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Review on the Role of Wood Ash in Improving Humus Formation during Aerobic Composting of Food Waste

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Abstract: This review examines the role of **wood ash** as an amendment in enhancing humus formation during the aerobic composting of food waste. Humus, a stable organic material derived from decomposed plant and microbial matter, is critical for soil health, carbon sequestration, and sustainable agriculture. However, optimizing humus production during composting remains a challenge due to variable feedstock quality and inefficient decomposition processes. Wood ash, a byproduct of biomass combustion, offers a promising solution by improving **microbial activity**, **regulating pH**, and **supplying essential nutrients** such as calcium, potassium, and phosphorus.

The review synthesizes current research on the mechanisms by which wood ash influences composting efficiency, including its effects on microbial communities, carbon-to-nitrogen (C:N) ratio balance, lignin decomposition, and humic substance stability. Key findings indicate that moderate wood ash application (4–8% by weight) accelerates organic matter breakdown, enhances compost maturity, and increases nutrient retention without significant heavy metal accumulation. However, excessive use can lead to **alkaline conditions**, **microbial imbalance, and potential environmental risks.**

A case study highlights the practical benefits of wood ash in composting, demonstrating improved temperature dynamics, pH stability, and nutrient enrichment at optimal dosages. Challenges such as heavy metal contamination, over-application risks, and long-term soil impacts are discussed, alongside recommendations for sustainable use. Future research directions include microbial community dynamics, feedstock-specific interactions, and standardized guidelines for ash application.

This review underscores the potential of wood ash as a sustainable composting additive, offering insights for waste management, soil fertility enhancement, and climate change mitigation through improved humus formation.

Keywords: *Wood ash, Aerobic Composting, Humus Formation, Soil Health, Microbial Activity, Sustainability.*

Cite this Article

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Introduction

Background and Importance of Composting

Africa's rapid population growth, increasing economic activities, and ever-expanding urbanization have resulted in unprecedented expanding of waste generation. Subsequently, this has led to expanding risky uncontrolled waste management practices due to the magnitude and the pollution from waste disposal sites, it has reached a state of emergency across the African continent. The organic fraction of municipal solid waste (MSW) in Africa accounts for approximately 57% of the total waste generated, making it the predominant component of MSW in the region.

Composting is a biological process that converts organic waste into nutrient-rich compost through microbial decomposition(Ayilara et al., 2020). It is a sustainable waste management practice that reduces landfill burden, minimizes greenhouse gas emissions, and recycles nutrients back into the soil. Aerobic composting, in particular, relies on oxygen-dependent microbes to break down organic matter efficiently while generating stable humus. This method not only enhances soil fertility but also reduces reliance on chemical fertilizers, thereby promoting environmental health (Sathiyapriya et al., 2024). The importance of composting is underscored by its ability to recycle nutrients, improve soil structure, and support microbial activity, which are essential for sustainable crop production. It contributes to humus formation, providing essential nutrients for crops and stimulating microbial activity, which improves soil vitality. Overall, producing nutrient-rich compost bio-inputs requires integrated research on compost enhancement and the microbial processes that drive nutrient transformation(Sathiyapriya et al., 2024).

Composting is an aerobic fermentation process driven by microorganisms that converts organic matter into stable, soil-enriching compost. This compost enhances soil structure and boosts its physical, chemical, and microbial properties. Despite these benefits, its application in agriculture is often limited by its slow nutrient release and relatively low levels of plant-available nutrients. To address this, researchers have explored nutrient supplementation and the addition of beneficial microorganisms during composting(Sánchez et al., 2017).

However, optimizing the composting process for improved humus formation remains a key challenge, requiring amendments such as wood ash to enhance decomposition and nutrient balance (Ayilara et al., 2020). Several studies on composting techniques and the impacts of different additives, including wood ash, help us to grasp the part wood ash plays in increasing humus generation during the aerobic composting of food waste (Ayilara et al., 2020; Ma, 2018). Additionally, incorporating ferrous salts during composting can accelerate humification and reduce carbon emissions by promoting biotic and abiotic functions (Ammari et al., 2015).

Role of Humus in Soil Health and Carbon Sequestration

Humus, the stable organic fraction of decomposed plant and microbial matter, plays a critical role in soil fertility and carbon cycling(Yifeng Zhang et al., 2021). It improves soil structure, enhances water retention, and supports microbial diversity(Skorokhodov et al., 2021). Compost application increases soil's water-holding capacity, reducing irrigation needs and enhancing crop resilience(Taneja et al., 2024) (Taneja et al., 2024). Additionally, humus acts as a long-term carbon sink, mitigating climate change by sequestering atmospheric carbon in soils. Effective humus formation during composting ensures that organic waste is converted into a valuable soil amendment that enhances agricultural productivity and environmental sustainability(Mi et al., 2018). Composting mitigates the environmental impact of waste by converting organic materials into valuable resources, thus addressing the global waste management crisis(Kumar et al., 2024)(Kumar, 2024).
Humus content is a critical component of global carbon cycling, with far-reaching implications for climate regulation(Hu et al., 2023). Plants absorb atmospheric CO_2 through photosynthesis, converting it into organic compounds that sustain ecosystems(Dusenge et al., 2019). When plants, animals, and organic fuels decompose or burn, CO_2 is released back into the atmosphere(Dusenge et al., 2019). However, soils act as the largest terrestrial carbon reservoir, storing more carbon than all living biomass and the atmosphere combined, approximately two to three times the atmospheric carbon pool(Rahman, 2013). Depletion of Soil Organic Matter(SOM), particularly through deforestation and agricultural conversion, releases significant CO_2, exacerbating climate change(Obalum et al., 2017). For instance, a mere 1% decline in SOM can drastically increase atmospheric CO_2 levels(Fred Magdoff, 2021). Despite its importance, humus content or, in general, soil organic matter's role in carbon sequestration is often underrepresented in climate mitigation strategies and land-management policies.

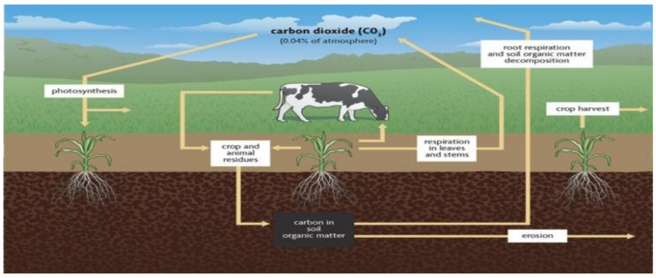

Fig 1: Humus(Organic Matter) Carbon Cycle flow chart.(Fred Magdoff, 2021)

Purpose of the Review

This review investigates the use of wood ash as an amendment in aerobic composting and its effects on humus formation. It specifically investigates the chemical and biological interactions between wood ash and decomposing organic matter, emphasizing the potential for improved compost stability, nutrient enrichment, and microbial activity.

By combining recent research findings, this review intends to provide insights into improving composting processes for increased humus output and soil health.

Methodology

This review adopts a systematic approach to evaluate the role of wood ash in enhancing humus formation during the aerobic composting of food waste. The methodology is structured to comprehensively analyze existing literature while identifying key trends, knowledge gaps, and practical applications.

Literature Search and Selection of Papers

The literature searches encompassed peer-reviewed journal articles, books, and technical reports from databases including Scopus, Web of Science, Google Scholar, and PubMed, using keywords such as "wood ash AND composting," "humus formation," and "soil amendment." Studies were selected based on their focus on wood ash's chemical properties, microbial interactions, and humus stabilization, excluding those on inorganic additives, anaerobic composting, or non-English publications. The analysis identified key knowledge gaps, such as long-term ecological impacts and feedstock-specific interactions, leading to practical recommendations like optimal ash incorporation rates (4–8% by weight) and heavy metal mitigation strategies. A conceptual framework was developed to elucidate wood ash's role in enhancing humus formation through physicochemical and microbial processes.

Aerobic Composting of Food Waste Principles of Aerobic Composting

Aerobic composting is a controlled biological process that decomposes organic waste in the presence of oxygen, converting it into stable humus through microbial activity(Bhave & Kulkarni, 2019). The key principles governing this process include maintaining optimal oxygen levels, moisture content (40–60%), and a balanced carbon-to-nitrogen (C:N) ratio (25:1–30:1) to support microbial metabolism(Amuah et al., 2022; Haug, 1979). Aerobic microorganisms, including bacteria and fungi, break down complex organic compounds into simpler forms, releasing heat, carbon dioxide, and water as byproducts(Lal, 2009). Temperature plays a critical role, with mesophilic (20–45°C) and thermophilic (50–70°C) phases ensuring efficient decomposition, pathogen inactivation, and weed seed destruction(Franke-Whittle & Insam, 2013; Lepesteur, 2022). Proper aeration, achieved through regular turning or forced airflow, prevents anaerobic conditions that can lead to foul odors and slower decomposition.(Briški & Vuković Domanovac, 2017).

The efficiency of aerobic composting depends on several interrelated factors, including particle size, feedstock diversity, and microbial community dynamics. Smaller particle sizes increase surface area for microbial action, while a mix of carbon-rich "browns" (e.g., leaves, straw) and nitrogen-rich "greens" (e.g., food scraps, manure) ensures a balanced nutrient supply(Wang et al., 2023). Microbial diversity drives the breakdown of cellulose, lignin, and other resistant compounds, ultimately forming humus, a stable organic material that enhances soil structure and fertility(Aguilar-Paredes et al., 2023; Palaniveloo et al., 2020). By adhering to these principles, aerobic composting transforms waste into a valuable soil amendment, closing nutrient loops and contributing to sustainable waste management and agriculture(Bhave & Kulkarni, 2019).

Factors Affecting Composting Efficiency

The efficiency of aerobic composting is influenced by multiple interdependent factors, including feedstock composition, aeration, moisture, and temperature(Alkoaik, 2019). A balanced C:N ratio (25:1–30:1) is essential for maintaining microbial activity, as deviations can either slow decomposition or cause nitrogen loss through volatilization (Azim et al., 2018). Optimal moisture levels (40–60%) are necessary for microbial metabolism, while inadequate or excessive moisture can lead to anaerobic zones or hinder heat generation(Meena et al., 2021). Particle size also plays a crucial role; smaller particles increase surface area for microbial colonization but may compact and restrict airflow. Temperature dynamics, driven by microbial activity, determine the rate of organic matter breakdown and pathogen reduction. like wood ash can modulate these factors by altering pH and nutrient availability, but their use must be carefully calibrated to avoid(Barthod et al., 2018).

Summary of factors influence the efficiency of aerobic composting and the quality of the final compost product:

Carbon-to-Nitrogen Ratio (C/N Ratio): A balanced C/N ratio (typically 25:1 to 35:1) promotes efficient microbial metabolism and prevents excessive ammonia loss or slow decomposition(W. Zhang et al., 2024). It is vital in humification, as it regulates organic matter decomposition and humus formation. An optimal ratio (25:1 to 30:1) ensures efficient microbial activity—carbon provides energy, while nitrogen supports protein synthesis(Yu et al., 2019). A high C/N ratio slows decomposition due to nitrogen scarcity, whereas a low ratio speeds it up but risks nitrogen loss. A balanced ratio promotes stable humus, improving soil fertility and structure(Xu et al., 2020). Additionally, the C/N ratio affects humus stability. Carbon-rich materials (e.g., straw) decompose slowly, enhancing long-term organic matter, while nitrogen-rich materials (e.g., manure) break down quickly but require balancing for sustained humification(Kacprzak et al., 2023). The studies concluded that proper C/N management ensures nutrient release, moisture retention, and microbial health, making it essential for sustainable soil practices(Mazzilli et al., 2015).

Oxygen Supply: Proper aeration is necessary to support aerobic microbial activity, prevent anaerobic conditions, and reduce odor emissions(Zubir et al., 2024). Oxygen supply is crucial in humification, as it sustains aerobic microbes that decompose organic matter efficiently(Li et al., 2022). Proper aeration prevents anaerobic conditions, ensuring faster breakdown and high-quality humus formation(S. Zhang et al., 2021). Aerobic decomposition enhances nutrient cycling and produces stable humic substances, while a lack of oxygen leads to slow, incomplete humification(Rastogi et al., 2020). Most studies mentioned that managing oxygen levels by turning or improving the airflow through composting or soil aeration is key to sustainable soil health and fertility(Xu et al., 2019).

Moisture Content: An optimal moisture range of 50-60% ensures microbial survival and enzymatic activity without waterlogging the compost pile(Ho et al., 2022). Moisture content is essential in humification, as it regulates microbial activity and organic matter breakdown(Li et al., 2021). Ideal moisture (50–60%) supports efficient decomposition, while too little or too much water disrupts the process(Larionova et al., 2017). Proper Moisture Management, as indicated by Haida et al 2021 and some other studies, prevents anaerobic conditions, nutrient loss, and incomplete humification, ensuring the production of high-quality humus for healthy, fertile soil(Haider, 2021).

Temperature: Thermophilic conditions (50-65°C) accelerate decomposition, kill pathogens, and enhance humus formation(J. Zhang et al., 2024). Temperature critically impacts humification by controlling microbial decomposition rates. Optimal warmth (55-65°C) speeds up breakdown, while extreme heat or cold disrupts the process(Haider, 2021; Q. Zhang et al., 2021). Managed temperatures ensure efficient organic matter conversion, pathogen reduction, and high-quality humus production, enhancing long-term soil health(Vikram et al., 2022).

pH Levels: A slightly acidic to neutral pH (6.0-8.0) supports microbial diversity and efficient organic matter breakdown. pH levels play a crucial role in humification by regulating microbial activity and humus formation(Zaccone et al., 2018). Neutral to slightly acidic pH (6.0–7.5) supports efficient decomposition, while extreme pH disrupts the process(Boguta et al., 2019). Proper pH management ensures high-quality humus production, improving soil structure and nutrient availability for sustainable soil health(Ampong et al., 2022).

Bulking Agents and Additives: Materials like wood ash, biochar, and sawdust improve aeration, regulate moisture, and enhance nutrient retention(Liu et al., 2021). Bulking agents like wood ash improve humification by enhancing aeration, pH balance, and nutrient supply(Rastogi et al., 2020). Its affordability and mineral content make it a valuable additive, but moderation is key to avoid excessive alkalinity(Abelenda & Aiouache, 2022). Proper use of wood ash and other bulking agents ensures faster decomposition and nutrient-rich humus, boosting soil fertility sustainably(Ren et al., 2023).

Microbial Activity and Humus Formation

Microorganisms, including bacteria, fungi, and actinomycetes, play a crucial role in decomposing food waste and facilitating humus formation. During aerobic composting, microbial enzymes break down carbohydrates, proteins, and lipids into simpler compounds, eventually leading to the synthesis of humic substances(Khatoon, 2017). Microorganisms play a fundamental role in humus formation by breaking down organic matter into stable, nutrient-rich compounds. Their combined activity determines the efficiency of organic matter breakdown and the quality of humus produced(Chungopast et al., 2021).

Bacteria: Primary decomposers that break down simple organic matter and generate heat during metabolism. Bacteria are the most abundant decomposers, rapidly breaking down simple sugars, proteins, and other easily degradable organic compounds(Perucci et al., 2015; Yiyue Zhang et al., 2021). They dominate the early stages of decomposition, generating heat and accelerating the breakdown process. Certain bacteria, such as cellulolytic and nitrogen-fixing species, enhance humus formation by converting complex plant materials into simpler forms and enriching the soil with bioavailable nitrogen(Chungopast et al., 2021; HL et al., 2021). Their fast metabolic rates make them crucial for initiating humification (Condron et al., 2010).

Fungi: Essential for degrading complex compounds such as lignin and cellulose, contributing to humus stability. Fungi specialize in decomposing tough, fibrous materials like lignin, and hemicellulose, which are resistant to bacterial breakdown(Kuhad et al., 2011). Through enzymatic action, fungi slowly degrade these complex compounds, contributing to the formation of stable humic substances. Mycorrhizal fungi further improve humus quality by forming symbiotic relationships with plant roots, enhancing nutrient exchange and soil aggregation(Waksman, 2025). Their filamentous growth helps bind soil particles, improving structure and moisture retention.

Actinomycetes: Decompose resistant organic materials and enhance the formation of humic substances. Actinomycetes, often considered a bridge between bacteria and fungi, thrive in later stages of decomposition(Bhatti et al., 2017). They excel at breaking down chitin, cellulose, and other recalcitrant materials, contributing to the earthy smell of mature compost(Javed et al., 2021). These microorganisms produce humic precursors and help stabilize organic matter, playing a key role in the final stages of humus formation. Their ability to decompose tough residues makes them essential for long-term soil fertility.

The integration of amendments like wood ash can influence microbial activity by regulating pH, providing essential minerals, and enhancing microbial community structure, ultimately promoting humus formation(Bougnom et al., 2011). Microbial activity drives humus formation, with bacteria initiating rapid decomposition, fungi breaking down complex organic matter, and actinomycetes stabilizing humus in later stages(Waksman, 2025). Together, they ensure efficient nutrient cycling and the production of high-quality, stable humus, which enhances soil structure, fertility, and plant growth. Managing microbial populations through proper composting and soil care optimizes humification for sustainable agriculture.

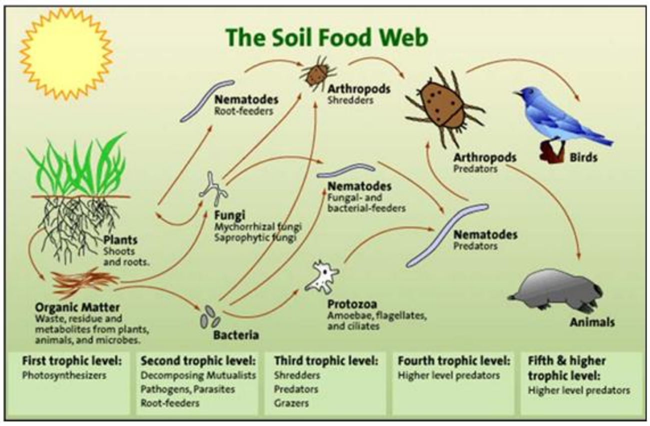

Fig. 2: The soil food web showing maintenance of the soil ecosystem(Khatoon, 2017)

Composition and Properties of Wood Ash

The composition and properties of wood ash play a significant role in enhancing humification, particularly in agricultural and environmental contexts. Wood ash, a byproduct of burning wood, contains essential nutrients and minerals that can improve soil quality and promote microbial activity, which are crucial for humification processes(Noviks, 2015). With its possible use as a sustainable resource in agriculture and environmental management and a soil supplement, wood ash, the inorganic waste left over from burning wood or wood-based biomass, has attracted growing attention(Sharma et al., 2019) .Tree species, combustion temperature, and processing technique all affect its composition and qualities. Harnessing the advantages of wood ash and controlling possible environmental issues depends on knowing its chemical profile, alkalinity, and nutritional contents(Sharma et al., 2019).

Wood ash significantly accelerates humification by increasing soil pH and supplying essential macro- and micronutrients (e.g., Ca, K, Mg, P) that stimulate microbial decomposition of organic matter(Ochecova et al., 2014). Studies show that wood ash application at 5–20 Mg ha^{-1} can enhance soil organic carbon (SOC) stabilization by up to 30%, as its alkaline nature (pH 10–13) promotes the formation of stable humic acids through Maillard reactions and lignin polymerization(Zagvozda et al., 2022). Additionally, trace metals like Fe and Mn in wood ash act as catalysts for oxidative enzymes (e.g., peroxidase, laccase) that drive humus formation(Mosoarca et al., 2020). However, excessive application (>30 Mg ha^{-1}) may disrupt microbial communities due to elevated salinity, underscoring the need for optimized dosing(Chaudhary et al., 2016).

Chemical Composition of Wood Ash

The humification-enhancing properties of wood ash are significantly influenced by its chemical composition, which varies based on the source and processing methods(Abbasi et al., 2013). The major components include alkaline earth metals, silica, and organic compounds, which contribute to its effectiveness as a soil amendment and its potential in construction materials(Hannam et al., 2017). The chemical composition of wood ash is predominantly oxides of essential plant nutrients. Along with minor elements such manganese (Mn), iron (Fe), and aluminum (Al), major ingredients usually include calcium oxide (CaO), potassium oxide (K_2O_5), and fewer amounts of magnesium oxide (MgO), Phosphorus pentoxide (P_2) and silica (SiO_2)(Zając et al., 2018). These oxides originate from mineral content absorbed during plant growth. The high concentration of CaO, which frequently exceeds 40%, is a distinguishing trait, imparting a strong alkaline character(Magdziarz et al., 2016). The variability in compositing is base the type of plant or wooden material and combustion efficiency, indicated in a study which elucidates the temperature-dependent phase transformations and elemental volatilization in wood ash, providing critical insights for optimizing combustion systems and managing ash deposition, while highlighting the need for further research on practical mitigation strategies and feedstock-specific behavior(Misra et al., 1993; Ryssen & Ndlovu, 2018).

Alkalinity and pH Regulation

Strong alkalinity of wood ash is one of its most notable features; this is mostly related to its high calcium oxide concentration(Aronsson & Ekelund, 2004). Wood ash functions as a liming agent and raises the pH of the soil when mixed with moisture to create calcium hydroxide(Scheepers & du Toit, 2016). In acidified soils, where it helps neutralize acidity and improves the bioavailability of vital nutrients, this quality is very helpful(Johan et al., 2021). Furthermore, supporting long-term pH stability in soil systems is the buffering capacity of wood ash, which enhances root development and microbial activity(Mahmood et al., 2003). This particular study concluded that its high alkalinity makes it an effective liming agent for acidic soils, while its nutrient content enhances soil fertility(Juárez et al., 2015). The ash's chemical makeup varies depending on the source material and combustion conditions. When applied properly, wood ash can serve as a sustainable alternative to synthetic soil amendments(Fernández-Delgado Juárez et al., 2015). However, the study fails to indicate its long-term sustainability and viability on soil health.

The general formula for estimating the concentration of a specific oxide component in wood ash is: Coxide=(ηash$F$mineral×$f$oxide)×100%.

Formula: Oxide Concentration from

$$C_{\text{oxide}} = \left(\frac{F_{\text{mineral}} \times f_{\text{oxide}}}{\eta_{\text{ash}}} \right) \times 100\%$$

Biomass, Where

Coxide = Concentration of the specific oxide (e.g., CaO, K_2O) in the wood ash (% by weight).

Fmineral= Total mineral (inorganic) content of the dry woody biomass (g minerals / g dry biomass). Typical values range from 0.005 (0.5%) for clean wood to >0.02 (2%) for bark or contaminated wood.

foxide = Mass fraction of the specific oxide within the total mineral content of the biomass (g oxide / g total minerals). This value is highly species-specific.

ηash = Ash yield, representing the fraction of the original dry biomass that remains as ash after complete combustion (g ash / g dry biomass).

Nutrient Contribution

Wood ash is recognized as an important source of plant nutrients, particularly potassium and phosphorus, which are required for a variety of physiological and metabolic activities in plants(Hannam et al., 2018). Potassium (K) in the form of K_2O promotes osmotic regulation, enzyme activation, and plant vigor(Kim et al., 2022). Phosphorus helps with energy transfer, root development, and flowering and fruit yielding(Okoli et al., 2024). Magnesium and trace minerals enhance the nutrient profile of wood ash, aiding in chlorophyll production and catalytic processes(Neina et al., 2020). Unlike synthetic fertilizers, wood ash provides a slow-release nutrient source, making it excellent for sustainable soil fertility augmentation when applied wisely(Guo et al., 2024).

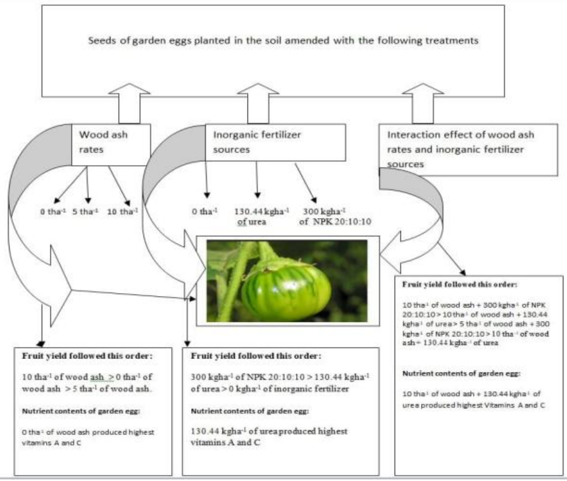

Fig. 3: indicates the effects on Fruit yield (Okoli et al., 2024)

Comparison of Wood Ash with Other Additives

Wood ash enhances compost quality by improving organic matter stabilization through its alkaline nature, which accelerates decomposition and increases humus formation, though less effectively than biochar(Bougnom et al., 2020). It raises pH, benefiting acidic soils but potentially reducing microbial diversity if over-applied, whereas lime offers similar pH moderation with fewer microbial impacts(Dědina et al., 2022). However, wood ash poses risks of heavy metal accumulation (e.g., Cd, Pb) if sourced from treated wood, unlike gypsum or rock phosphate, which provide minerals with lower contamination risks(Dědina et al., 2022; Rodríguez et al., 2019). See the Summary comparison Table of wood ash with other additives.

Comparison Table: Wood Ash vs. Other Compost Additives

Parameter	**Wood Ash**	**Biochar**	**Lime**	**Gypsum**	**Rock Phosphate**
Organic Matter Stabilization	Moderate (speeds decomposition)(Zagvozda et al., 2022)	High (enhances C sequestration)(Ameloot et al., 2013)	Low(Akula et al., 2021)	Low(Jha & Sivapullaiah, 2016)	Low(Akande et al., 2004)
pH Balance	Raises pH significantly	Mildly alkaline	Raises pH moderately	Neutral to slight pH increase	Neutral
Microbial Diversity	Can reduce if over applied	Enhances	Moderate impact	Minimal impact	Minimal impact
Heavy Metal Risk	High (if from treated wood) (Zagvozda et al., 2022)	Low(Ameloot et al., 2013)	Low(Akula et al., 2021)	Very low(Jha & Sivapullaiah, 2016)	Moderate (depends on source)(Akande et al., 2004)

This comparison table evaluates five compost additives wood ash, biochar, lime, gypsum, and rock phosphate based on their effects on organic matter stabilization, pH balance, microbial diversity, and heavy metal risk. Wood ash stands out for its moderate organic matter stabilization (speeding decomposition) and significant pH-raising capacity, making it ideal for acidic soils common in Developing countries (Zagvozda et al., 2022). While biochar excels in carbon sequestration (Ameloot et al., 2013), wood ash is often the most practical choice for developing nations due to its low cost (as a byproduct of biomass energy), local availability, and immediate nutrient release (e.g., K, Ca, Mg) crucial for smallholder farmers. However, caution is needed to avoid over-application (which can reduce microbial diversity) and ensure ash is sourced from untreated wood to minimize heavy metal risks (Zagvozda et al., 2022). Lime and gypsum offer pH or structural benefits but lack nutrient contributions, while rock phosphate's efficacy depends on costly processing. Thus, wood ash provides a balanced, affordable, and accessible solution for soil improvement in resource-limited settings.

Case Study (Previous Studies on Wood Ash in Composting)

A study conducted by Juárez, M. F. D., Gómez-Brandón, M., & Insam, H. (2015). The topic of this study was "Merging two waste streams, wood ash and biowaste, results in improved composting process and end products." The primary objective was to investigate how different proportions of wood ash (0%, 3%, 6%, 9%, 12%, and 15%) influence the composting process of biowaste. Specifically, the research aimed to analyze the effects on gas emissions (CO_2, O_2, and CH_4), chemical parameters (pH, electrical conductivity, and inorganic nitrogen), and the overall quality of the final compost. Additionally, the study sought to identify the optimal ash dosage that enhances composting efficiency without compromising the safety and maturity of the end product, ensuring compliance with standards like the Austrian Compost Ordinance.

The experiment was conducted at a municipal composting plant using six windrows, each containing one ton of communal biowaste (a mix of food/garden waste and tree cuttings). The biowaste was amended with varying percentages of wood ash (0% as control, 3%, 6%, 9%, 12%, and 15% by weight). Over 49 days, the composting process was monitored by measuring temperature, gas emissions (CO_2, O_2, CH_4), pH, electrical conductivity (EC), and inorganic nitrogen (NH_4^+ and NO_3^-). The final compost was assessed for maturity using the Dewar self-heating test, toxicity through plant growth assays (using cress, Lepidium sativum), and quality by analyzing heavy metal content (Cd, Pb, Cu, Zn) and macronutrient levels (P, K, Ca, Mg). Statistical analysis, including repeated measures ANOVA, was employed to evaluate the effects of ash dosage and composting time.

The study revealed that wood ash addition, even at 15%, did not hinder the composting process. Higher ash dosages (6–15%) initially accelerated microbial activity, leading to faster temperature increases (peaking at 70.8°C in 3% ash by day 21, compared to 64.8°C in the control). Gas emissions showed elevated CO_2 and CH_4 levels in the early stages, though CH_4 dropped to zero by day 28 as aerobic conditions stabilized. Ash also improved pH buffering (rising from 7.3 in the control to 8.5 in 15% ash) and increased macronutrient content (e.g., phosphorus rose from 3.64 g/kg to 6.76 g/kg), similar to findings by Abbasi et al. during composting. However, heavy metals like cadmium and zinc exceeded Class A+ limits at ash dosages above 9%, making 8–9% the optimal range for balancing benefits and safety. All composts achieved Reifegrad V maturity, confirming their stability for agricultural use.

The study concluded that wood ash is an effective additive for biowaste composting, enhancing decomposition rates, nutrient content, and pH stability. The study identified 8–9% as the optimal ash dosage, as it maximizes composting efficiency while keeping heavy metal concentrations within acceptable limits, a finding consistent with Mupambwa et al., who noted that moderate addition yields better optimal conditions without exceeding acceptable heavy metal rates. However, strict quality control is essential to ensure ash-derived pollutants do not compromise compost safety. These findings support the sustainable reuse of wood ash in waste management, aligning with circular economy principles.

To safely integrate wood ash into composting practices, the study recommends pre-screening ashes for heavy metals to avoid contamination risks, limiting dosage to 8–9% to comply with quality standards like the Austrian Compost Ordinance, optimizing aeration to minimize methane emissions, and conducting region-specific pilot trials to refine application guidelines. However, gaps remain that warrant further research, including long-term soil impact assessments, exploration of alternative ash sources (e.g., agricultural residues), cost-benefit analyses for large-scale implementation, and the development of harmonized regulatory standards for ash quality and compost safety. Addressing these gaps will optimize wood ash use in composting, ensuring both environmental sustainability and agronomic benefits while expanding its practical applicability.

Optimal Application Rates of Wood Ash

The determination of optimal wood ash application rates in aerobic composting is vital for maximizing its agronomic and ecological benefits while minimizing adverse impacts. Wood ash, as established in numerous studies, contains valuable plant nutrients such as calcium, potassium, magnesium, and phosphorus. It also possesses significant liming potential due to its high pH, primarily driven by calcium carbonate and calcium oxide content. These characteristics make it a promising additive for enhancing microbial activity and promoting humification processes during composting. However, the application rate must be carefully regulated to avoid issues such as excessive alkalinity, nutrient imbalances, or heavy metal contamination.

Research conducted at a semi-industrial composting plant, as included in this manuscript, demonstrated that application rates ranging from 6% to 12% (w/w) had beneficial effects on compost dynamics. Specifically, ash-amended composts exhibited increased temperatures during early composting stages, improved pH regulation, enhanced organic matter mineralization, and greater nutrient enrichment in the final product. However, rates above 9% also led to an increase in heavy metal concentrations (e.g., cadmium and lead), which resulted in a downgrade of compost quality according to the Austrian Compost Ordinance. These findings suggest that while higher ash rates can boost nutrient availability and compost stability, they also raise the risk of regulatory non-compliance and potential soil contamination.

A meta-analysis of ash usage in composting suggests that 4–8% by weight represents a generally safe and effective range for most organic feedstocks. Within this range, wood ash supports microbial diversity, optimizes the carbon-to-nitrogen (C:N) ratio, and enhances the breakdown of recalcitrant compounds like lignin. Importantly, the exact optimal rate may vary depending on the type of feedstock used (e.g., food waste, manure, straw), the ash's chemical composition, and the local environmental context. For instance, composts rich in acidic substrates (like citrus waste or pine needles) may tolerate slightly higher ash dosages.

Given the variability of ash composition, largely influenced by wood type, combustion conditions, and ash collection practices, site-specific testing is essential. Regular analysis of ash samples for pH, nutrient content, and heavy metals is recommended before application. Blending wood ash with acidic or nitrogen-rich materials can further moderate its effects and broaden its application in composting.

In conclusion, while wood ash is an effective compost additive, its application rate must be carefully managed. An optimal range of 4–8% by weight is generally supported by both empirical findings and literature, but local validation is necessary to ensure environmental safety and compost quality.

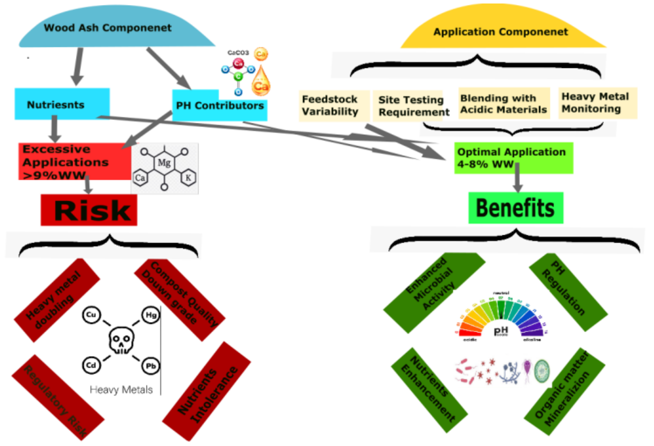

Fig 4: Visual explanation of Optimal Application rate

Risks of Overuse and High pH Levels

One of the primary challenges associated with the use of wood ash in aerobic composting is the risk of overuse, which often leads to elevated pH levels and downstream ecological consequences. Wood ash, inherently alkaline due to its calcium oxide and other metal oxide content, typically has a pH range between 9 and 13. While this alkalinity is beneficial in neutralizing acidic compost and enhancing microbial activity, excessive application can create overly alkaline conditions that are detrimental to microbial diversity, organic matter decomposition, and nutrient availability.

The microbial ecosystem of a composting system is highly sensitive to pH fluctuations. Many beneficial microorganisms, including fungi critical for lignin decomposition, thrive in slightly acidic to neutral pH environments (6.0–7.5). When pH levels exceed 9.0, the activity of acidophilic microbes, such as nitrifying bacteria and certain saprophytic fungi, is significantly suppressed. This microbial imbalance can slow decomposition, reduce humus formation, and impair nitrogen cycling. Furthermore, the overuse of ash may favor only a limited range of alkali-tolerant bacteria (e.g., Bacillus, Actinobacteria), thereby reducing overall microbial diversity, which is crucial for producing mature, nutrient-rich compost.

High pH levels also impact nutrient dynamics. Alkaline conditions increase the volatilization of ammonia, resulting in nitrogen loss from the compost pile. This not only reduces the nitrogen content of the final product but may also contribute to odor problems and air quality issues. Additionally, elevated pH can lead to the precipitation of certain micronutrients such as iron, manganese, and zinc, making them less available to plants. Therefore, although the compost may appear nutrient-rich, the bioavailability of those nutrients could be compromised under excessively alkaline conditions.

Another concern with over-application of wood ash is the potential accumulation of heavy metals. Ash derived from treated wood or industrial sources may contain lead, cadmium, and chromium, which can accumulate in the compost and, when applied to soil, pose risks to plant, animal, and human health. Elevated pH further facilitates the mobility of certain heavy metals, increasing their leachability and potential to contaminate groundwater.

To mitigate these risks, it is essential to maintain ash application within the recommended 4–8% range and to blend ash with materials that help buffer pH, such as acidic food waste or biochar. Regular pH monitoring throughout the composting process is also necessary. If high pH is detected, compost managers may introduce acidifying agents (e.g., sulfur, peat moss) or increase aeration to facilitate CO_2 release, which can lower pH over time.

In summary, while wood ash is a powerful tool in compost enhancement, its overuse can undermine microbial ecology, nutrient stability, and environmental safety. Maintaining balanced pH levels through controlled application is key to realizing its full potential without compromising compost quality.

Sustainability and Long-Term Effects

The integration of wood ash into composting systems presents a compelling opportunity for enhancing sustainability in organic waste management. However, its long-term effects on soil health, crop productivity, and ecosystem stability require comprehensive evaluation. Sustainability in this context involves not just immediate benefits to compost quality but also the enduring consequences of repeated ash use in agricultural landscapes.

One of the long-term advantages of using wood ash is its contribution to soil nutrient reserves. Ash provides essential macronutrients (notably calcium, potassium, and phosphorus) and trace elements, contributing to sustained soil fertility. Additionally, the alkalinity of ash helps to correct soil acidity, a persistent issue in many agricultural systems, especially those affected by acid rain or intensive fertilization. This pH regulation enhances nutrient availability and promotes beneficial microbial activity, particularly in acidified soils.

Another sustainable feature of wood ash is its potential to increase soil organic carbon through humus stabilization. Calcium ions in ash aid the formation of mineral-organic complexes, which protect humic substances from microbial degradation. This effect supports long-term carbon sequestration, aligning with climate change mitigation strategies. Moreover, humus-rich soils demonstrate improved water retention, cation exchange capacity, and erosion resistance, which are vital attributes for resilient agricultural systems.

Nevertheless, concerns about the sustainability of wood ash use stem from the risk of cumulative heavy metal buildup and potential toxicity. Long-term application of ash, especially from contaminated sources, can lead to elevated concentrations of elements such as cadmium, lead, and chromium. These metals persist in soil, bioaccumulate in crops, and may enter the food chain, posing serious health risks. Furthermore, consistent high-pH inputs can lead to microelement deficiencies (e.g., iron, boron), altering plant physiological responses and reducing crop quality over time.

Another sustainability consideration is the source and variability of wood ash. Ash derived from clean, untreated biomass is ideal, but not always available. Inconsistent sourcing introduces unpredictability in ash composition, making it difficult to standardize application rates and predict long-term outcomes. Additionally, the sustainability of harvesting and burning wood must be assessed; large-scale biomass combustion may conflict with forest conservation goals and carbon neutrality if not managed responsibly.

To ensure long-term sustainability, periodic soil testing is crucial. This includes monitoring of pH, nutrient levels, heavy metals, and microbial biomass. Integrated composting strategies that combine ash with other organic amendments (e.g., manure, crop residues, biochar) can help balance nutrient profiles and reduce environmental risks. Regulatory frameworks and guidelines should also be updated to reflect current research, ensuring safe application rates and standardized testing of ash quality.

In conclusion, wood ash can contributes significantly to sustainable composting and soil management if applied judiciously. While its immediate benefits are clear, long-term sustainability depends on responsible sourcing, careful monitoring, and adaptive management strategies that prioritize both environmental health and agricultural productivity.

Conclusion and Future Research Directions

Summary of Key Findings

This review underscores the multifaceted and promising role of wood ash as an amendment in enhancing humus formation during aerobic composting of food waste. Wood ash application has been shown to significantly improve the efficiency and quality of composting by influencing critical physicochemical and biological parameters. Specifically, the alkaline nature of wood ash helps buffer pH, creating an environment favorable for microbial proliferation and enzymatic activity, particularly among lignin-degrading microorganisms such as Actinobacteria and certain fungi. These microbial shifts accelerate the breakdown of complex organic materials like lignocellulose, thereby promoting faster and more efficient humification processes.

Moreover, wood ash contributes essential macronutrients such as calcium, potassium, and phosphorus, which enhance microbial metabolism and increase the nutrient profile of the final compost product. Application of moderate amounts (typically between 4% and 8% by weight) was associated with improved organic matter stabilization, enhanced humic substance formation, and increased compost maturity without introducing toxic effects. However, the findings consistently emphasize that the positive impacts of wood ash are highly dose-dependent. Exceeding recommended dosages, particularly above 10%, led to undesirable consequences such as excessive pH elevation, suppression of beneficial microbial diversity, and accumulation of heavy metals like cadmium and lead (Fernández-Delgado Juárez et al., 2015).

Importantly, the review highlights the potential of wood ash to support sustainable agricultural practices by improving soil fertility, promoting carbon sequestration through stable humus formation, and reducing dependence on synthetic fertilizers. However, these benefits can only be fully realized through responsible sourcing of wood ash, careful monitoring of application rates, and regular assessment of compost and soil quality. In conclusion, moderate and well-managed use of clean wood ash represents a viable strategy to enhance composting outcomes and support broader environmental and agricultural sustainability goals.

Knowledge Gaps and Areas for Further Study

While current research confirms the significant benefits of wood ash in composting systems, several important knowledge gaps must be addressed to optimize its application and ensure environmental safety. Firstly, there is limited understanding of how wood ash influences the structure, succession, and functional dynamics of microbial communities during the different stages of composting. While shifts in microbial populations have been noted, detailed metagenomic or functional profiling studies under varying ash dosages and environmental conditions remain scarce.

Furthermore, although short-term improvements in compost quality are well-documented, there is a lack of long-term field studies assessing the cumulative effects of applying ash-amended compost on soil biota, nutrient cycling, and crop performance. In particular, the fate and bioavailability of heavy metals in soils receiving ash-enriched compost over multiple growing seasons require urgent investigation to avoid unintended soil degradation or health risks.

Another important gap is the interaction between wood ash and different types of organic feedstocks. Most research has focused on general biowaste; however, how ash behaves when combined with high-lignin materials like wood chips, straw, or forest residues is not well understood. These interactions could significantly influence the rate of humification and compost stability, suggesting a need for substrate-specific guidelines.

Comparative studies between wood ash and other alkaline or nutrient-rich amendments, such as lime, biochar, and gypsum, are also limited. Understanding the relative advantages and drawbacks of each could help refine best practices in compost management. Finally, standardized protocols for wood ash characterization, including assessment of heavy metal content, solubility, and reactivity, are urgently needed to support regulatory frameworks and practical decision-making.

Addressing these research gaps through interdisciplinary and long-term studies will be crucial for advancing the sustainable and safe use of wood ash in composting and broader soil health initiatives.

Recommendations for Practical Applications

For practical use, it is recommended that wood ash be applied at rates between 4–8% by weight in compost mixtures, depending on its chemical composition. Ash should be sourced from clean, untreated biomass to minimize heavy metal contamination. Compost piles amended with ash should be regularly monitored for pH, EC, and metal content. To balance the alkaline effect of wood ash, co-composting with acidic or nitrogen-rich materials is advisable. Moreover, standardizing regulatory frameworks for ash use in composting would support its safe and widespread adoption. Future efforts should focus on establishing region-specific guidelines based on ash type, waste composition, and soil requirements to maximize the environmental and agronomic benefits of wood ash-enhanced compost.

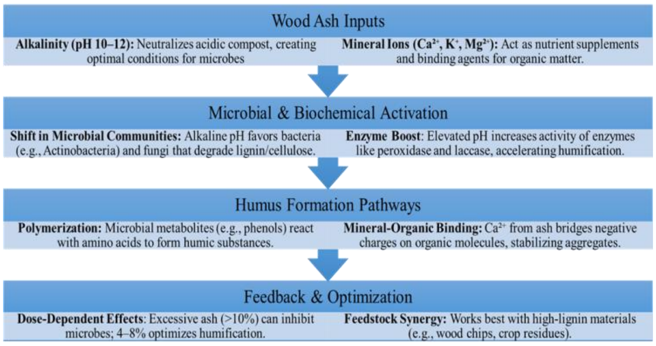

Fig 5: Humification Flowchart Pathways using Wood Ash

Conflict of Interest Statement

This review was conducted independently, and no funding or influence from external organizations affected the research, analysis, or conclusions presented. All cited studies and data sources are referenced transparently for academic integrity.

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