Biocatalysis and Agricultural Biotechnology 62 (2024) 103456

Contents lists available at ScienceDirect

Biocatalysis and Agricultural Biotechnology

journal homepage: www.elsevier.com/locate/bab

Characterizations of ash derived from the crops' waste biomass for soil improvement and assisted phytoremediation

Abdulmannan Rouhani [a,*], Valentina Pidlisnyuk [b], Karim Suhail Al Souki [b]

[a] Department of Environment, Faculty of Environment, Jan Evangelista Purkyně University in Ústí nad Labem, Pasteurova 15, CZ-400 96, Czech Republic

[b] Department of Environmental Chemistry and Technology, Faculty of Environment, Jan Evangelista Purkyně University in Ústí nad Labem, Pasteurova 15, CZ-400 96, Czech Republic

A R T I C L E I N F O

Keywords:
Herbaceous plant
Agricultural crop
Biomass ash
Circular economy
Soil amendment

A B S T R A C T

The biomass ash can play a crucial role in agriculture by acting as a valuable fertilizer that fosters nutrient cycles and contributes to the conservation of nutrient's resources. The paper begins by discussion of the chemical properties of ashes derived from the herbaceous and agricultural crops. It then evaluates the effect of biomass ash on the soil properties and plant growth in the field and greenhouse conditions. Finally, the paper evaluates the impact of ash to phytoremediation practices, when nutrients presented in biomass ash were returned to the natural cycles to secure sustainable biomass utilization. Beside nutrients, some potentially toxic elements were presented in biomass ash which can threaten the environment. Rice husk ash followed by bagasse and wheat straw ashes were the most studied materials which showed positive effects on agricultural soil and crops. Furthermore, a positive impact of rice husk ash on the phytoremediation efficiency of *Ricinus communis* and *Vetiver Grass* were reported. The results of the current studies show a great potential of biomass ash when applying for the agricultural and environmental remediation actions thorough the careful assessment which ensures the circularity in the revitalization.

1. Introduction

The European Commission introduced a circular economy as a novel approach for preserving the biosphere and natural resources while increasing the recycling of waste. In pursuit of this objective, the European Union is actively striving to shift from a linear to a circular economic model, wherein already existing resources, including organic matter and nutrients found in 'waste' materials, are efficiently recycled (Mosoarca et al., 2020; Pomoni et al., 2024). Some activities within the initiatives include revising fertilizer regulations and establishing the End of Waste Plan (European Commission, 2011, 2016). In this regards utilization of ash is become important in research and outreach (Thind et al., 2012; Saletnik et al., 2018; Singh et al., 2019), giving a perspective for circularity. The properties of biomass ash as affected by feedstock varieties and conditions of thermal conversion were reviewed in earlier studies, suggesting potential biomass utilization and reusing options (Obernberger et al., 2006; Vassilev et al., 2014). The utilization of ash will enhance the value of a material that is currently considered as waste and often disposed to the sanitary landfills (Cruz et al., 2017;

This article is part of a special issue entitled: Agri-Waste Valorization for Bioproducts published in Biocatalysis and Agricultural Biotechnology.

* Corresponding author.

E-mail addresses: abdulmannan.rouhani@ujep.cz, a.rohani70@gmail.com (A. Rouhani), valentyna.pidlisniuk@ujep.cz (V. Pidlisnyuk), Karim.Souki@ujep.cz (K.S. Al Souki).

https://doi.org/10.1016/j.bcab.2024.103456
Received 2 June 2024; Received in revised form 14 November 2024; Accepted 2 December 2024
Available online 5 December 2024
1878-8181/

Wang et al., 2024).

Number of study findings have proven that incorporation of biomass ash can considerably improve properties of soil, promote plant growth, and increase a crop yield. Additionally, this practice helps to mitigate environmental concerns concerning the release of potentially toxic elements (PTEs) (Antonkiewicz et al., 2022; Rolka et al., 2024). The composition of biomass ash includes Al, Ca, Fe, K, Mg, Mn, Na, Si, and Ti, along with potentially toxic elements (PTEs) (Baxter et al., 2012; Shen et al., 2024). While such elements as Ca and Mg can regulate soil pH and increase crop yield, elements like Zn and Cu can be hazardous depending of their concentration in the ash (Maheswaran et al., 2019). Ash can contribute to the carbon sequestration by promoting the humification of organic material, which raises the carbon stability in soil (Pandey and Singh, 2010; Liang et al., 2024). One of the most environmentally friendly and sustainable waste disposal technique is returning ash derived from biomass combustion to the soil. This results in the restoration of substantial amounts of micro- and macronutrients that were initially taken by plants from the soil, thereby halting the mineral circulation (Zając et al., 2018). This shifting integrates the bioeconomy and circular economy into the industrial manufacturing process while enable the sustainable utilization of ash and improving the e waste management (Kardung and Drabik, 2021; Kershaw et al., 2021).

An essential requirement for sustainable ash application is the assessment of its safety and potential adverse effect on the environment. Thus, it is highly important to use proper management procedures for the various ash fractions generated through combustion of biomass (Tarelho et al., 2013; Gadore et al., 2024). Several European countries, including Sweden, Germany, Finland, Denmark, and Austria, have established regulations for managing ashes derived after thermochemical conversion of biomass to energy (Haglund and Group, 2008, Koppejan and van Loo, 2007; Obernberger and Supancic, 2009, Insam and Knapp, 2011). These documents determine the permissible ash fluxes for being recycled in agricultural or forest soils, the maximum permissible levels for certain plant nutrients, and PTE concentrations, surface load restrictions, and additional recommendations regarding the suitable application (Freire et al., 2015).

Regulatory EU framework has not yet adequately addressed the recycling and using of biomass ash as fertilizer and/or soil amendment, despite the fact that the EU Thematic Strategy for Soil Protection has emphasized the significance of promoting soil treatment using nutrient recycling. In addition, certain member states have acknowledged the value of recycled biomass ash within framework of the circular economy.

The significance of regulation rules related biomass ash derived from the energy sector has been widely recognized. These regulations play a crucial role in promotion the adoption of effective management practices and enhancing the value of ash as a raw material (Silva et al., 2019). However, the existing publications on utilization of the biomass ash as soil fertilizer and amendment is relatively limited; it is in particular about ash derived from the herbaceous and agricultural plants, Additionally, majority of and research studies focused on wood biomass ash while herbaceous and agricultural crop ashes (HACA) got much less attention. Thus, this review provides an overview of production, properties and utilization of biomass ash derived from herbaceous and agricultural crops. The main objectives of the study are: (1) to summarize and structure the peer-reviewed data; (2) to overview the chemical properties of ash; (3) to assess potential application of ash as soil fertilizer and amendment; and (4) to study impact of ash while utilized in the phytoremediation practices. The current review indicates a significant potential for the utilization of biomass ash in the agricultural remediation and environmental revitalization, reliant upon careful assessment and the promotion of circularity in waste treatment process.

2. Methodology

He summarized data on properties and composition of HACA were used based on numerous peer-reviewed publications (2000 - to date). The search was carried out at the "Web of Science", "Scopus", and "Google Scholar" databases with the following terms: "Biomass ash" OR "herbaceous ash" OR "agricultural biomass ash" AND "phytoremediation" AND "soil amendment". Based on these keywords, 64 articles were found, out of which 28 were used for the analysis; the remaining 36 articles were excluded caused described utilization of the wood ash which was not in the scope of the current review. Thus, totally fifteen varied biomass ashes, i.e. bagasse, rice-husk, rice straw, rice hull, wheat straw, spice residues, mustard stalk, rape meal, rye straw, rye cereal, alfalfa stem, *Miscanthus sinensis*, *Dicranopteris pedate*, *Phragmites australis* and *Arundo donax* were overviewed in details to investigate their chemical composition, potential to use as soil fertilizer and/or amendment, and ability to use in the phytoremediation process of the contaminated soil. The information on biomass ash type, production method and combustion temperature, chemical properties, using dose, and experimental design are presented in Table 1. Tables 2 and 3 illustrate the chemical characteristics and elemental content of biomass ashes. Fig. 1 illustrates that the most frequently occurred and analyzed elements in HACA are Cu (15 times), Zn (15 times), K (15 times), and Mg (15) times followed by Pb (14 times), P (14 times), Cr (13 times), Ca (13 times), Cd (13 times), and Ni (13 times). Despite the great attention to PTEs and nutrients the polycyclic aromatic hydrocarbons (PAHs) were neglected.

3. Results and discussion

3.1. Critical aspects of biomass ash

Ash derived from the solid biomass combustion contains relatively soluble forms of valuable plant nutrients including Ca, K, Mg, and P (Obernberger and Supancic, 2009; Insam and Knapp, 2011). During high temperatures' biomass combustion, the immerse concentrations of Ca, Mg, and K are commonly presented in ash in the form of carbonates. This occurs as a result of mineralization, where the basic cations are converted into oxides which then undergo hydration and subsequent carbonation under the atmospheric

Table 1
Conducted studies on properties of HACA and their application as soil fertilizer and amendment.

Ash type	Method of produced ash	Temperature (°C)	Porosity properties	Crystallinity	Chemical properties	Dosage	Experiment type	References
Bagasse ashes	Gasification and combustion	1050 °C	ng		Si P, Na, N, Mg, K, Fe, Ca, C, Al	13.2 g Ga 0 g–31.6 g Com.	Lab and greenhouse experiment	Dombinov et al. (2022)
Dicranopteris pedate	Combustion	AshDp500: 500 °C; AshDp815: 815 °C	ng		Cd, Pb, Th, U, rare earth elements (REEs)	0.5, 1, 2, and 4 % (dry weight)	Greenhouse experiment	Wei et al. (2020)
Rice-husk ash	Combustion	ng	Total surface area: 24.252 (m^2g^{-1}); Pore surface area: 4.417 (m^2g^{-1}); Pore volume: 0.016 (cm^3g^{-1})	ng	S, P, Na, N, Mg, K, Ca, C	10% (w/w)	Pot experiments	Samsuri et al. (2019)
Rice-husk ash	Combustion	Power plant	ng	Crystalline structures with various macro- and micro-pores	Ti, Si, O, Na, Mg, K, Fe, Cu, Ca, C, Al	5 t ha-1 rice-husk ash 10 days before sowing of seeds	Field experiment	Singh et al. (2019)
Miscanthus sinensis re-burned cyclone ash	Combustion	550 °C	ng	ng	Zr, Zn, W, V, Tl, Th, Ta, Sr, Sn, Si, Sb, S, Rb, Pb, P, O, Ni, Nb, Na, Mo, Mn, Mg, Li, K, In, Hf, Ge, Ga, Fe, Cs, Cu, Cr, Cl, Cd, Ca, Be, Ba, As, Al, Ag, and REEs	–	Lab experiment	Vigliaturo et al. (2019)
Rice husk ash	Combustion	ng	ng	Crystalline structure with a larger radius	Zn, Si, P, O, Ni, Mn, K, Fe, Ca, C	0, 2.5% and 5% (w/w)	Pot experiments	Kiran & Prasad (2019)
Wheat straw ash	Combustion	600–700 °C	ng	ng	PAHs	–	–	Košnář et al. (2018)
Bagasse ash	Combustion	–	ng	ng	Ca, Cu, Fe, K, Mg, Mn, N, P, S, Zn	20, 40, 60, 80 and 100 tons/ha	Greenhouse experiment	Gonfa et al. (2018)
Combined ash of energy crops and agricultural plants	Combustion	–	ng	ng	Zn, Sr, S, Pb, Ni, Na, N, Mo, Mn, Mg, Cu, Cr, Cd, Ca, C, As, Al	1.5, 3.0, 4.5 t ha^{-1}	Field experiment	Saletnik et al. (2018)
Rice-husk ash	ng	ng	Total surface area: 24.252 (m^2g^{-1}); Pore surface area: 4.417 (m^2g^{-1}); Pore volume: 0.016 (cm^3g^{-1})	ng	P, S, Na, Mg, K, N, Ca, C	5%, 10%, and 20% (w/w)	Pot experiment	Tariq et al. (2016)
Combined ash of poplar bark, rice straw and wheat straw	Combustion	Power plant	ng	ng	Zn, Se, Pb, P, Ni, Na, Mo, Mn, Mg, Hg, K, Fe, Cu, Cr, Co, Cd, Ca, As, Al	–	Lab experiment	Shi et al. (2016)
Spice residue (capsacin or pepper)	Combustion	Pepper plant biomass	Surface area: 1 m^2g^{-1}	Low cystallinity percentage (43%)	Zn, Ti, Sr, Pb, Ni, Mn, Cu, Cr, Co, Cd, Bi, Ba, B	–	–	Abraham et al. (2013)
Phragmites australis and Arundo donax	Combustion	850 °C	ng	ng	Zn, Pb, Mn, Cu, Cr, Cd	–	Lab experiment	Bonanno et al. (2013)
Rice husk ash	Combustion	Power plant	ng	ng	Zn, S, Pb, P, Ni, N, Mn, Mg, K, Fe, Cu, Cr, Cd, Ca, As, Al	10 and 20 Mg ha^{-1}	Field experiment	Thind et al. (2012)
Bagasse ash	Combustion	Power plant	ng	ng		10 and 20 Mg ha^{-1}	Field experiment	

(*continued on next page*)

Table 1 (*continued*)

Ash type	Method of produced ash	Temperature (°C)	Porosity properties	Crystallinity	Chemical properties	Dosage	Experiment type	References
Wheat straw ash	Gasification	–	ng	ng	Zn, Si, S, Pb, P, Ni, Mo, Mn, Mg, K, Fe, Cu, Cr, Cl, Cd, Ca, Al	3.18, 1.04, 9.46 t dry matter ha^{-1} (based on pot surface area)	Greenhouse experiment	Müller-Stöver et al. (2012)
Combined ash of rice and wheat straws	Combustion	Power plant	Particle size distribution < 90 μm	ng	P, Fe, Si, Mg, Ca, Ti, Al, Na, K, Mn, Zn, Cu, As, Se, Mo, Pb, Co, Cd, Ni, Cr	–	Lab experiment	Wang et al. (2012)
Mustard stalk	Combustion	Power plant	Particle size distribution < 135 μm		Zn, Y, V, U, Th, Ta, Sr, Sc, Rb, Pb, Ni, Mn, Hf, Ga, Cu, Cs, Cr, Co, Ba, and REEs	–	–	Singh et al. (2011)
Rape meal ash	Combustion	860 °C	ng	ng	Zn, Pb, P, Ni, Mg, K, Hg, Cu, Cr, Cd	2.5 g	Lab experiment	Schiemenz & Eichler-Löbermann (2010)
Rye straw ash	Combustion	750 °C	ng	ng	Zn, Pb, P, Ni, Mg, K, Hg, Cu, Cr, Cd	9.8 g	Lab experiment	
Rye cereal ash	Combustion	650–850 °C	ng	ng	Zn, Pb, P, Ni, Mg, K, Hg, Cu, Cr, Cd	1.9 g	Lab experiment	
Rice hull ash	ng	Rice milling industry	ng	ng	na	5 Mg ha^{-1}	Field experiment	Phongpan and Mosier (2003)
Alfalfa stem ash	Gasification	–	ng	ng	Zn, V, Ti, Sr, Si, Se, S, Rb, Pb, P, Ni, Na, N, Mo, Mn, Mg, Li, K, Hg, Fe, Cu, Cr, Co, Cl, Cd, Ca, C, Be, Ba, B, As, Al	0.61–14.6 g ash kg^{-1} soil (0.9–21.6 Mg ha^{-1})	Growth chamber study	Mozaffari et al. (2000, 2002)

Note: ng = not given.

Table 2
Concentrations of macro- and micronutrients (%) in HACA.

Ash type	pH	N	C	S	Na	K	Si	Ca	P	Al	Fe	Mg	References
Bagasse ash (Gas.)	9.9	0.05	53.7	na	0.04	1.04	0.56	0.99	0.41	2.98	3.32	0.57	Dombinov et al. (2022)
Bagasse ash (Comb.)	7.1	0.1	5.05	na	0.1	1.21	14.62	1.26	0.38	3.86	5.38	0.46	
Rice husk ash	8.22	0.87	58.94	na	na	0.49	13.08	0.00	0.19	na	0.032	na	Kiran & Prasad (2019)
Rice husk ash	10.33	0.047	6.44	nd	0.074	0.098	na	0.058	0.23	na	na	0.78	Samsuri et al. (2019)
Rice-husk ash	10.54	na	21.12	na	1.14	0.26	26.31	0.31	na	nd	nd	0.31	Singh et al. (2019)
Miscanthus sinensis re-burned cyclone ash	na	na	na	0.14	0.07	2	26	3	0.06	0.1	nd	0.12	Vigliaturo et al. (2019)
Bagasse ash	10.2	0.17	na	0.0001	na	0.05	na	1.45	0.00008	na	0.0003	0.70	Gonfa et al. (2018)
Combined ash of energy crops and agricultural plants	12.89	0.17	1.22	1.97	<0.01	na	na	13.12	na	<0.01	na	3.13	Saletnik et al. (2018)
Combined ash of poplar bark, rice straw and wheat straw	12.28	na	na	na	0.59	3.45	na	7.81	0.44	2.11	1.01	1.02	Shi et al. (2016)
Rice husk ash	10.22	nd	na	nd	na	0.75	na	0.36	0.30	0.81	0.17	0.16	Thind et al. (2012)
Bagasse ash	9.96	nd	na	nd	na	1.18	na	0.93	0.54	0.13	0.23	0.39	
Wheat straw ash	10.9	na	na	0.23	na	12	18	5.8	1.1	0.28	0.31	0.97	Müller-Stöver et al. (2012)
Combined ash of rice and wheat straws	11.3	na	na	na	1.02	4.54	21.84	na	0.43	na	1.92	1.57	Wang et al. (2012)
Mustard stalk	9.2	na	na	na	na	na	na	na	na	na	na	na	Singh et al. (2011)
Rape meal ash	na	na	na	na	na	7.3	na	na	8.0	na	na	5.5	Schiemenz & Eichler-Löbermann
Rye straw ash	na	na	na	na	na	5.3	na	na	1.0	na	na	1.0	(2010)
Rye cereal ash	na	na	na	na	na	10.8	na	na	10.5	na	na	3.3	
Alfalfa stem fly ash	11.8	1.04	42.4	0.38	0.27	1.20	0.75	8.5	1.5	0.29	0.24	2.03	Mozaffari et al. (2000)
Alfalfa stem Bottom ash	–	0.13	6.3	0.13	0.19	6.08	0.52	19.3	2.98	0.59	0.59	1.05	

Not: nd = not detected. na = not analyzed.

Table 3
Concentrations of PTEs (mg kg^{-1}) in HACA and their limited values.

Ash type	Organs	PTEs									References
		As	Cd	Co	Cr	Cu	Mn	Ni	Pb	Zn	
Dicranopteris pedate (500 °C)	ng	na	2.9	na	na	na	na	na	134.4	na	Wei et al. (2020)
Dicranopteris pedate (815 °C)	ng	na	1.7	na	na	na	na	na	64.2	na	
Rice husk ash	husk	na	na	na	na	na	48.20	na	na	48.30	Kiran & Prasad (2019)
Miscanthus sinensis re-burned cyclone ash	straw	<5	3.1	1.4	16	33	100	11	6	442	Vigliaturo et al. (2019)
Bagasse ash		na	na	na	na	0.40	19	na	na	10.50	Gonfa et al. (2018)
Combined ash of energy crops and agricultural plants	ng	<0.01	<0.01	na	50	110	1930	12	<0.01	710	Saletnik et al. (2018)
Combined ash of poplar bark, rice straw and wheat straw	straw	12.5	3.14	6.58	39.25	43.6	818.6	16.96	43.29	478.3	Shi et al. (2016)
Spice residue (capsacin or pepper)	ng	na	4	7	14	207	200	10	10	410	Abraham et al. (2013)
Phragmites australis	leaf	na	<0.10	na	0.22	3.67	68.7	6.13	12.3	19.5	Bonanno et al. (2013)
	stem	na	<0.10	na	0.14	1.87	14.5	2.64	8.43	11.1	
Arundo donax	leaf	na	<0.10	na	3.15	12.6	23.8	4.22	17.5	10.8	
	stem	na	<0.10	na	0.87	5.24	10.1	1.82	13.9	10.3	
Rice husk ash	husk	1.51	4.3	na	4.1	10	180	1.65	3.86	20	Thind et al. (2012)
Bagasse ash	ng	6.54	0.5	na	6.78	40	110	3.60	6.38	40	
Wheat straw ash	straw	na	0.07	na	100	31	400	48	<10	160	Müller-Stöver et al. (2012)
Combined ash of rice and wheat straws	straw	15	1	10	54	47	1342	24	4	51	Wang et al. (2012)
Mustard stalk	stalk	<0.1	na	7	61	113	77	35	na	161	Singh et al. (2011)
Rape meal ash	meal	na	0.5	na	227.9	77.1	na	273.6	11.9	348	Schiemenz & Eichler-Löbermann (2010)
Rye straw ash	straw	na	0.1	na	4.7	24.5	na	3.7	<1.5	80.9	
Rye cereal ash	cereal	na	1.3	na	13.7	170.9	na	13.1	2.6	750.5	
Alfalfa fly ash	stem	<0.62	<0.96	<1.9	7.7	41	250	6.7	<13.5	117	Mozaffari et al. (2000)
Alfalfa Bottom ash	stem	<0.62	<0.96	<1.9	20	22.3	597	12.7	<13.5	137	
Concentration limits of PTEs for biomass ash application as a soil amendment											
Austria (Class A/B)		20/20	5/8	ng	150/250	200/250	na	150/200	100/200	1200/1500	Lanzerstorfer (2014)
Denmark		ng	5	ng	100	ng	ng	30	120	ng	Niu & Tan (2016)
Finland		40	25	ng	300	700	ng	150	150	4500	Nurmesniemi et al. (2012)
Germany		40	1.5	ng	2	70	ng	80	150	ng	Silva et al. (2019)
Lithuania		30	30	ng	100	400	ng	70	300	700	Stupak et al. (2008)
Sweden		30	30	ng	100	400	ng	70	300	7000	Emilsson (2006)

Note: nd = not detected; na = not analyzed; ng = not given.

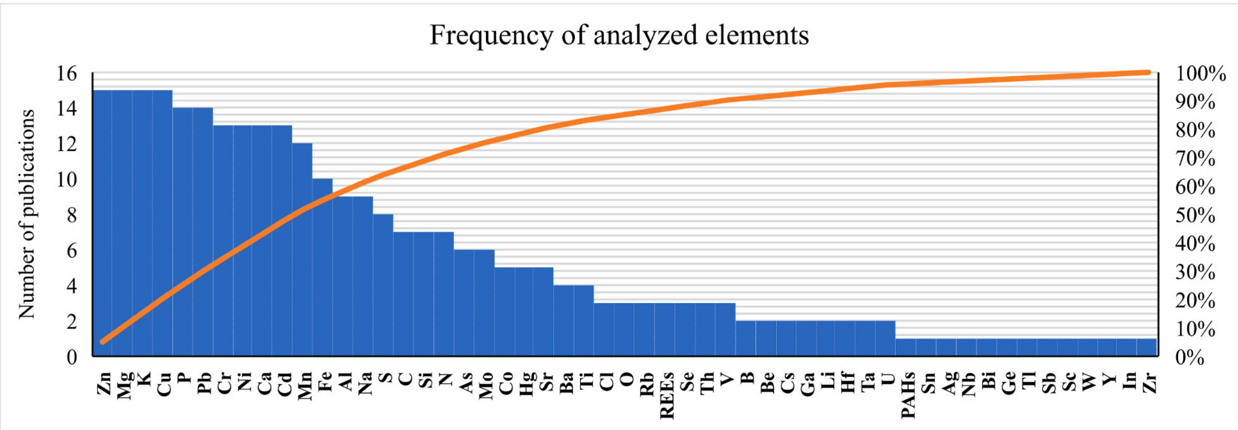

Fig. 1. Frequency of analyzed elements in HACA.

conditions (Saarsalmi et al., 2010; Ochecova et al., 2014). P can be identified as phosphates of Fe, K, and most notably Ca (Tan and Lagerkvist, 2011). Therefore, incorporation of ash into agricultural soil can assist to close the natural mineral cycle simultaneously minimizing the requirement for the chemical fertilizers. On the other hand, biomass ash, is extremely alkaline and may contents the significant levels of PTEs, which have to be managed. Three factors contribute to the variation in the soil nutrient availability: (i) release of nutrients from ash; (ii) alteration in the chemical equilibrium of soil, which is pH-dependent; and (iii) variation, predominantly increasing of the microbial activity (Demeyer et al., 2001). In this regards the soil with higher pH as a result of adding biomass ash can immobilize some metals (Freire et al., 2015).

Another problem to be addressed is the existence in the content of ash persistent organic pollutants (POPs), including para-dibenzodioxines/furanes (PCDD/F) and PAHs as a result of incomplete combustion or transformation in the flue gas pathway. The level of their concentrations is determined by combustion conditions and fuel composition. Subsequently, POPs are dispersed within the ash and flue gas pathways (Enell et al., 2008; Lopes et al., 2009; Masto et al., 2015). PCDD/Fs are produced during combustion from organic precursors contented phenols and lignin. The effect can happen through de novo reactions caused by pyrosynthesis at the high temperature or via the presence of particulate carbon and chlorine (Lavric et al., 2004; Gulyurtlu et al., 2007). However, as it is seen from Fig. 1, the presence of PAHs in the ash have been ignored.

Literature reports indicate that some biomass ashes, more particularly rice husk ash, typically contains high level of silica (e.g., 87–99.8%), which is highly porous and lightweight, and possesses a high external surface area (Samsuri et al., 2019; Fernandes et al., 2024). Silica exists in two forms including amorphous and crystalline (Gupta et al., 2022), and its crystalline form is well-known for causing cancer (Rice et al., 2001; Yuvakkumar et al., 2014). As reported (Brandariz et al., 2023) the elevated exposure levels of crystalline silica are associated with the risk of lung cancer Crystallinity is influenced by the combustion temperature and duration of the process; elevated calcination temperatures or extended calcination times result in the emergence of crystalline silica (Shen et al., 2011). Therefore, the utilization of biomass ash derived from rice hunk contents high levels of crystalline silica which indeed requires a careful consideration.

The acid neutralization capacity (ANC), which measures and represents the ash buffering capability, is significant indicator in the context of soil application (Wahlström et al., 2009). ANC is a metric that quantifies the matrix's resistance to acid attack, which impacts its function to endure and release pollutants. This is mainly because the solid matrix's integrity depends on capacity to sustain alkaline conditions, while the solubility of pollutants is greatly impacted by pH (Giampaolo et al., 2002; Pöykiö et al., 2014). The long-term maintenance of slightly alkaline or neutral pH levels in waste materials is crucial due to the minimal leachability of pollutants within the pH range. Leachability increases substantially with deviation from the pH range (Wahlström et al., 2009). The material fineness and Ca and Mg carbonates contribute to the liming impact of ash on changing the soil pH; however, Al and Si compounds might also be important in this regard (Pitman, 2006; Wahlström et al., 2009; Carter et al., 2009). Although the positive impact of utilizing alkaline materials as soil amendments is widely acknowledged, it is important to consider the implications they have on the processes which regulate the migration of elements in the amended soil (Carter et al., 2009). The existence of char in biomass ash can significantly decrease its final neutralizing capacity, with respect to the burnout efficiency (Pitman, 2006).

3.2. Properties of biomass ash

A valuable approach for sustainable management of biomass ash generated at the large-scale combustion facilities is the identification of ash properties and type. These characteristics is a foundation for establishing criterias to determine the suitability of using ash materials for environmental or commercial purposes (Cruz et al., 2019). The concentration of macro- and micronutrients in HACA are presented in Table 2. As shown, the highest pH level is recorded in combined ash derived from combustion of energy crops and agricultural plants (12.89). However, there was ash received after combustion of bagasse that exhibited a distinctive lower pH (7.1) compared to the remaining ash. The neutralizing ash impact on soil acidity determines by the positive and negative factors during ash utilization, such as the immobilization of PTEs and elevated CO_2 emissions. Therefore, the duration of the neutralization impact and its subsequent consequences are the key questions still need to be addressed. With high probability the answer will be determined by the quantity of added ash and the initial site acidity (Huotari et al., 2015; Uwiringiyimana et al., 2024).

The plant growth is dependent on a set of vital primary and secondary macronutrients, including S, P, N, Mg, K, and Ca (White and Brown, 2010; Barker and Pilbeam, 2015). In order to maintain the soil productivity, P and K have to be provided in organic matter form (compost, manure, or digestate) and inorganic fertilizers since these elements cannot be restored in the soil on human timeframes through mobilization from atmospheric deposition or primary minerals (Bradshaw, 2000; Cleveland et al., 2013). Often Ca, Mg, and S are limited in some soil types which requests their addition. (Zhao et al., 1996; Gransee and Führs, 2013). Indeed, the majority of these nutrients are accumulated in the ash after combustion of biomass allowing the potential reuse of elements and recovery according to the waste hierarchy. However, the approach works if the levels of contaminants in the ash are within acceptable limits for particular recovery options (Zhai et al., 2021).

As stated by Dombinov et al. (2022) the ash from bagasse combustion contains the higher levels of Al (3.86 %) and Fe (5.38 %) compared with the results reported by Gonfa et al. (2018) indicated the lower amounts of Fe P, K, and S in ash derived from bagasse biomass. Rice-husk ash showed different levels of nutrients containing higher concentrations of Na (1.14%) and Si (26.31%) detected by Singh et al. (2019) and higher level of C (58.94%) reported by Kiran and Prasad (2019). Samsuri et al. (2019) and Kiran and Prasad (2019) detected lowest level of N (0.047%) and Ca (0.00%) in rice-husk ash. Bottom ash derived from alfalfa stem contained a higher content of Ca (19.3%) and concomitantly, lowest level of Si (0.52%) among other ashes assessed in this study. While highest concentration of S (1.97%) was recorded in combined ashes of the energy crops and agricultural plants, while low levels of C (1.22%), Na (<0.01%), and Al (<0.01%) were reported. High content of Mg (5.5%) was detected for rape meal ash; however, the lowest level of this element (0.12%) was reported for *Miscanthus sinensis* re-burned cyclone ash. Furthermore, greatest concentrations of N (1.04%), K (12%), and P (10.5%) were recorded in alfalfa stem fly ash, wheat straw ash, and rye cereal ash. Ash derived from the agricultural waste is usually rich in K, Ca, and P. It is demonstrated (Zhai et al., 2021) that these nutrients could be recovered from the ash of cereal residues therefore can be utilized as fertilizer.

From the perspective of closing the elements cycle, the returning of biomass ash to the soil is an advantage; however, here is the caution that simultaneously ash may contain an excessive amount of PTEs. Therefore, the application of ash has to be in accordance with the permittable level of elements' content which regulates by respected legislation (Tosti et al., 2019). Table 3 indicates the contents of PTEs (Zn, Pb, Ni, Mn, Cu, Cr, Co, Cd, and, As) in the HACA with regard to the limit values in Austria, Denmark, Finland, Germany, Lithuania, and Sweden. Compared to other countries, Germany has a significantly lower permissible level value for PTEs such as Cd, Cr, and Cu. The soil characteristics and ways for utilization have to be considered during determination the appropriate threshold PTEs values in biomass ash utilized as a soil amendment. It has to be mentioned that utilization of ash to agricultural soil has to ensure the higher standards in comparison with application of ash to degraded industrial or mining soils when the goal of nutrient recycling and restoring of soil function is expected to ensure less strict regulations (Asensio et al., 2013; Cruz et al., 2017).

The reported concentration of As in ash is commonly lower than the limit value. Spice residue ash has the highest level of Cu (207.0 mg kg^{-1}) which surpassed the German and Austrian (class A) threshold limits (Lanzerstorfer (2014)) while lowest concentration reported for bagasse ash (0.4 mg kg^{-1}). However, Cd concentration in Dicranopteris pedate ash (1.7–2.9 mg kg^{-1}), *Miscanthus sinensis* ash (3.1 mg kg^{-1}), spice residue ash (4 mg kg^{-1}) and combined ash of poplar bark, rice straw and wheat straw (3.14 mg kg^{-1}) were higher than the German limit value. If we disregard Cr in *Phragmites australis* leaf (0.22 mg kg^{-1}) and stem (0.14 mg kg^{-1}) ash, as well as *Arundo donax* stem ash (0.87 mg kg^{-1}) the concentration of this element was lower compared to the limit. Rape meal ash had the highest level of Ni (273.6 mg kg^{-1}) over the limited value, followed by concentration of this element in wheat straw ash (48 mg kg^{-1}), and mustard stalk ash (35 mg kg^{-1}) whose concentrations exceeded the limit in Denmark.

The highest level of Pb was identified in the combined *Dicranopteris pedate* ash (134.4 mg kg^{-1}), and was higher than the limits determined by standards of Denmark and Austria (class A). Moreover, combined ash of energy crops and agricultural plants (710 mg kg^{-1}) and rye cereal ash (750.5 mg kg^{-1}) contented the highest level of Zn. Through the revised literature. There is no reported threshold for Co and Mn values in biomass ash. Combined ash of rice and wheat straw contented the highest value of Co (10 mg kg^{-1}), while *Miscanthus sinensis* re-burned cyclone ash had the lowest content of this element (1.4 mg kg^{-1}). The high value of Mn was detected in the combined ash generated from the energy crops and agricultural plants (1930 mg kg^{-1}). Same time the lowest level of Mn was recorded in *Arundo donax* stem ash (10.1 mg kg^{-1}). Among ashes overviewed in the current study, a rape meal ash appeared as the most polluted by Cr, Ni, and Zn. It is reported that biomass ash can improve the soil micronutrient environment specifically, ensuring the content of Zn, Mn, Cu, which promotes ash use as a fertilizer (Wierzbowska et al., 2020). It has to be stressed that chemical composition of varied ashes differs depending of the initial biomass, processing technology, and combustion temperature (Cruz et al., 2019).

Conclusively, the threat of pollutants' leaching is a serious concern during application of biomass ash as soil amendment. However, the reviewed literature indicate that the total quantity of pollutants does not necessarily directly correlates with the potential for leaching in a specific utilization scenario (van der Sloot, 2000; Kosson et al., 2002).

3.3. HACA impact to soil and crops

The rice hulls have traditionally been dumped in landfills, which led to a significant source of eutrophication, aesthetic pollution, and disturbances in aquatic life (Kamath and Proctor, 1998; Mane et al., 2007). The utilization of rice husks as a source of energy has received an encouragement due to increasing interests toward the environmentally friendly industries (Wang et al., 1999). Rice husk, as an enormous and easily accessible biomass resource, was used in heat generation for paddy parboiling due to its low calorific value (12.1–15.2 MJ kg^{-1}) and moisture content (varied within the range of 8–10%) (Foo and Hameed, 2009). However, in the recent decades the release of rice husk ash (RHA) into the environment received considerable criticisms. This is primarily due to bio-accumulative, persistent, and carcinogenic impacts of RHA, which can lead to loss of appetite (respiratory failure), breath shortness, fatigue, silicosis syndrome, and even death (Occupational Safety and Health Administration, US Department of Labor, 2002). The reported carcinogenic impact of RHA is related to its crystallinity (Beidaghy Dizaji et al., 2022; Samsuri et al., 2019).

The urgent need for transformation of RHA into a more valuable product has been emphasized additionally because of high cost of ash disposal (in ash pond or landfill) which is equal to \$50/tonne in developed states and \$5/tonne in developing countries (Foo and Hameed, 2009). Nowadays, the extensive applicability of RHA is under the observation. For instance, the impacts of RHA on the agronomic and biophysical characteristics of soil were studied during cultivation of wheat crop in a dry tropical environment. Findings showed (Singh et al., 2019) that RHA addition initially led to elevated soil CO_2 release; however, a decrease in this efflux was detected later throughout different growth phases and in overall CO_2 level in the soil. The study revealed the potential to decrease greenhouse gas emissions from nutrient-poor dry tropical soils and demonstrated that RHA remaining after energy generation and mineral extraction could be used as a material for improving agronomic conditions and soil health when combined with the mineral fertilizers and farm-yard manure Singh et al. (2019) It is noteworthy to mention that there are other influencing factors which might impact the quality and composition of RHA, including climate, soil types, harvesting season, the number of fertilizers used during rice cultivation, geographical and environmental aspects (Beidaghy Dizaji et al., 2019).

Research was conducted on the leachability and bioavailability of As, Cd, and Mn in the gold mine tailings using iron-coated rice husk (Fe-RHA) and unmodified RHA (Tariq et al., 2019). It was found that the leachability and bioavailability of As, Cd, and Mn in mine tailings were significantly impacted by Fe-RHA and RHA application. Furthermore, the leachability and availability of As were enhanced through RHA and Fe-RHA addition; the opposite finding was reported for Cd and Mn. Studies shown that the unmodified rice husk had a lower adsorption capacity compared to the modified rice husk (El-Shafey, 2007; Sahu et al., 2009). The functional groups contained in bioadsorbents,i.e.: amide, carbonyl, phenol, thioether, sulfate, phosphate imidazole, amino, hydroxyl, sulphydryl, and carboxyl, enabled to form metal complexes or chelates (Amin et al., 2006). Chemical treatments had the potential to enhance the number of functional groups (Lata and Samadder, 2014). Tartaric acid, epichlorohydrin, sodium hydroxide, sodium carbonate, and hydrochloric acid were the most frequently utilized chemicals to activate rice husk (Wong et al., 2003; Kumar and Bandyopadhyay, 2006) and can decrease the crystallinity of cellulose and reduce the content of lignin and hemicellulose, which subsequently enhance the rice husk's porosity and surface area (Wan Ngah and Hanafiah, 2008).

The bagasse ash (BA) has a lower silica concentration compared to RHA. The low cost and easy availability of this material makes it suitable for agricultural use as amendment and for improving the soil fertility. while the current applied disposal method poses a risk to the environment and encroachment on productive land (Patterson et al., 2004). A three and a half years of field experiment was carried out to investigate the potential utilization of RHA and BA as soil amendments for enhancing the rice-wheat system (RWS) productivity. The application of BA and RHA considerably improved the wheat and rice grains yield: being applied in wheat production cycle the mean grain yield increased by 24 and 25%, and the subsequent rice crop increased by 11 and 10%, respectively, for BA and RHA incorporation. Direct utilization of BA and RHA to rice and wheat production increased rice yield by 11 and 8%, and wheat yield by 14 and 10%, respectively. The BA and RHA addition to rice production cycle at a rate of 20 Mg ha^{-1} decreased the RWS productivity compared to the addition of these amendments at a rate of 10 Mg ha^{-1} to wheat production. The ash showed no substantial impact on the levels of PTEs in the wheat's grain and straw. In general, application of two types of ash rendered positive P balance in RWS; while the K balance stayed negative (Thind et al., 2012). The reason why direct utilization of BA and RHA led to greater yield increasing for wheat compared with rice could be due to the greater response of winter-grown wheat to utilized P (Yadvinder-Singh et al., 2009). According to Sciemenz and Eichler-Lobermann (2010), ash derived from crop biomass can be used as an ideal source of P, similar to highly soluble commercial P fertilizers.

A series of laboratory and greenhouse studies were conducted to gain a comprehensive understanding and accurate prediction of P availability to plants derived from different bagasse-based ash sources, fertilization impacts on soybeans. When bagasse was thermally co-processed with sewage sludge or chicken manure, the total P mass fraction in the ash was raised to the low-grade P rock levels, however the low P mass fraction and plant P availability of pure BA restricted its application as a fertilizer for soybeans. It was further proven that the co-combustion of bagasse and poultry manure increased plant P availability by forming plant-available Ca-alkali phosphates (Dombinov et al., 2022). An investigation was conducted on impact of filter cake and BA on wheat productivity in greenhouse conditions. The finding indicated that the yield and its components achieved via BA treatments were significantly higher than those earned with filter cake treatments, except for straw yield, dry biomass, and tillers. The analysis of linear regression showed a strong and positive correlation among the uptake of total Zn, S, P, N, Mg, K, Cu, Ca, and grain yield. While there was a linear correlation among N, Zn uptake and grain yield, a quadratic correlation was observed with total S, P, Mg, K, Cu, and Ca, uptake. These finding suggested that filter cake and BA can effectively improve wheat yield in acidic soil by providing essential nutrients (Gonfa et al., 2018).

The valuable properties of ash received from plant biomass were highlighted because the material contains substantial amounts of biogenic elements that are essential for the proper development of crops and demonstrates the potential to effectively address shortages of macro- and microelements in the soil (James et al., 2012). The report by Piekarczyk (2013) stated that the wheat straw ash (1.0 t ha^{-1}) utilization as a fertilizer resulted in an elevation of the soil absorbable macroelements. However, these improvements did not prove to be statistically significant. The finding was explained by the relatively low nutrient levels contended in the ash. The impact of applying ash on soil fertility varied depending on the source of ash, dosage, and its elemental composition (Bakisgan et al., 2009). Experiment was carried out to assess whether two distinct ashes received, consequently, from a residual fiber of citrus peels (CP) and low temperature circulating fluidized bed gasification of wheat straw (SA), could be applied as fertilizers. Results showed that after ash application, soil microbial characteristics did not change considerably. In most cases, SA increased soil ammonium acetate/acetic acid-extractable K and Olsen-P levels and improved barley and maize yields, while faba bean did not respond favorably to amendment by ash. The application of CP ash did not result in any significant improvement of soil nutrients content or biomass harvest (Müller-Stöver et al., 2012). Saletnik et al. (2018) assessed the potential of utilizing biochar and ash derived from plant biomass as fertilizers for growing *Miscanthus x giganteus*. Even in the first and second year of cultivation, the study revealed that the application of fertilizer encompassing ash at a rate of 1.5 t ha-1, coupled with biochar and a mixture of biochar and ash at the same rate, resulted in the highest dry matter biomass yield compared to control.

Bonanno et al. (2013) assessed the potential of utilizing ash derived from energy crop's biomass (*Phragmites australis* and *Arundo donax*) grown in an urban stream impacted by residential sewage as a fertilizer for agricultural and forest applications. Study finding indicated that compared to the initial plant tissues, receiving ash contained about 3–5 times higher concentrations of elements. Nevertheless, this metal-enriched ash exhibited significantly lower level of elemental concentrations compared to the permissible thresholds for ash reuse in forestry and agricultural sectors. Instead of being regarded as a hazardous waste product, the biomass ash received from the constructed wetlands might be utilized as fertilizer (Bonanno et al., 2013). Ash derived from bioenergy crops appears to be a more viable option for recycling purposes due to its lower PTEs concentration compared to woody biomass ash. This is particularly evident in macrophytes, when harvested above part biomass are less enriched in elements compared to roots. Consequently, a lower concentration of PTEs can be found in macrophyte ash derived from leaves and stems (Bonanno et al., 2013). The successful implementation of the energy crops biomass chain relies on the assumptions of cost-effectiveness, high productivity, and proximity between production and application sites (Borin et al., 2009). The most advantageous method for utilization the energy crops in phytoremediation is the returning of biomass ash to the field or forest, as this would combine three distinct technologies into a single sustainable process (Bonanno et al., 2013).

The available reserves of P on a global scale are currently decreasing and are expected to be ran out in the future (Haarr, 2005). Thus, finding solutions for P recycling through the application the residues and wastes is increasingly crucial for preservation the global P reserves. Although biomass ash is almost entirely devoid of N, it contented P and other essential elements for plant growth. Ash can have varying levels of nutrients (Zimmermann and Frey, 2002; Patterson et al., 2004). In comparison, Ohno and Erich (1990) revealed that just a small amount of P supplied by ash was extractable and available for plants. Pels et al. (2005) reported a low P solubility in biomass ash. On the other hand, Mozaffari et al. (2002) showed that alfalfa stem ash had favorable impacts on Olsen P in loamy soil (extracted with $NaHCO_3$). They demonstrated that a linear regression could adequately explain the association between the rate of ash application and the extractable P level in soil. Onwuka et al. (2007) observed improved maize growth and enhanced available P concentration in the soil by fertilizing with cocoa husk ash. Two pot experiments were conducted to evaluate the impact of crop biomass ashes (straw, rape meal, and cereal) on P fertilization. The experiment was undertaken using a P deficient, poor loamy sandy soil. Utilization of rape meal ash resulted in the highest P uptake (86.7 mg pot^{-1}), while the control sample exhibited the lowest P uptake (66.6 mg pot^{-1}). Compared to the control, the application of ash commonly resulted in higher P uptake by crop and readily available P reservoir in the soil. The utilization of crop biomass ash to catch same crops appeared to be a highly promising approach (Schiemenz and Eichler-Löbermann, 2010). Ikpe and Powell (2002) observed that millet ash increased millet yields and Phongpan and Mosier (2003) discovered that rice hull ash increased rice yield.

Qin et al. (2019) recently discovered that pyrolysis residue ash of a *Dicranopteris* species have a high concentration of over 6 mg kg^{-1} REE, making it a valuable REE bio-ore. Additionally, it is widely recognized that applying REE micro-fertilizers to the soil or foliage at a suitable dosage can enhance the yield and quality of the crops undergoing treatment (Wei et al., 2001, 2004). To determine the potential of REE-enriched ash derived from *Dicranopteris pedata* as a fertilizer to promote the growth of water spinach (*Ipomoea aquatica Forsskal*), a pot experiment was established. It was found that soil fertility improved by using *D. pedata* ash at rates up to 4%, which subsequently led to the higher quality and yield of *I. aquatica* shoots. Weight and height of the shoots was boosted by using *D. pedate* ash; in addition, the shoots showed better quality having higher content of soluble protein, vitamin C, and soluble sugar and a relatively low nitrates level. Amendment by *D. pedata* ash led to high absorption of free amino acids by *I. aquatica*. Furthermore, the levels of microelements detected in the harvested part of *I. aquatica* were within the acceptable limits set by the National Standard in China related to elements' concentration in the vegetable leaves (Wei et al., 2020). This study indicates the feasibility of utilizing *D. pedata* ash enriched with REEs as a fertilizer during cultivation of *I. aquatica*.

Even though the idea of using ash as a soil amendment has been investigated for many years, numerous regions and countries persist in dispose of this material to the local landfill instead of utilization. (Elliott et al., 2022). The primary factor preventing regular utilization of biomass ashin environmentally friendly way is the lack of field scale experiment assessing real interactions between soil, crop development, soil amendment, and long-term impact (Medaiyese et al., 2023).

3.4. *Ash assisted phytoremediation*

Number of studies have been examined the biomass ash potential for improving the properties of soil, interaction with contaminants, and reducing the bioavailability of pollutants (Mozaffari et al., 2002; Schiemenz and Eichler-Löbermann, 2010; Thind et al., 2012; Singh et al., 2019; Wei et al., 2020). Nevertheless, there is a deficiency of precise data regarding the stabilization of the PTEs in plants and soil induced by ash amendments, and their specific effects on plant growth.

In a study conducted over a 60-days period, tolerance and toxicity of Pb in *Ricinus communis* by RHA and biochar amendments at the varied dosages in Pb-polluted soils were investigated. *R. communis* seedlings were cultivated in soil spiked with different Pb concentrations (0, 400, and 800 mg kg^{-1}). The soil was treated with RHA and *Prosopis juliflora* biochar (PJB) at varying rates (0, 2.5%, and 5% w/w). In addition to improving soil pH, intake of nutrients, and antioxidant enzymatic activities, adding biochar and RHA to soils elevated Pb resistance in *R. communis*. Compared to unamended plants, biochar addition considerably ($p < 0.05$) enhanced chlorophyll (38–52%), protein (72%) and plant growth parameters (leaf number, nodes, leaf diameter, and height), along with RHA amendment showing a less extensive improvement (increasing protein content by 77% and chlorophyll by 10–31%). Compared to PJB, soil application of RHA consistently reduced accumulation of Pb in the leaf, shoot, and root. The application of PJB at a rate of 5% resulted in 59% reduction of Pb accumulation in roots, while RHA reduced it by 87%. The availability of soil Pb was substantially decreased by amendments, leading to a reduction in oxidative damage. This was confirmed by the decreased malondialdehyde (MDA), hydrogen peroxide (H_2O_2), and proline production in plants (Kiran and Prasad, 2019).

The RHA possesses a large number of functional groups (C = = C–H, =C–O, and C–O), which directly reduce the elements availability by ensuring the high surface areas. Moreover, Si presented in RHA contributes to stabilization of the metallic pollutants (Pb-Zn) (Bosio et al., 2014). The role of RHA for Pb adsorption in polluted soils and the aqueous solution utilized in wastewater treatment was described by Naiya et al. (2009) and Singh et al. (2019). The increased growth of plants in polluted soil by Pb due to the application of RHA and biochar can be attributed to such factors as: reduction of phytoavailable, presence of macroporous structures that which assist in retaining nutrients and increasing of water holding capacity, and evidence of total cations concentration, ultimately leading to the higher crops' yield (Lebrun et al., 2017; Singh et al., 2019).

The impact of Fe-coated and uncoated RHA on the phytoremediation applied to the gold mine tailing soil was studied using Vetiver Grass (*Vetiveria zizanioides (Linn.) Nash*). RHA and Fe-RHA treatment decreased Zn, Mn, Cu, Cr, Cd, and As phytoavailability (Tariq et al., 2016). Samsuri et al. (2019) studied the effect of NPK fertilizer on the absorption of PTEs by vetiver grass (*Vetiveria zizanioides* L. *Nash*) grown in gold-mine tailings when the soil was treated with RHA and Fe-RHA. The RHA and NPK addition were resulted in improvement of soil agrochemical parameters, i.e.: dissolved organic carbon (DOC), pH, and essential nutrient levels. Given its high tolerance to PTEs, vetiver grass could be considered as a suitable option for phytoremediation of PTEs-polluted soil tailings. This grass showed a significant capacity for absorption ofPTEs, although their translocation from the root to the aboveground part was relatively limited, with the exception for Cr. The results clearly indicated that incorporating of RHA or Fe-RHA into the soil tailings, along with NPK, had a great potential in enhancing the uptake of PTEs by the vetiver grass (Samsuri et al., 2019).

Metalloids (As) and cationic PTEs (Zn, Pb, Mn, Cu, Cr, and Cd) can be detected in the mine tailing soil (Rouhani et al., 2024). Due to the strong attraction for oxygen, As primarily prevails as oxyanions, which can cause some remediation challenges. Mobility of As in the soil was influenced by soil pH: higher pH level led to increased mobility of this element. As is prone to bound anion exchange sites on soils, more particularly to Al, Fe, and Mn oxides and oxyhydroxides (Masscheleyn et al., 1991). Because of this, the immobilization of As could be enhanced by coating RHA with Fe. This was achieved through the adsorption of As ions on Fe oxides, which replaced the surface hydroxyl groups. Additionally, the immobilization process was influenced by the formation of insoluble secondary oxidation minerals and/or amorphous Fe(III) arsenates (Kumpiene et al., 2008). An overview of biomass ash impact on soil, crops, and phytoremediation is presented in Fig. 2.

4. Conclusion and outlook

The biomass ash is a byproduct that is physically and chemically variable and can be proposed for improving a soil health and effective assisted phytoremediation. The material is characterized by the high alkaline pH value, along with high content of PTEs (Pb, Hg, Cr, Cd, and As) and essential elements for growth (Zn, S, P, Na, Mn, Fe, Ca, and B). Taking into consideration the circular economy goal to prolong the value of the different production cycles which ensures waste utilization biomass ash can be considered as a value material when applied as amendment and/or fertilizer in agriculture and supported remediation process. The overviewed research papers confirmed that in well-targeted sites, biomass ash increased the plants yield, total nutrients concentrations and/or reduces the soil acidity. The residues combustion ash produced from alfalfa stem, wheat straw, and rye cereal are rich in such nutrients as Ca, P, and K and can be utilized effectively as an economic fertilizer and/or soil amendment. It was shown that RHA improved the phytoremediation efficacy of several plants like *Ricinus communis* and Vetiver Grass. Simultaneously, there are some disadvantages associated with biomass ash utilization for soil improvement and supported phytoremediation because these materials contain certain harmful contaminants. Therefore, the using of ash requires a careful assessment and thorough intensive chemical control. Although the current review has offered a better understanding on the application of HACA in the soil, there are many remaining gaps concerning the biomass ash utilization in agricultural and phytoremediation actions without negative environmental impacts. Summarizing, the future studies should consider the following recommendations:

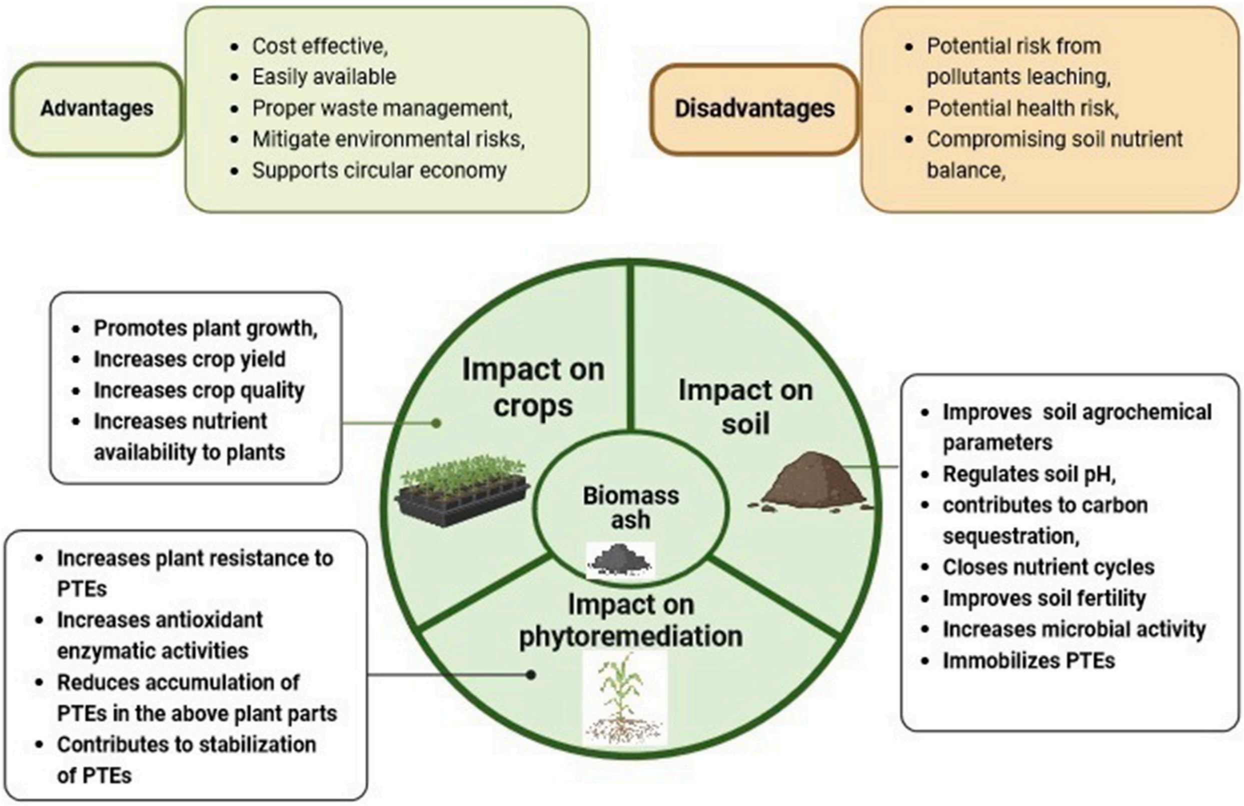

Fig. 2. Impact of biomass ash on soil, crop, and phytoremediation.

- Understanding the fate of PTEs during physical-chemical treatment of biomass waste.
- Elaborating the way of transferring PTEs from ash to soil and crops.
- Validating the levels of PTEs concentration in the edible parts of the crops, and propose solutions supporting the reduction of PTE's concentrations.
- Assessing a lifecycle starting from the production of biomass ash toward application in agriculture and supported phytoremediation, accounting the possible backup processes and the associated environmental impact.
- Performing a comprehensive evaluation of biomass ash, encompassing technical and environmental aspects, focusing on the total content and leaching elements.
- Studying the application of ash received from the different bioenergy crops, and to explore the soil-ash interaction in the context of assisted phytoremediation.
- Initiating studies on potential utilization of biomass ash for phytoremediation of soil polluted by organic and mixture of organic and PTEs compounds.
- Providing long-term field scale experiments to validate the outcomes of small scale-controlled greenhouse experiments, and to assess the potential risk of ash contamination to soil and crops.

CRediT authorship contribution statement

Abdulmannan Rouhani: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Conceptualization. **Valentina Pidlisnyuk:** Writing – review & editing, Writing – original draft, Conceptualization. **Karim Suhail Al Souki:** Writing – review & editing, Writing – original draft.

Funding

This research was supported by project NATO SPS MYP G6094 and project "RUR - Region to University, University to Region", registration number CZ.10.02.01/00/22_002/0000210, co-financed by the European Union.

Declaration of competing interest

We wish to confirm that there are no known conflicts of interest associated with this publication, and there has been no significant financial support for this work that could have influenced its outcome.

We confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed. We further confirm that all have approved the order of authors listed in the manuscript of us.

We confirm that we have given due consideration to the protection of intellectual property associated with this work and that there are no impediments to publication, including the timing of publication, concerning intellectual property. In so doing, we confirm that we have followed the regulations of our institutions concerning intellectual property.

We understand that the Corresponding Author is the sole contact for the Editorial process (including Editorial Manager and direct communications with the office). He is responsible for communicating with the other authors about progress, submissions of revisions, and final approval of proofs. We confirm that we have provided a current, correct email address accessible by the Corresponding Author.

Data availability

No data was used for the research described in the article.

References

Abraham, R., George, J., Thomas, J., Yusuff, K.K.M., 2013. Physicochemical characterization and possible applications of the waste biomass ash from oleoresin industries of India. Fuel 109, 366–372. https://doi.org/10.1016/j.fuel.2013.02.067.

Amin, M.N., Kaneco, S., Kitagawa, T., Begum, A., Katsumata, H., Suzuki, T., Ohta, K., 2006. Removal of arsenic in aqueous solutions by adsorption onto waste rice husk. Ind. Eng. Chem. Res. 45 (24), 8105–8110. https://doi.org/10.1021/ie060344j.

Antonkiewicz, J., Kowalewska, A., Mikołajczak, S., Kołodziej, B., Bryk, M., Spychaj-Fabisiak, E., Babula, J., 2022. Phytoextraction of heavy metals after application of bottom ash and municipal sewage sludge considering the risk of environmental pollution. J. Environ. Manag. 306 (114517). https://doi.org/10.1016/j.jenvman.2022.114517.

Asensio, V., Vega, F.A., Andrade, M.L., Covelo, E.F., 2013. Technosols made of wastes to improve physico-chemical characteristics of a copper mine soil. Pedosphere 23 (1), 1–9. https://doi.org/10.1016/S1002-0160(12)60074-5.

Bakisgan, C., Dumanli, A.G., Yürüm, Y., 2009. Trace elements in Turkish biomass fuels: ashes of wheat straw, olive bagasse and hazelnut shell. Fuel 88 (10), 1842–1851. https://doi.org/10.1016/j.fuel.2009.04.027.

Brandariz, J.R., Ríos, M.P., Pedreira, C.C., Martínez, C., Varela-Lema, L., Ruano-Ravina, A., 2023. EP01. 01-21 respirable crystalline silica exposure and lung cancer risk: a review of cut-off points. J. Thorac. Oncol. 18 (11), S421–S422. https://doi.org/10.1016/j.jtho.2023.09.759.

Barker, A.V., Pilbeam, D.J., 2015. Handbook of Plant Nutrition. CRC Press.

Baxter, X.C., Darvell, L.I., Jones, J.M., Barraclough, T., Yates, N.E., Shield, I., 2012. Study of Miscanthus x giganteus ash composition–Variation with agronomy and assessment method. Fuel 95, 50–62. https://doi.org/10.1016/j.fuel.2011.12.025.

Beidaghy Dizaji, H., Zeng, T., Hartmann, I., Enke, D., Schliermann, T., Lenz, V., Bidabadi, M., 2019. Generation of high quality biogenic silica by combustion of rice husk and rice straw combined with pre-and post-treatment strategies—a review. Appl. Sci. 9 (1083). https://doi.org/10.3390/app9061083.

Beidaghy Dizaji, H., Zeng, T., Hölzig, H., Bauer, J., Klöß, G., Enke, D., 2022. Ash transformation mechanism during combustion of rice husk and rice straw. Fuel 307 (121768). https://doi.org/10.1016/j.fuel.2021.121768.

Bonanno, G., Cirelli, G.L., Toscano, A., Giudice, R.L., Pavone, P., 2013. Heavy metal content in ash of energy crops growing in sewage-contaminated natural wetlands: potential applications in agriculture and forestry? Sci. Total Environ. 452, 349–354. https://doi.org/10.1016/j.scitotenv.2013.02.048.

Borin, M., Molari, G., Toscano, A., Zimbone, S.M., 2009. Production and energy transformation of herbaceous biomasses irrigated with treated wastewater–first results. In 17th European Biomass Conference & Exhibition-From research to industry and markets 1–5. ETA-Florence Renewable Energies.

Bosio, A., Rodella, N., Gianoncelli, A., Zacco, A., Borgese, L., Depero, L.E., Bontempi, E., 2014. A new method to inertize incinerator toxic fly ash with silica from rice husk ash. Environ. Chem. Lett. 11, 329–333. https://doi.org/10.1007/s10311-013-0411-9.

Bradshaw, A., 2000. The use of natural processes in reclamation—advantages and difficulties. Landsc. Urban Plann. 51 (2–4), 89–100. https://doi.org/10.1016/S0169-2046(00)00099-2.

Carter, C.M., Van der Sloot, H.A., Cooling, D., 2009. pH-dependent extraction of soil and soil amendments to understand the factors controlling element mobility. Eur. J. Soil Sci. 60 (4), 622–637. https://doi.org/10.1111/j.1365-2389.2009.01139.x.

Cleveland, C.C., Houlton, B.Z., Smith, W.K., Marklein, A.R., Reed, S.C., Parton, W., Running, S.W., 2013. Patterns of new versus recycled primary production in the terrestrial biosphere. Proc. Natl. Acad. Sci. USA 110 (31), 12733–12737. https://doi.org/10.1073/pnas.1302768110.

Cruz, N.C., Rodrigues, S.M., Carvalho, L., Duarte, A.C., Pereira, E., Römkens, P.F., Tarelho, L.A., 2017. Ashes from fluidized bed combustion of residual forest biomass: recycling to soil as a viable management option. Environ. Sci. Pollut. Control Ser. 24, 14770–14781. https://doi.org/10.1007/s11356-017-9013-6.

Cruz, N.C., Silva, F.C., Tarelho, L.A., Rodrigues, S.M., 2019. Critical review of key variables affecting potential recycling applications of ash produced at large-scale biomass combustion plants. Resources. Conserv. Recycl. 150 (104427). https://doi.org/10.1016/j.resconrec.2019.104427.

Demeyer, A., Nkana, J.V., Verloo, M.G., 2001. Characteristics of wood ash and influence on soil properties and nutrient uptake: an overview. Bioresour. Technol. 77 (3), 287–295. https://doi.org/10.1016/S0960-8524(00)00043-2.

Dombinov, V., Herzel, H., Meiller, M., Müller, F., Willbold, S., Zang, J.W., Schrey, S.D., 2022. Sugarcane bagasse ash as fertilizer for soybeans: effects of added residues on ash composition, mineralogy, phosphorus extractability and plant availability. Front. Plant Sci. 13, 1041924. https://doi.org/10.3389/fpls.2022.1041924.

Elliott, A., Mahmood, T., Kamal, A., 2022. Boiler ash utilization in the Canadian pulp and paper industry. J. Environ. Manag. 319 (115728). https://doi.org/10.1016/j.jenvman.2022.115728.

El-Shafey, E.I., 2007. Sorption of Cd (II) and Se (IV) from aqueous solution using modified rice husk. J. Hazard Mater. 147 (1–2), 546–555. https://doi.org/10.1016/j.jhazmat.2007.01.051.

Emilsson, S., 2006. International Handbook: from Extraction of Forest Fuels to Ash Recycling. Swedish Forest Agency, Stockholm.

Enell, A., Fuhrman, F., Lundin, L., Warfvinge, P., Thelin, G., 2008. Polycyclic aromatic hydrocarbons in ash: determination of total and leachable concentrations. Environ. Pollut. 152 (2), 285–292. https://doi.org/10.1016/j.envpol.2007.06.055.

European Commission, 2011. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions Youth Opportunities Initiative. Belgium, Brussels. European Commission. http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=COM:2011:0933:FIN:EN:PDF.

European Commission, 2016. Proposal for a Regulation of the European Parliament and of the Council Laying Down Rules on the Making Available on the Market of CE Marked Fertilising Products and Amending Regulations (EC) No 1069/2009 and (EC) No 1107/2009 COM (2016) 0157 Final–2016/0084 (COD).

Fernandes, I.J., Moraes, C.A., Egea, J.R., Sousa, V.C., 2024. Production and characterization of silica materials from rice husk ash by different combustion processes. Powder Technol. 436 (119473). https://doi.org/10.1016/j.powtec.2024.119473.

Foo, K.Y., Hameed, B.H., 2009. Utilization of rice husk ash as novel adsorbent: a judicious recycling of the colloidal agricultural waste. Adv. Colloid Interface Sci. 152 (1–2), 39–47. https://doi.org/10.1016/j.cis.2009.09.005.

Freire, M., Lopes, H., Tarelho, L.A., 2015. Critical aspects of biomass ashes utilization in soils: composition, leachability, PAH and PCDD/F. Waste Manag. 46, 304–315. https://doi.org/10.1016/j.wasman.2015.08.036.

Gadore, V., Mishra, S.R., Sillanpää, M., Ahmaruzzaman, M., 2024. Emerging applications of waste fly ash for remediation of environmental contaminants: a high-value and sustainable approach towards utilization of waste materials. Nanotechnology for Environmental Engineering 9 (2), 207–237. https://doi.org/10.1007/s41204-024-00362-z.

Giampaolo, C., Mastro, S.L., Polettini, A., Pomi, R., Sirini, P., 2002. Acid neutralisation capacity and hydration behaviour of incineration bottom ash–Portland cement mixtures. Cement Concr. Res. 32 (5), 769–775. https://doi.org/10.1016/S0008-8846(01)00760-8.

Gonfa, A., Bedadi, B., Argaw, A., 2018. Effect of bagasse ash and filter cake amendments on wheat (Triticum turgidum L. var. durum) yield and yield components in nitisol. Int. J. Recycl. Org. Waste Agric. 7, 231–240. https://doi.org/10.1007/s40093-018-0209-7.

Gransee, A., Führs, H., 2013. Magnesium mobility in soils as a challenge for soil and plant analysis, magnesium fertilization and root uptake under adverse growth conditions. Plant Soil 368, 5–21. https://doi.org/10.1007/s11104-012-1567-y.

Gulyurtlu, I., Crujeira, A.T., Abelha, P., Cabrita, I., 2007. Measurements of dioxin emissions during co-firing in a fluidised bed. Fuel 86 (14), 2090–2100. https://doi.org/10.1016/j.fuel.2007.01.037.

Gupta, A., Pandey, V., Yadav, M.K., Mohanta, K., Majhi, M.R., 2022. A comparative study on physio-mechanical properties of silica compacts fabricated using rice husk ash derived amorphous and crystalline silica. Ceram. Int. 48 (23), 35750–35758. https://doi.org/10.1016/j.ceramint.2022.07.098.

Haarr, A., 2005. The Reuse of Phosphorus. Eureau Position Paper EU2-04-SL09, 2005.

Haglund, N., Group, Expert, 2008. NT Technical Report – Guideline for Classification of Ash from Solid Biofuels and Peat Utilized for Recycling and Fertilizing in Forestry and Agriculture. Norway, Nordic Innovation Centre, Oslo.

Huotari, N., Tillman-Sutela, E., Moilanen, M., Laiho, R., 2015. Recycling of ash–For the good of the environment? For. Ecol. Manag. 348, 226–240. https://doi.org/10.1016/j.foreco.2015.03.008.

Ikpe, F.N., Powell, J.M., 2002. Nutrient cycling practices and changes in soil properties in the crop-livestock farming systems of western Niger Republic of West Africa. Nutrient Cycl. Agroecosyst. 62, 37–45. https://doi.org/10.1023/A:1015199114833.

Insam, H., Knapp, B.A., 2011. Recycling of Biomass Ashes. Springer Science & Business Media.

James, A.K., Thring, R.W., Helle, S., Ghuman, H.S., 2012. Ash management review—applications of biomass bottom ash. Energies 5 (10), 3856–3873. https://doi.org/10.3390/en5103856.

Kamath, S.R., Proctor, A., 1998. Silica gel from rice hull ash: preparation and characterization. Cereal Chem. 75 (4), 484–487. https://doi.org/10.1094/CCHEM.1998.75.4.484.

Kardung, M., Drabik, D., 2021. Full speed ahead or floating around? Dynamics of selected circular bioeconomies in Europe. Ecol. Econ. 188 (107146). https://doi.org/10.1016/j.ecolecon.2021.107146.

Kershaw, E.H., Hartley, S., McLeod, C., Polson, P., 2021. The sustainable path to a circular bioeconomy. Trends Biotechnol. 39 (6), 542–545. https://doi.org/10.1016/j.tibtech.2020.10.015.

Kiran, B.R., Prasad, M.N.V., 2019. Biochar and rice husk ash assisted phytoremediation potentials of Ricinus communis L. for lead-spiked soils. Ecotoxicol. Environ. Saf. 183 (109574). https://doi.org/10.1016/j.ecoenv.2019.109574.

Koppejan, J., van Loo, S., 2007. The Handbook of Biomass Combustion and Co-firing (1st ed.). Routledge. https://doi.org/10.4324/9781849773041.

Košnář, Z., Mercl, F., Tlustoš, P., 2018. Ability of natural attenuation and phytoremediation using maize (Zea mays L.) to decrease soil contents of polycyclic aromatic hydrocarbons (PAHs) derived from biomass fly ash in comparison with PAHs–spiked soil. Ecotoxicol. Environ. Saf. 153, 16–22. https://doi.org/10.1016/j.ecoenv.2018.01.049.

Kosson, D.S., van der Sloot, H.A., Sanchez, F., Garrabrants, A.C., 2002. An integrated framework for evaluating leaching in waste management and utilization of secondary materials. Environ. Eng. Sci. 19 (3), 159–204. https://doi.org/10.1089/109287502760079188.

Kumar, U., Bandyopadhyay, M., 2006. Sorption of cadmium from aqueous solution using pretreated rice husk. Bioresour. Technol. 97 (1), 104–109. https://doi.org/10.1016/j.biortech.2005.02.027.

Kumpiene, J., Lagerkvist, A., Maurice, C., 2008. Stabilization of As, Cr, Cu, Pb and Zn in soil using amendments–a review. Waste Manag. 28 (1), 215–225. https://doi.org/10.1016/j.wasman.2006.12.012.

Lanzerstorfer, C., 2014. Chemical and physical characterization of cyclone fly ashes from five grate-fired biomass combustion plants. Carpath J Earth Env 9, 129–135.

Lavric, E.D., Konnov, A.A., De Ruyck, J., 2004. Dioxin levels in wood combustion—a review. Biomass Bioenergy 26 (2), 115–145. https://doi.org/10.1016/S0961-9534(03)00104-1.

Lata, S., Samadder, S.R., 2014. Removal of heavy metals using rice husk: a review. Int. J. Environ. Res. Dev. 4 (2), 165–170.

Lebrun, M., Macri, C., Miard, F., Hattab-Hambli, N., Motelica-Heino, M., Morabito, D., Bourgerie, S., 2017. Effect of biochar amendments on as and Pb mobility and phytoavailability in contaminated mine technosols phytoremediated by Salix. J. Geochem. Explor. 182, 149–156. https://doi.org/10.1016/j.gexplo.2016.11.016.

Liang, F., Wei, S., Xue, L., Yan, S., 2024. Adopting green absorbent for CO2 capture and agricultural utilization: biogas slurry and biomass ash case. Green Carbon. https://doi.org/10.1016/j.greenca.2024.03.001.

Lopes, H., Gulyurtlu, I., Abelha, P., Crujeira, T., Salema, D., Freire, M., Cabrita, I., 2009. Particulate and PCDD/F emissions from coal co-firing with solid biofuels in a bubbling fluidised bed reactor. Fuel 88 (12), 2373–2384. https://doi.org/10.1016/j.fuel.2009.02.024.

Mane, V.S., Mall, I.D., Srivastava, V.C., 2007. Kinetic and equilibrium isotherm studies for the adsorptive removal of Brilliant Green dye from aqueous solution by rice husk ash. J. Environ. Manag. 84 (4), 390–400. https://doi.org/10.1016/j.jenvman.2006.06.024.

Masscheleyn, P.H., Delaune, R.D., Patrick Jr., W.H., 1991. Effect of redox potential and pH on arsenic speciation and solubility in a contaminated soil. Environ. Sci. Technol. 25 (8), 1414–1419. https://doi.org/10.1021/es00020a008.

Masto, R.E., Sarkar, E., George, J., Jyoti, K., Dutta, P., Ram, L.C., 2015. PAHs and potentially toxic elements in the fly ash and bed ash of biomass fired power plants. Fuel Process. Technol. 132, 139–152. https://doi.org/10.1016/j.fuproc.2014.12.036.

Maheswaran, G., Krishnapillai, M., Churchill, D., Galagedara, L., 2019. Fly-ash from a pulp and paper mill: a potential liming material for agricultural soils in Western Newfoundland. Can. Biosyst. Eng. 61, 1–15. https://doi.org/10.7451/CBE.2019.61.1.9.

Medaiyese, A.O., Wu, J., Unc, A., 2023. Utility of wood ash, paper sludge and biochar for the mitigation of greenhouse gases emissions from acid boreal soils. J. Environ. Manag. 330 (117202). https://doi.org/10.1016/j.jenvman.2022.117202.

Mosoarca, G., Vancea, C., Popa, S., Boran, S., Tanasie, C., 2020. A green approach for treatment of wastewater with manganese using wood ash. J. Chem. Technol. Biotechnol. 95 (6), 1781–1789. https://doi.org/10.1002/jctb.6376.

Mozaffari, M., Rosen, C.J., Russelle, M.P., Nater, E.A., 2000. Chemical characterization of ash from gasification of alfalfa stems: implications for ash management (Vol. 29, No. 3, pp. 963–972. Crop Science Society of America, and Soil Science Society of America. American Society of Agronomy. https://doi.org/10.2134/jeq2000.00472425002900030035x.

Mozaffari, M., Russelle, M.P., Rosen, C.J., Nater, E.A., 2002. Nutrient supply and neutralizing value of alfalfa stem gasification ash. Soil Sci. Soc. Am. J. 66 (1), 171–178. https://doi.org/10.2136/sssaj2002.1710.

Müller-Stöver, D., Ahrenfeldt, J., Holm, J.K., Shalatet, S.G.S., Henriksen, U., Hauggaard-Nielsen, H., 2012. Soil application of ash produced by low-temperature fluidized bed gasification: effects on soil nutrient dynamics and crop response. Nutrient Cycl. Agroecosyst. 94, 193–207. https://doi.org/10.1007/s10705-012-9533-x.

Naiya, T.K., Bhattacharya, A.K., Mandal, S., Das, S.K., 2009. The sorption of lead (II) ions on rice husk ash. J. Hazard Mater. 163 (2–3), 1254–1264. https://doi.org/10.1016/j.jhazmat.2008.07.119.

Niu, Y., Tan, H., 2016. Ash-related issues during biomass combustion: alkali-induced slagging, silicate melt-induced slagging (ash fusion), agglomeration, corrosion, ash utilization, and related countermeasures. Prog. Energy Combust. Sci. 52, 1–61. https://doi.org/10.1016/j.pecs.2015.09.003.

Nurmesniemi, H., Mäkelä, M., Pöykiö, R., Manskinen, K., Dahl, O., 2012. Comparison of the forest fertilizer properties of ash fractions from two power plants of pulp and paper mills incinerating biomass-based fuels. Fuel Process. Technol. 104, 1–6. https://doi.org/10.1016/j.fuproc.2012.06.012.

Obernberger, I., Brunner, T., Bärnthaler, G., 2006. Chemical properties of solid biofuels—significance and impact. Biomass Bioenergy 30 (11), 973–982. https://doi.org/10.1016/j.biombioe.2006.06.011.

Obernberger, I., Supancic, K., 2009. Possibilities of ash utilization from biomass combustion plants, 29 June–03 July Proceedings of the 17th European Biomass Conference & Exhibition. Germany, Hamburg.

Occupational Safety and Health Administration, 2024. US department of labour 2002 silica (crystalline); available online at. https://www.osha.gov/silica-crystalline/health-effects.

Ochecova, P., Tlustos, P., Szakova, J., 2014. Wheat and soil response to wood fly ash application in contaminated soils. Agron. J. 106 (3), 995–1002. https://doi.org/10.2134/agronj13.0363.

Ohno, T., Erich, M.S., 1990. Effect of wood ash application on soil pH and soil test nutrient levels. Agriculture. Ecosystems & Environment 32 (3–4), 223–239. https://doi.org/10.1016/0167-8809(90)90162-7.

Onwuka, M.I., Osodeke, V.E., Okolo, N.A., 2007. Amelioration of soil acidity using cocoa husk ash for maize production in Umudike area of south east Nigeria. Tropical and Subtropical Agroecosystems 7 (1), 41–45.

Pandey, V.C., Singh, N., 2010. Impact of fly ash incorporation in soil systems. Agric. Ecosyst. Environ. 136 (1–2), 16–27. https://doi.org/10.1016/j.agee.2009.11.013.

Patterson, S.J., Acharya, S.N., Thomas, J.E., Bertschi, A.B., Rothwell, R.L., 2004. Barley biomass and grain yield and canola seed yield response to land application of wood ash. Agron. J. 96 (4), 971–977. https://doi.org/10.2134/agronj2004.0971.

Pels, J.R., De Nie, D.S., Kiel, J.H.A., 2005. Utilization of Ashes from Biomass Combustion and Gasification. 14th European Biomass Conference & Exhibition. France, Paris, pp. 17–21. October 2005, ECN-RX-05-182.

Phongpan, S., Mosier, A.R., 2003. Impact of organic residue management on nitrogen use efficiency in an annual rice cropping sequence of lowland Central Thailand. Nutrient Cycl. Agroecosyst. 66, 233–240. https://doi.org/10.1023/A:1024475229663.

Piekarczyk, M., 2013. Content of absorbable forms of some macro-and microelements in light soil fertilized with ash from winter wheat straw. Fragm. Agron 30, 92–98.

Pitman, R.M., 2006. Wood ash use in forestry–a review of the environmental impacts. Forestry 79 (5), 563–588. https://doi.org/10.1093/forestry/cpl041.

Pomoni, D.I., Koukou, M.K., Vrachopoulos, M.G., Vasiliadis, L., 2024. Circular economy: a multilevel approach for natural resources and wastes under an agri-food perspective. Water-Energy Nexus. https://doi.org/10.1016/j.wen.2023.12.003.

Pöykiö, R., Nurmesniemi, H., Olli, D.A.H.L., Mäkelä, M., 2014. Chemical fractionation method for characterization of biomass-based bottom and fly ash fractions from large-sized power plant of an integrated pulp and paper mill complex. Trans. Nonferrous Metals Soc. China 24 (2), 588–596. https://doi.org/10.1016/S1003-6326(14)63099-5.

Qin, B., Liu, W., He, E., Li, Y., Liu, C., Ruan, J., Tang, Y., 2019. Vacuum pyrolysis method for reclamation of rare earth elements from hyperaccumulator Dicranopteris dichotoma grown in contaminated soil. J. Clean. Prod. 229, 480–488. https://doi.org/10.1016/j.jclepro.2019.05.031.

Rice, F.L., Park, R., Stayner, L., Smith, R., Gilbert, S., Checkoway, H., 2001. Crystalline silica exposure and lung cancer mortality in diatomaceous earth industry workers: a quantitative risk assessment. Occup. Environ. Med. 58 (1), 38–45. https://doi.org/10.1136/oem.58.1.38.

Rolka, E., Wyszkowski, M., Żołnowski, A.C., Skorwider-Namiotko, A., 2024. Role of woody biomass ash material in immobilization of cadmium, lead and zinc in soil. Materials 17 (2206). https://doi.org/10.3390/ma17102206.

Rouhani, A., Gutiérrez, M., Newton, R.A., Al Souki, K.S., 2024. An overview of potentially toxic element pollution in soil around lead-zinc mining areas. Environ. Rev. https://doi.org/10.1139/er-2024-0052.

Saarsalmi, A., Smolander, A., Kukkola, M., Arola, M., 2010. Effect of wood ash and nitrogen fertilization on soil chemical properties, soil microbial processes, and stand growth in two coniferous stands in Finland. Plant Soil 331, 329–340. https://doi.org/10.1007/s11104-009-0256-y.

Sahu, J.N., Agarwal, S., Meikap, B.C., Biswas, M.N., 2009. Performance of a modified multi-stage bubble column reactor for lead (II) and biological oxygen demand removal from wastewater using activated rice husk. J. Hazard Mater. 161 (1), 317–324. https://doi.org/10.1016/j.jhazmat.2008.03.094.

Saletnik, B., Zagula, G., Bajcar, M., Czernicka, M., Puchalski, C., 2018. Biochar and biomass ash as a soil ameliorant: the effect on selected soil properties and yield of giant miscanthus (Miscanthus x giganteus). Energies 11 (2535). https://doi.org/10.3390/en11102535.
Samsuri, A.W., Tariq, F.S., Karam, D.S., Aris, A.Z., Jamilu, G., 2019. The effects of rice husk ashes and inorganic fertilizers application rates on the phytoremediation of gold mine tailings by vetiver grass. Appl. Geochem. 108 (104366). https://doi.org/10.1016/j.apgeochem.2019.104366.
Schiemenz, K., Eichler-Löbermann, B., 2010. Biomass ashes and their phosphorus fertilizing effect on different crops. Nutrient Cycl. Agroecosyst. 87, 471–482. https://doi.org/10.1007/s10705-010-9353-9.
Shen, J., Liu, X., Zhu, S., Zhang, H., Tan, J., 2011. Effects of calcination parameters on the silica phase of original and leached rice husk ash. Mater. Lett. 65 (8), 1179–1183. https://doi.org/10.1016/j.matlet.2011.01.034.
Shen, H., Zhou, C., Xu, S., Huang, Y., Shi, J., Liu, G., Dou, C., 2024. Study on the solidification performance and mechanism of heavy metals by sludge/biomass ash ceramsites, biochar and biomass ash. Environ. Geochem. Health 46 (78). https://doi.org/10.1007/s10653-023-01846-8.
Shi, R.Y., Li, J.Y., Xu, R.K., Qian, W., 2016. Ameliorating effects of individual and combined application of biomass ash, bone meal and alkaline slag on acid soils. Soil Tillage Res. 162, 41–45. https://doi.org/10.1016/j.still.2016.04.017.
Silva, F.C., Cruz, N.C., Tarelho, L.A., Rodrigues, S.M., 2019. Use of biomass ash-based materials as soil fertilisers: critical review of the existing regulatory framework. J. Clean. Prod. 214, 112–124. https://doi.org/10.1016/j.jclepro.2018.12.268.
Singh, S., Ram, L.C., Masto, R.E., Verma, S.K., 2011. A comparative evaluation of minerals and trace elements in the ashes from lignite, coal refuse, and biomass fired power plants. Int. J. Coal Geol. 87 (2), 112–120. https://doi.org/10.1016/j.coal.2011.05.006.
Singh, R., Srivastava, P., Singh, P., Sharma, A.K., Singh, H., Raghubanshi, A.S., 2019. Impact of rice-husk ash on the soil biophysical and agronomic parameters of wheat crop under a dry tropical ecosystem. Ecol. Indicat. 105, 505–515. https://doi.org/10.1016/j.ecolind.2018.04.043.
Stupak, I., Asikainen, A., Röser, D., Pasanen, K., 2008. Review of recommendations for forest energy harvesting and wood ash recycling. Sustainable use of forest biomass for energy: A synthesis with focus on the baltic and nordic region 155–196. https://doi.org/10.1007/978-1-4020-5054-1_7.
Tan, Z., Lagerkvist, A., 2011. Phosphorus recovery from the biomass ash: a review. Renew. Sustain. Energy Rev. 15 (8), 3588–3602. https://doi.org/10.1016/j.rser.2011.05.016.
Tarelho, L.A.C., Teixeira, E.R., Silva, D.F.R., Modolo, R.C.E., Silva, J.J.F., Gomes, A.P.D., Pereira, C., Amorim, M.J., Lopes, M.H.D., Freire, M., 2013. Forest biomass residues combustion in a thermal power plant with FBC and ash characteristics and management options. In: Proceedings of the 21st European Biomass Conference and Exhibition. Denmark, Copenhagen, pp. 3–7. June.
Tariq, F.S., Samsuri, A.W., Karam, D.S., Aris, A.Z., 2016. Phytoremediation of gold mine tailings amended with iron-coated and uncoated rice husk ash by vetiver grass (Vetiveria zizanioides (Linn.) Nash). Applied and Environmental Soil Science 2016. https://doi.org/10.1155/2016/4151898.
Tariq, F.S., Samsuri, A.W., Karam, D.S., Aris, A.Z., Jamilu, G., 2019. Bioavailability and mobility of arsenic, cadmium, and manganese in gold mine tailings amended with rice husk ash and Fe-coated rice husk ash. Environ. Monit. Assess. 191, 1–12. https://doi.org/10.1007/s10661-019-7359-6.
Thind, H.S., Sharma, S., Vashistha, M., Singh, G., 2012. Land application of rice husk ash, bagasse ash and coal fly ash: effects on crop productivity and nutrient uptake in rice–wheat system on an alkaline loamy sand. Field Crops Res. 135, 137–144. https://doi.org/10.1016/j.fcr.2012.07.012.
Tosti, L., van Zomeren, A., Pels, J.R., Dijkstra, J.J., Comans, R.N., 2019. Assessment of biomass ash applications in soil and cement mortars. Chemosphere 223, 425–437. https://doi.org/10.1016/j.chemosphere.2019.02.045.
Uwiringiyimana, E., Lai, H.W., Ni, N., Shi, R.Y., Pan, X.Y., Gao, J.N., Xu, R.K., 2024. Comparative efficacy of alkaline slag, biomass ash, and biochar application for the amelioration of different acidic soils. Plant Soil 1–15. https://doi.org/10.1007/s11104-024-06678-8.
Van der Sloot, H.A., 2000. Comparison of the characteristic leaching behavior of cements using standard (EN 196-1) cement mortar and an assessment of their long-term environmental behavior in construction products during service life and recycling. Cement Concr. Res. 30 (7), 1079–1096. https://doi.org/10.1016/S0008-8846(00)00287-8.
Vassilev, S.V., Baxter, D., Vassileva, C.G., 2014. An overview of the behaviour of biomass during combustion: Part II. Ash fusion and ash formation mechanisms of biomass types. Fuel 117, 152–183. https://doi.org/10.1016/j.fuel.2013.09.024.
Vigliaturo, R., Kehrli, D., Garra, P., Dieterlen, A., Trouvé, G., Dietze, V., Gieré, R., 2019. Opaline phytoliths in Miscanthus sinensis and its cyclone ash from a biomass-combustion facility. Ind. Crop. Prod. 139 (111539). https://doi.org/10.1016/j.indcrop.2019.111539.
Wahlström, M., Laine-Ylijoki, J., Kaartinen, T., 2009. Acid neutralization capacity of waste-specification of requirement stated in landfill regulations. Nordic Council of Ministers 2009, 51. https://doi.org/10.6027/TN2009-580.
Wan Ngah, W., Hanafiah, M.A.K.M., 2008. Removal of heavy metal ions from wastewater by chemically modified plant wastes as adsorbents: a review. Bioresour. Technol. 99 (10), 3935–3948. https://doi.org/10.1016/j.biortech.2007.06.011.
Wang, X., Sun, C., Cai, H., Zhang, J., 1999. Origin of the Chinese cultivated rice (Oryza sativa L.). Chin. Sci. Bull. 44, 295–304. https://doi.org/10.1007/BF02885476.
Wang, G., Shen, L., Sheng, C., 2012. Characterization of biomass ashes from power plants firing agricultural residues. Energy & Fuels 26 (1), 102–111. https://doi.org/10.1021/ef201134m.
Wang, R., ZongGuo, X., Hu, R., Wu, J., Xu, Y., Yu, Z., Zhang, Y., 2024. Biomass ash as soil fertilizers: supercharging biomass accumulation by shifting auxin distribution. Chemosphere 357 (141910). https://doi.org/10.1016/j.chemosphere.2024.141910.
Wei, Z., Ming, Y., Xun, Z., Fashui, H., Bing, L., Ye, T., Chunhua, Y., 2001. Rare earth elements in naturally grown fern Dicranopteris linearis in relation to their variation in soils in South-Jiangxi region (Southern China). Environ. Pollut. 114 (3), 345–355. https://doi.org/10.1016/S0269-7491(00)00240-2.
Wei, Z.G., Hong, F.S., Yin, M., Li, H.X., Hu, F., Zhao, G.W., Wong, J.W.C., 2004. Off-line separation and determination of rare earth elements associated with chloroplast pigments of hyperaccumulator Dicranopteris dichotoma by normal-phase liquid chromatography and ICP–MS. Anal. Bioanal. Chem. 380, 677–682. https://doi.org/10.1007/s00216-004-2757-0.
Wei, Z., Gao, B., Cheng, K.Y., Kaksonen, A.H., Kolev, S.D., Wong, J.W., Cui, J., 2020. Exploring the use of Dicranopteris pedata ash as a rare earth fertilizer to Ipomoea aquatica Forsskal. J. Hazard Mater. 400 (123207). https://doi.org/10.1016/j.jhazmat.2020.123207.
White, P.J., Brown, P., 2010. Plant nutrition for sustainable development and global health. Ann. Bot. 105 (7), 1073–1080. https://doi.org/10.1093/aob/mcq085.
Wierzbowska, J., Sienkiewicz, S., Żarczyński, P., Krzebietke, S., 2020. Environmental application of ash from incinerated biomass. Agronomy 10 (482). https://doi.org/10.3390/agronomy10040482.
Wong, K.K., Lee, C.K., Low, K.S., Haron, M.J., 2003. Removal of Cu and Pb from electroplating wastewater using tartaric acid modified rice husk. Process Biochem. 39 (4), 437–445. https://doi.org/10.1016/S0032-9592(03)00094-3.
Yadvinder-Singh, Gupta, R.K., Thind, H.S., Ladha, J.K., 2009. Poultry litter as a nitrogen and phosphorous source for the rice–wheat cropping system. Biol. Fertil. Soils 45, 701–710. https://doi.org/10.1007/s00374-009-0373-z (2009).
Yuvakkumar, R., Nathanael, A.J., Rajendran, V., Hong, S.I., 2014. Rice husk ash nanosilica to inhibit human breast cancer cell line (3T3). J. Sol. Gel Sci. Technol. 72, 198–205. https://doi.org/10.1007/s10971-014-3455-9.
Zając, G., Szyszlak-Bargłowicz, J., Gołębiowski, W., Szczepanik, M., 2018. Chemical characteristics of biomass ashes. Energies 11 (2885). https://doi.org/10.3390/en11112885.
Zhai, J., Burke, I.T., Stewart, D.I., 2021. Beneficial management of biomass combustion ashes. Renew. Sustain. Energy Rev. 151 (111555). https://doi.org/10.1016/j.rser.2021.111555.
Zhao, F.J., Hawkesford, M.J., Warrilow, A.A., McGrath, S.P., Clarkson, D.T., 1996. Responses of two wheat varieties to sulphur addition and diagnosis of sulphur deficiency. Plant Soil 181, 317–327. https://doi.org/10.1007/BF00012066.
Zimmermann, S., Frey, B., 2002. Soil respiration and microbial properties in an acid forest soil: effects of wood ash. Soil Biol. Biochem. 34 (11), 1727–1737. https://doi.org/10.1016/S0038-0717(02)00160-8.