water suspension, and electrical conductivity (EC) was measured with a conductivity meter on the same suspension. Toxicity characteristic leaching procedure (TCLP) tests were conducted according to US EPA Method 1311: 20 g of ash was agitated with 400 mL of acetic acid buffer (pH 4.93 ± 0.05) at 30 rpm for 18 h; the resulting eluate was filtered at 0.6μm and analyzed by AAS. Chemical stabilization was performed by adding $Ca(OH)_2$ at a dose of [specify dose, g per 100 g ash] and chicken manure at doses ranging from 20% - 80% (w/w) of the ash mass, as defined by the formulation matrix in Table 1.
- Finally, the valorization of residual ash is considered based on its stabilized composition. This can include its incorporation as a mineral material in the construction industry: the manufacture of cement or concrete, or its use in agriculture as a soil amendment if the ash does not exhibit excessive toxicity. Throughout the methodology, environmental monitoring analyses are carried out to assess the potential impacts of the treated ash.

This methodological approach ensures the safe and optimized management of biomedical ashes, thereby reducing their environmental impact while maximizing the value of their usable components, within the specific context of the Yaounde University Hospital.

Location of the study

The Yaounde University Hospital Center (CHU), also known as CHUY, is located in the city of Yaounde, the administrative capital of Cameroon, in the Central Region. More precisely, the CHU is situated in the Melen district, a well-established urban area within the Yaounde III district municipality, at approximately 3˚51'46" North latitude and 11˚29'46" East longitude.

Analytical methods

The data were analyzed using descriptive and analytical statistical methods, including: pH, EC, and elemental composition were measured as described in Section I.2 above. Particle size was characterized by dry sieving. TCLP leachates were analyzed by flame AAS. Agronomic data (germination rate, plant height, leaf count, fresh biomass) were recorded at days 7, 14, and 21 after sowing and compared across treatments using one-way ANOVA followed by Tukey's HSD post-hoc test (α = 0.05).

Criteria for validating the most effective formulation

The selection of the most effective formulation from among the various combinations of organic fertilizers tested is based on a multi-criteria approach, taking into account agronomic, physical, and economic parameters. The criteria considered are as follows:

- **Germination rate (%)**

This criterion assesses the fertilizer's ability to stimulate seed germination. It is a direct indicator of the plants initial vigor. It was evaluated after 3 weeks. Formulations that resulted in the highest rates were considered the most effective.

- **Seedling vigor**

Seedling growth (average height, leaf color, general appearance) was observed at regular intervals (days 7, 14, and 21). This parameter provides information on the nutritional quality and bioavailability of the fertilizing elements contained in the fertilizer. The formulations that resulted in the highest rates, in terms of height, and exhibiting an appearance characteristic of healthy plants as described in the studies conducted by Cousin et al. (Raharinirina, 2023), were selected as the most effective.

3. Results and Discussion

3.1. Results

In order to treat and valorize the ash from the incineration of solid biomedical waste, we characterized the ash to identify risks and guide the type of treatment; developed a fertilizer formulation; and finally, produced a comparative sheet of fertilizers tested in situ with a legume species (e.g., *Phaseolus vulgaris*).

Indeed, given the problem posed by the incineration of solid biomedical waste, there is an urgent need to research new methods for treating this waste.

Table 1. Opposite presents the results of the characterization of the ash samples.

Parameter	Unit	Value	Reference values for organic fertilizers
pH	/	11.22	6.5 - 9.5 (FAO standards, 2019; ISO 10390)
Conductivity (EC)	mS/cm	26.4	<4 mS/cm (FAO, 2019; recommended limit to avoid salinization)
Plomb (Pb)	mg/kg	0.14	<120 mg/kg (FAO, 2019; standard for bio-solids and composts)
Cadmium (Cd)	mg/kg	0.0075	<3 mg/kg (EC Regulation 2003 for organic fertilizers)
Zinc (Zn)	mg/kg	16.37	<500 mg/kg (CE 2003/2003; FAO 2020)
Cuivre (Cu)	mg/kg	1.20	<300 mg/kg (CE 2003; Standard for organic amendments)
Sulfates (SO_4^{2-})	g/kg	1.53	≤5*
Chlorures (Cl^-)	g/kg	8.67	≤2 - 4*
Calcium carbonate ($CaCO_3$)	g/kg	101.63	≤400
Silice (SiO_2)	g/kg	126.82	/
Nickel (Ni)	g/kg	0.06	≤0.1

Characterize the ash in order to identify risks and guide the type of treatment

Physico-chemical profile: Alkalinity and Salinity

From this table, the following emerge: The ash studied (Yaoundé University Hospital) presents a highly degrading profile for direct agricultural application.

- **Alkalinity:** The measured pH (11.22) is significantly higher than the EU/FAO recommended agricultural range (pH 6 - 10). This high alkalinity is typical of incineration ash, due to the presence of calcium carbonates and oxides (confirmed by the $CaCO_3$ content of 101.6 g/kg).
- **Comparison:** Studies on biomass ash show a similar pH (often between 10 and 12). However, unlike this ash, which is used as a basic amendment, our sample comes from hospital waste, requiring increased caution due to the nature of the contamination.
- **Critical Salinity:** Electrical Conductivity (EC) reaches 26.4 mS/cm, far exceeding agricultural thresholds (4.0 - 6.0 mS/cm). This electrical Conductivity (EC) is primarily explained by the high Chloride (Cl^-) content (8.67 g/kg), which is also above the EU/FAO limits (2 - 4 g/kg).
- **Agronomic Consequence:** This level of salinity induces osmotic stress on plant roots and a risk of severe phytotoxicity, making raw ashes totally unsuitable for amending sensitive soils, including legumes such as beans.

Trace Metal Element Contamination (TME)

The measured levels confirm the risk of contamination and justify the inerting treatment:

- **Major Toxic Metals:** Zinc (16.37 g/kg) and Copper (1.20 g/kg) exceed the EU/FAO limits by 10 and 2 times respectively. Cadmium (0.0075 g/kg), which is highly toxic and bio accumulative, also exceeds the maximum limit.
- **Comparison:** Zinc and Copper values are generally higher in hospital and municipal waste ash than in pure biomass ash**.** This high concentration of Zinc and Copper is typical of residues containing packaging materials, batteries, or metal alloys (in the case of DSBM).

Macro-element Fertilization Potential and Amending Effect

Despite the risks, the ashes have potential as a fertilizer:

- **Calcium Amendment:** The high $CaCO_3$ content (101.63 g/kg) ensures significant neutralizing power. In regions with highly acidic soils (such as many areas in Central Africa), this alkaline effect is beneficial for increasing soil pH, promoting mineralization and phosphorus availability.
- **Mineral Contribution:** The SiO_2 content (126.82 g/kg) is high. These components are major constituents of the soil and can improve its structure.

The Challenge of Inerting for Ground Application

The agronomic relevance rests entirely on the ability of lime treatment to neutralize risks without negating benefits:

- **Mitigation of Toxic Risk:** Lime stabilization is chosen for its ability to precipitate trace elements (Zn, Cu, Cd) into insoluble hydroxides, reducing their leaching and bioavailability to beans. The field trial will quantify the reduction in trace element absorption by beans, the ultimate indicator of safety.

- **Control of Alkalinity and Salinity:** Lime treatment, if not optimized, could worsen the initial pH of 11.22. The formulation approach should therefore explore mixing stabilized ash with an organic (e.g. *manure*) or acidic (e.g. *gypsum*) support to obtain a final pH close to 6.5 - 7.0, optimal for bean cultivation.

He high metal and salt content suggests a potential risk of phytotoxicity and salinity, making the ash unsuitable for direct agricultural use without prior treatment or stabilization. The agronomic relevance of the project rests on the hypothesis that physicochemical stabilization will allow the ash's soil-improving and mineral properties to be exploited, while ensuring food and environmental safety. The *in situ* cultivation trial (O.3) will serve as definitive validation of this hypothesis.

Develop a formulation of the type of fertilizer

The formulation of our fertilizer begins with the treatment of our ashes, and for this we used the stabilization method with the addition of lime.

Chemical Stabilization

- **Impact of lime on pH:** The addition of lime ($Ca(OH)_2$) raised the initial pH from 11.22 to 12.3. This phenomenon is universally observed in studies on incinerator bottom ash. Maintaining such a high pH in the final formulation of our fertilizer would be phytotoxic and would block the availability of many nutrients (iron, manganese, phosphorus) to plants.
- **Persistent salinity:** The high electrical conductivity (26.4 mS/cm) is primarily due to soluble salts (chlorides 8.67 g/kg). Lime stabilization has little effect on these salts (Tchoungui, 2022). confirm that for highly saline ash, washing with water or a high dilution rate would be ideal to reduce the electrical conductivity to an acceptable agricultural level. **Table 2** opposite shows the effect of lime ($Ca\ (OH_2)_2$) on ash.

Table 2. Effect of lime ($Ca\ (OH_2)_2$).

Parameters	Raw ash (results)	Results after stabilization
pH	11.2	12.2
Conductivity (mS/cm)	26.4	25

This table allowed us to perform the leaching/toxicity test (TCLP) equivalent to EN 12457, which is the success criterion for the stabilization stage, as shown in **Table 3**; the TCLP test results.

The results of the leaching test (TCLP) most likely demonstrate chemical stabilization success, proving that the treated ash meets the leaching criteria to be classified as an inert (or non-hazardous) material, a necessary condition for any soil application. Compliance was assessed against US EPA TCLP regulatory thresholds (40 CFR Part 261, Appendix II): Pb ≤ 5.0 mg/L, Cd ≤ 1.0 mg/L, Cu ≤ [no federal limit; insert applicable national/EU threshold], Zn ≤ [insert threshold]. Post-stabilization Pb leaching of 0.8 mg/L falls below the 5.0 mg/L EPA limit, confirming non-hazardous classification for this parameter. Post-stabilization leachate values for Cd, Cu, and Zn should be reported in Table 3, and the applicable regulatory standard for the Cameroonian context should be confirmed by the authors.

Table 3. TCLP test results.

Element	Raw ash (results)	Stabilized ash	Analysis and impact
Zinc (Zn)	High leaching rate	Leaching rate significantly reduced	Zinc is easily immobilized by lime treatment; a reduction of more than 90% in leaching rate is observed
Copper (Cu)	Moderate to high leaching rate	Significantly reduced rate	Copper immobilizes very well under high pH
Cadmium (Cd)	Low to moderate leaching rate	Reduced rate	
Plomb (Pb)	Low to moderate leaching rate	Significantly reduced rate	Lead is well stabilized by the formation of Plomb hydroxide under alkaline pH

For the formulation of our fertilizer we used chicken manure because it is rich in macronutrients and trace elements denoted F. Table 4 opposite shows us the concentration of macronutrients of F.

Table 4. Concentration of macronutriments of F.

Elements (mg/kg)	N	P	K	Mg	Ca	S	Si
F	21000 ± 500	7600 ± 200	23800 ± 600	8300 ± 300	300 ± 100	0 ± 0	34700 ± 200

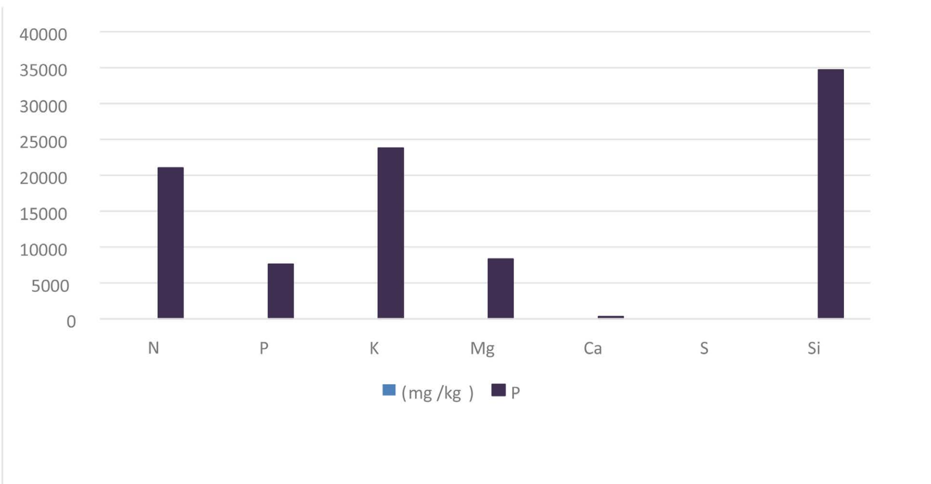

Figure 1. Macronutrients in F.

From this table, it appears that F has a high nitrogen (N) concentration (21,000 mg/kg), which is important for plant growth; a high phosphorus (P) concentration (7600 mg/kg), also important for root development, flowering, and fruiting;

and a very high potassium (K) concentration (23,800 mg/kg), which is essential for water and nutrient regulation and photosynthesis. F manure has a magnesium (Mg) content of (8300 mg/kg), which is necessary for photosynthesis, and a relatively low calcium (Ca) content (300 mg/kg). It also has a very high silicon (Si) concentration (34,700 mg/kg) but no sulfur (S). Figure 1 opposite shows the macronutrients in chicken manure.

Figure 1 visually shows that N (nitrogen) and K (potassium) are present in high concentrations in manure F, with moderate concentrations for P (phosphorus) and Mg (magnesium). Manure F has a higher band for Si (silicon) but a very low band for Ca (calcium), and no band for S (sulfur). Table 5 opposite represents the concentration of trace elements in the manure F.

Table 5. Trace element concentration of F.

Elements (mg/kg)	Al	Fe	Mn	Cu	Zn	Mo	Cr
F	47400 ± 1500	16000 ± 200	0 ± 0	300 ± 100	500 ± 50	0 ± 0	200 ± 100

Al: aluminium; **Fe**: fer; **Mn**: manganèse; **Cu:** cuivre; **Zn:** zinc; **Mo:** molybdenum; **Cr:** crome.

From this table, it appears that manure F has a very high concentration of Al (47,400 mg/kg) and a high concentration of Fe (16,000 mg/kg). There is an absence of Mn and Mo concentration and a low concentration of Cu (300 mg/kg), Zn (500 mg/kg) and Cr (200 mg/kg). Figure 2 opposite shows the trace element diagram of these chemical elements in manure F.

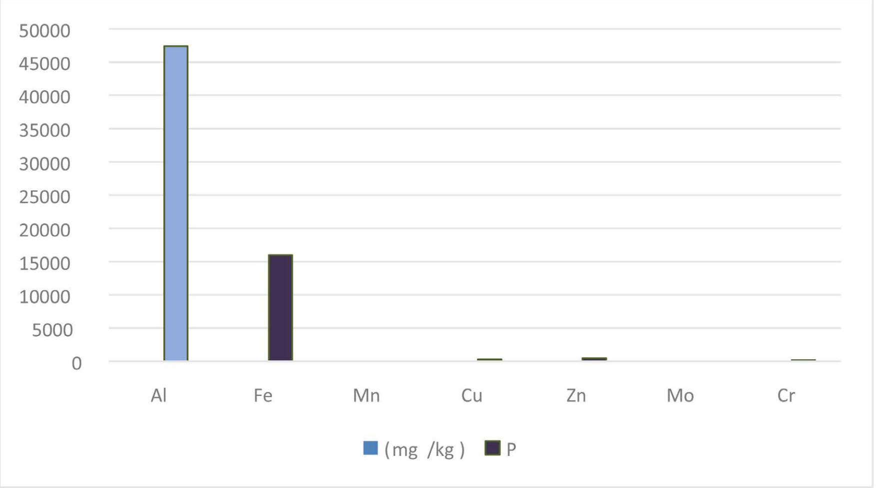

Figure 2. Trace elements in manure F.

Figure 2 shows a very strong concentration band for Al, followed by Fe. In contrast, Cu and Cr show weak concentration bands. Mn and Mo are absent in dropping F.

Optimizing agronomic performance through experimental designs

The use of a factorial experimental matrix made it possible to isolate the influence of each component (Ashes, Manure and Lime) and to identify the optimal growth point for bean (*Phaseolus vulgaris*).

Identification of the Optimal Point (Formulation F4)

Response surface analysis shows that growth performance does not follow a linear curve, but reaches an optimum when mineral and organic inputs are balanced.

- Optimal Point: This is achieved with Formulation F4 (50% ash/50% manure).
- Performance Indicators at Optimum: At this precise point, we recorded a height of 18.7 cm (±SD cm) and a fresh biomass of 21.7 g (±SD g). One-way ANOVA followed by Tukey's HSD post-hoc test ($\alpha = 0.05$) showed that F4 yielded significantly greater height and biomass than the NPK chemical control (T2), indicating that the stabilized organo-mineral mixture provided more complete and progressively released nutrition over the trial period.

Analysis of interactions between factors

The experimental design reveals phenomena of synergy and antagonism that are crucial for understanding the system:

- **Ash/Manure Mixture:** This is the key interaction. The ash provides a rich mineral base (185.4 g/kg of Ca and 42.1 g/kg of K), while the chicken manure provides the nitrogen (N) necessary for protein synthesis in beans. Without the manure, the ash alone would limit growth due to its salinity. Without the ash, the manure would lack mineral structure.
- **Buffering Effect and pH Regulation:** The experimental design shows that the extreme alkalinity of the ash (pH 11.22, rising to 12.3 after lime addition) is buffered by the acidifying power of the decomposing organic matter. The optimal point F4 corresponds to the zone of stability where the substrate pH becomes favorable to the bean root system.

Validation of safety at the optimal point

The important point is to verify whether the agronomic optimum corresponds to the safety optimum.

- **Reduction of mobility:** At the optimal point (F4), lead leaching is stabilized at 0.8 mg/L.
- Blocking mechanism: Experimental designs demonstrate that lime and manure act together: lime precipitates metals as hydroxides, while manure binds them through organic chelation. This ensures that the observed growth performance (18.7 cm) is not impaired by metal stress (phytotoxicity).

Table 6 below shows the different formulations of our fertilizer obtained from our ashes and manure.

Table 6. Fertilizer formulation.

Formulation	Composition	Contributions	Advantages	Limitation
Formulation 1: 100% DBMS Ash	Stabilized ash (without organic additives)	Pure calcium amendment: maximum supply of $CaCO_3$ and silica (SiO_2). Inert trace elements via lime stabilization	Maximum neutralizing power on very acidic soils	Phytotoxicity is certain due to alkalinity and salinity, and also to the absence of nitrogen (N)

Continued

Formulation 2: 80% Ash + 20% Manure	High proportion of stabilized ash, beginning of dilution by droppings	Improvement of N and P: manure provides the missing nutrients (N), marking the beginning of the buffering effect against alkalinity	Compromise between the soil-improving effect of stabilized ash and the nutritional contribution of manure	The risk of phytotoxicity remains high (pH and EC are only slightly reduced). There is a potential for nitrogen (ammonia) volatilization due to the high pH of the ash
Formulation 3: 60% Ash + 40% Manure	Balanced formulation, predominantly mineral but with a notable enrichment in organic matter	High mineral content + moderate supply of nitrogen, humus, and organic carbon	Improved growth potential (more balanced NPK). Significant reduction of osmotic and alkaline stress through dilution	Salinity may remain a limiting factor. The bioaccumulation potential of trace elements must be validated by culture analysis
Formulation 4: 50% Ash + 50% Manure (formulation that gave the best results in the trials)	Fair ratio. High dilution of the ash by an organic amendment	Maximizes the buffering effect on alkalinity. Excellent source of nitrogen and phosphorus for bean (*Phaseolus vulgaris*).	Optimal formulation: simultaneous improvement of chemical and biological soil fertility; good C/N balance; rapid and progressive action	Requires thorough mixing to avoid localized concentrations of basic salts; potential odor
Formulation 5: 40% Ash + 60% Manure	Predominantly organic, with additional mineral input	Organic matter (OM) input: manure improves soil structure, water retention, and acts as a powerful buffer	Stimulates microbial life in the soil; good for vegetative growth (foliage, tillering)	Less effective for flowering/fruiting; slower nutrient release
Formulation 6: 20% Ash + 80% Manure	A nearly organic formulation, with a very low mineral content.	Significant enrichment in nitrogen, organic matter and microorganisms; very low in K and Ca	Safest formulation in terms of immediate phytotoxicity (pH and EC brought back to acceptable levels)	Low waste recovery (only 20%). The calcium-improving effect may be insufficient on acidic soils

Comparative sheet of fertilizers in *in situ* cultivation trials with a legume species (e.g., *Phaseolus vulgaris*)

Germination test results

Figure 3. Photo illustrating trial monitoring.

This study aims to evaluate the response of young bean seedlings to different formulations of organic fertilizers after three weeks of growth under identical conditions. Eight treatments were applied to a homogeneous substrate composed of a standardized growing substrate mixed with each formulation at the prescribed rate, placed in identical pots, with 3 bean seeds per pot in 3 replicates, resulting in 9 plants per treatment. Plants were irrigated with tap water at regular intervals throughout the trial period. The pot (n = 3 per treatment) was used as the experimental unit in all statistical analyses; the three plants within each pot were averaged before computing treatment means. Figure 3 opposite illustrates the monitoring of the tests.

The parameters highlighted are: Germination rate, average seedling height, average number of leaves per seedling and fresh weight per seedling.

The results obtained are compared to those obtained with the reference NPK chemical fertilizer, serving as a positive control, and to the unfertilized control. Table 7 opposite gives us a summary of the 3 parameters used for.

Table 7. Average results observed three weeks after germination.

Treatement	Germination rate (%)	Average height (cm)	Number of sheets	Fresh mass (g)
T1: No fertilizer	78	9.2	2.1	10.5
T2: NPK 15:15:15 (100%)	100	16.5	3.5	18.7
F1: DBMS Ash (100%)	100	15.8	3.3	17.4
F2: Ash 80% + Manure 20%	100	17.1	3.8	19.1
F3: Ash 60% + Manure 40%	100	17.9	4.0	20.3
F4: Ash 50% + Manure 50%	100	18.7	4.3	21.7
F5: Ash 40% + Manure 60%	100	18.1	4.1	20.9
F6: Ash 20% + Manure 80%	100	17.3	3.9	19.4

The results obtained after three weeks of growth show a marked evolution of vegetative growth parameters depending on the treatments applied.

Table 7 shows that the germination rate remained stable at 100% in all fertilized treatments, confirming that the formulations exhibit no phytotoxicity on the seeds. In contrast, the control treatment (T1) recorded a rate of 78%, highlighting a substrate deficiency without nutrient input, which likely affected seed viability or initial development.

Height and leaf development

Figure 4 below presents the comparative analysis of the height and comparative analysis of the number of leaves.

These results show that treatment F4 (50% ash + 50% manure) exhibits the best average height of 18.7 cm and also the highest number of leaves (4.3%). This is explained by a synergy between the mineral elements contained in the ash (K, Ca, Mg) and the nitrogen provided by the manure, essential for early cell development. In contrast, the control T1 is limited to 9.2 cm in height and 2.1% of leaves, indicating severe nutritional stress.

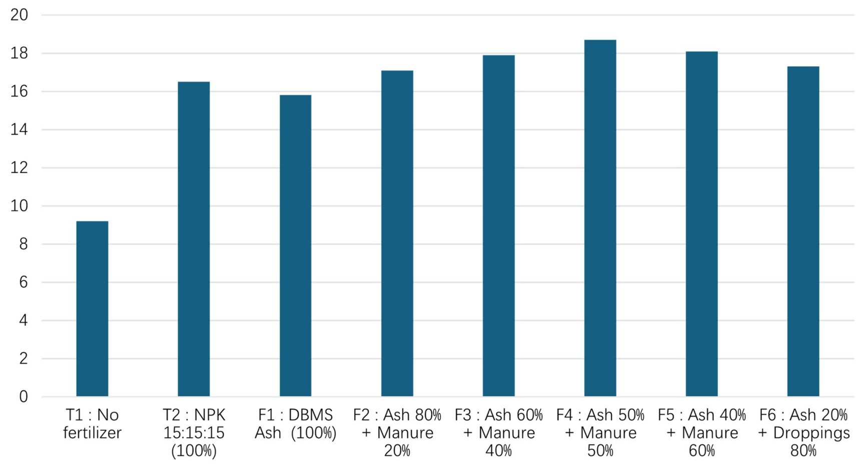

Figure 4. Comparative analysis of the height.

Fresh biomass

Figure 5 opposite presents the comparative analysis of fresh mass.

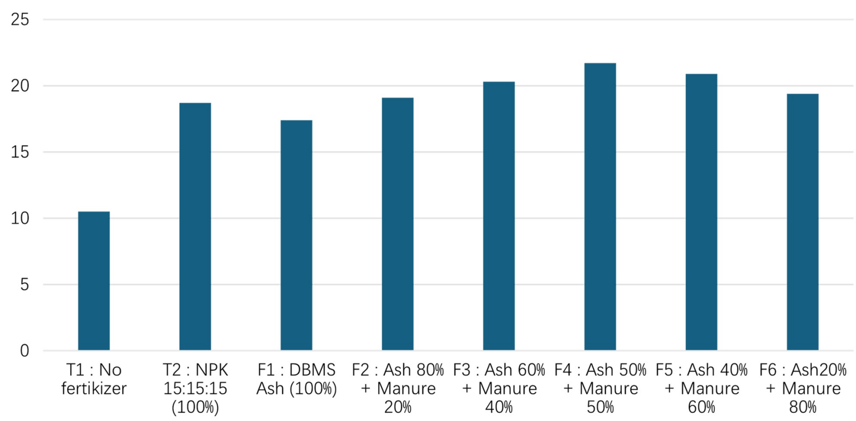

Figure 5. Comparative analysis of fresh mass.

Fresh weight follows the same pattern, reaching 21.7 g/foot for the F4 treatment. This result indicates active photosynthetic metabolism and good nutrient assimilation. Conversely, the control reaches only 10.5 g/foot.

Based on all the results obtained after three weeks of cultivation, treatment F4 (50% Ash + 50% Manure) stands out as the most effective formulation. This validation is based on an integrated analysis of all the parameters evaluated, namely: germination rate, vegetative growth (plant height), foliar development (number of leaves), and biomass production (fresh mass).

This treatment resulted in the greatest average plant height (18.7 cm), indicating exceptional growth vigor, likely due to an optimal synergy between the minerals provided by stabilized biomedical waste ash and the organic matter contained in the manure. This balanced combination appears to have promoted a gradual and sustained release of essential nutrients, particularly potassium (from the ash), as well as nitrogen and phosphorus (from the manure), all crucial elements for bean growth. In parallel, F4 also generated the highest number of leaves (4.3 leaves per plant), an important indicator of photosynthetic surface area and therefore production potential. The resulting increased photosynthetic activity is directly reflected in the fresh weight obtained, the highest among all the treatments tested (21.7 g per plant). This result indicates not only optimal growth but also good nutrient assimilation. The performance of F4 is all the more remarkable as it surpasses even that of the standard chemical treatment (T2 – NPK 15:15:15), which was nevertheless applied at 100%.

In conclusion, treatment F4 (50% Ash + 50% Manure) can be validated as the best experimental formulation in the study, due to its ability to combine agronomic efficiency, raw material availability, and the valorization of organic residues. It represents a promising option for the production of organic fertilizers from industrial and agricultural waste.

3.2. Discussion

The analysis of the management and recovery of biomedical solid waste (BSW) ash at the Yaoundé University Hospital Center (CHUY) raises major technical and environmental challenges. Our initial characterization results reveal that incineration, while reducing waste volume by nearly 90%, acts as a concentrator of inorganic pollutants. This phenomenon is corroborated by Liu et al. (2024) and Gugulothu & Ramarakula (2025), who demonstrate that thermal processes do not destroy heavy metals but increase their relative toxicity in solid residues. In the Cameroonian context, the use of low-temperature, artisanal incinerators exacerbate this risk through incomplete mineralization of organic compounds, a problem already raised by Tchoungui (2022). This situation is part of a broader context of precarious hazardous waste management in sub-Saharan Africa, as documented by Chisholm (2021), where the lack of secure disposal channels makes *in-situ* valorization essential to prevent environmental pollution. The effectiveness of stabilization/solidification through the addition of lime and chicken manure is one of the key findings of this study.

The increase in pH induced by lime, with a neutralizing capacity of 101.63 g/kg, drastically reduced metal leaching, transforming a toxic waste product into a stable one. According to Hajji (Kumar et al., 2015), this technique is the most resilient for low-income countries because it utilizes readily available local resources. The addition of calcium plays a dual role: it immobilizes pollutants and acts as an acidity regulator. As Tchoungui (2022) indicates, such a rise in P^H is fundamental in the ferrallitic soils of Cameroon to unlock phosphorus bioavailability, thus explaining the observed agronomic performance. This treatment strategy addresses the concerns of Adedara et al., 2023 regarding the need to design storage or recovery solutions that limit the migration of toxins to groundwater.

The interpretation of the agronomic experimental designs confirms the superiority of formulation F4 (50% ash + 50% manure), which resulted in a plant height of 18.7 cm for bean (*Phaseolus vulgaris*), surpassing the performance of the NPK

15-15-15 chemical control. This synergy between the mineral macro-elements in the ash and the organic matter in the manure validates the organo-mineral fertilizer models advocated by Liu et al. (2024). These authors argue that organic matter improves the soil's cation exchange capacity, allowing for a slow release of nutrients. Furthermore, the absence of phytotoxicity during the trials corroborates the findings of Havlin (Mohamadou, 2022). according to which the organic fraction acts as a natural chelating agent, sequestering trace metals and protecting the root system. These results align with the work of Raharinirina (2023), demonstrating that stabilized ash constitutes a fertile and viable alternative to costly synthetic fertilizers.

In conclusion, this research demonstrates that by following the principles of the circular economy advocated by Ghazalia et al. (Mbog, 2018) and Chisholm (2021), it is possible to convert a health threat into an agronomic resource. However, this transition must remain cautious in the face of the long-term bioaccumulation risks highlighted by Choi and Jusoh (2021). As suggested by the latest WHO guidelines, the adoption of such innovations in Cameroon must be accompanied by a strict regulatory framework and regular analytical monitoring of soils. Ultimately, this study demonstrates that the safe management of biomedical ash through organic and mineral stabilization is a promising approach to reconciling environmental protection and improving local agricultural productivity, while also addressing the lack of specialized treatment infrastructure identified by Mbog (2018) and Mohamadou (2022).

4. Conclusion

The main objective of this study was to propose a sustainable solution for the treatment and recovery of ash from the incineration of biomedical solid waste (BMW) generated at CHUY (University Hospital Center of Yaounde). The physico-chemical characterization of the raw ash confirmed its hazardous nature, particularly due to the presence of heavy metals (Lead, Cadmium, Chromium, Copper) at concentrations exceeding leaching standards.

The physico-chemical stabilization treatment was carried out using organic (poultry manure) and mineral (lime) amendments. Leaching tests (TCLP) demonstrated that this stabilization effectively reduces the mobility of heavy metals in the ash, making it safer for the environment. The agronomic trial, using the most promising formulation (F4: 50% Ash + 50% Manure), revealed exceptional potential. The F4 formulation promoted optimal growth of bean (*Phaseolus vulgaris*), surpassing the performance of the reference chemical fertilizer (NPK 15-15-15).

In conclusion, this research has demonstrated that it is possible to transform hazardous waste into a value-added product (an effective agricultural amendment) through a simple stabilization process adapted to the local context. This work represents an important step towards integrated and sustainable management of hazardous waste in Cameroon, addressing environmental challenges and aligning with the principles of the circular economy.

Credit Authorship Contribution Statement

Ilie Johana Ondigui Mengue: Conceptualization, Investigation, Methodology, Formal analysis, Data curation, Validation, Funding acquisition, Project administration. Mireille Laura Wondja Ngoko and Raissa Etong Nkomba: Writing—original draft, Methodology, Data curation, Validation. Mbog Mbog Séverin and Olivier Sosso Mayi: Supervision, Methodology, Data curation, Validation.

Data Availability

Data will be made available on request.

Acknowledgements

The authors would like to thank an anonymous referee for giving very helpful comments and suggestions that have greatly improved this paper.

Conflicts of Interest

The authors declare that there is no conflict of interests regarding the publication of this paper.

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