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Ph.D. thesis

Integrated Approaches to Soil Management, Crop Resilience, and Sustainable Agriculture

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České Budějovice
2025

Declaration

I declare that I am the author of this qualification thesis and that I used only sources and literature displayed in the list of references in its preparation.

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Signature

Abstrakt

Degradace půdy, zejména acidifikace, představuje vážnou výzvu pro globální zemědělství, protože ohrožuje produktivitu plodin, půdní biodiverzitu a dlouhodobou udržitelnost. Zemědělci tradičně spoléhají na vápenec ke korekci kyselosti půdy, avšak jeho vysoké náklady a omezená dostupnost vyvolaly potřebu hledání alternativních půdních přísad. Tato disertační práce, založená na literárním přehledu, se zaměřuje především na potenciál dřevního popela jako udržitelné strategie hospodaření s půdou a současně využívá doplňující studie, které rozšiřují diskusi o další půdní přísady, mikrobiální procesy a biotechnologické inovace.

Dřevní popel, vedlejší produkt spalování biomasy, je bohatý na vápník, draslík, hořčík a stopové živiny. Jeho alkalická povaha z něj činí účinnou náhradu vápna, která dokáže neutralizovat kyselost půdy a zároveň dodat plodinám základní živiny. Tato práce syntetizuje poznatky z různých studií s cílem zhodnotit roli dřevního popela při zlepšování úrodnosti půdy, zvyšování výnosů plodin a podpoře ekologicky šetrného zemědělství. Zvláštní pozornost je věnována variabilitě složení dřevního popela, pufrační kapacitě půdy a rizikům spojeným s jeho nadměrnou aplikací či akumulací těžkých kovů.

Vedle hlavního zaměření na dřevní popel tato disertační práce zahrnuje také další články, které poskytují širší kontext pro udržitelné hospodaření s půdou. Přehled o rostlinných zbytcích zdůrazňuje jejich přínos k tvorbě půdní organické hmoty a koloběhu živin, zatímco jiný článek o biocharu hodnotí jeho roli při zlepšování půdní struktury, sekvestrace uhlíku a mikrobiální aktivity. Mikrobiální rozměr je zastoupen studiemi o těkavých organických sloučeninách (VOCs) produkovaných rhizobakteriemi, které mohou stimulovat růst rostlin a koloběh živin. Dále je zařazena studie dynamiky půdní organické hmoty (SOM), která se zaměřuje na kvantitativní metody hodnocení dlouhodobé úrodnosti, a přehled nástrojů založených na nukleových kyselinách, které představují moderní přístupy ke zvyšování odolnosti plodin vůči klimatickému stresu. Tyto články dohromady ukazují, jak lze dřevní popel začlenit do širších rámců hospodaření s půdou.

Z metodologického hlediska je práce založena na literární rešerši, nikoli na experimentu. Uplatňuje systematický přehled literatury, strukturovanou extrakci dat a tematickou syntézu napříč více recenzovanými studiemi. Každý článek byl analyzován z hlediska cílů, metodologie a výsledků, následovaná byla srovnávací analýza k identifikaci synergií a omezení. Tento přístup umožnil jak detailní zaměření na dřevní popel, tak i širší pochopení jeho vztahu k jiným strategiím hospodaření s půdou.

Zjištění ukazují, že dřevní popel má značný potenciál jako levná a ekologická půdní přísada, avšak jeho aplikace vyžaduje pečlivé přizpůsobení konkrétním půdním podmínkám. Rostlinné zbytky a biochar doplňují dřevní popel obohacováním organické hmoty a zlepšováním půdní struktury, zatímco mikrobiální a molekulární inovace představují budoucí směry pro adaptivnější a odolnější zemědělské systémy. Napříč všemi tématy práce identifikuje významné mezery, včetně potřeby standardizovaných aplikačních protokolů, dlouhodobé terénní validace a integrovaných strategií, které kombinují chemické, biologické a technologické přístupy.

Závěrem tato práce tvrdí, že dřevní popel může hrát klíčovou roli v udržitelném zemědělství, pokud je aplikován odpovědně a v kombinaci s doplňujícími postupy. Začleněním dřevního popela do širších ekologických a technologických souvislostí přispívá práce k budování odolných agroekosystémů, snižování závislosti na chemických hnojivech a podpoře udržitelných cest k zajištění globální potravinové bezpečnosti.

Klíčová slova: dřevní popel, kyselost půdy, úrodnost půdy, biochar, rostlinné zbytky, udržitelné zemědělství

Abstract

Soil degradation, particularly soil acidification, is a serious challenge for global agriculture, threatening crop productivity, soil biodiversity, and long-term sustainability. Farmers have traditionally relied on lime to correct soil acidity, yet its high cost and limited availability have raised the need for alternative amendments. This paper-based thesis focuses primarily on the potential of wood ash as a sustainable soil management strategy, while also drawing on complementary studies that broaden the discussion to other soil amendments, microbial processes, and biotechnological innovations.

Wood ash, a byproduct of biomass combustion, is rich in calcium, potassium, magnesium, and trace nutrients. Its alkaline nature makes it an effective liming substitute, capable of neutralizing soil acidity and supplying essential nutrients to crops. The thesis synthesizes findings from diverse studies to evaluate the role of wood ash in improving soil fertility, enhancing crop yields, and contributing to environmentally friendly agriculture. Special emphasis is placed on understanding the variability of wood ash composition, soil buffering capacity, and the risks of over-application or heavy metal accumulation.

Alongside the central focus on wood ash, this thesis incorporates additional papers that provide a broader context for sustainable soil management. A review on crop residues highlights their contribution to soil organic matter and nutrient cycling, while another on biochar evaluates its role in improving soil structure, carbon sequestration, and microbial activity. The microbial dimension is represented by studies on rhizobacterial volatile organic compounds (VOCs), which can stimulate plant growth and nutrient turnover. Further, a paper on soil organic matter (SOM) dynamics examines quantitative methods for assessing long-term fertility, and a review of nucleic acid-based tools explores modern approaches for enhancing crop resilience under climate stress. Together, these papers demonstrate how wood ash can be integrated into wider soil management frameworks.

Methodologically, the thesis is paper-based rather than experimental. It applies a systematic literature review, structured data extraction, and thematic synthesis across multiple peer-reviewed studies. Each article was analyzed in terms of objectives, methodology, and outcomes, followed by a comparative evaluation to identify synergies and limitations. This approach allowed for both an in-depth focus on wood ash and a broader understanding of its relationship with other soil management strategies.

The findings indicate that wood ash holds significant promise as a low-cost, eco-friendly amendment, but its application requires careful calibration to site-specific soil properties. Crop residues and biochar complement wood ash by enriching organic matter and improving soil structure, while microbial and molecular innovations represent future directions for more adaptive and resilient farming systems. Across all topics, the thesis identifies important gaps, including the need for standardized application protocols, long-term field validation, and integrative strategies that combine chemical, biological, and technological approaches.

This work argues that wood ash can play a central role in sustainable agriculture when applied responsibly and supported by complementary practices. By situating wood ash within broader ecological and technological contexts, the thesis contributes to building resilient agroecosystems, reducing dependency on chemical fertilizers, and supporting sustainable pathways for global food security.

Keywords: wood ash, soil acidity, soil fertility, biochar, crop residues, sustainable agriculture

Contents

Chapter 1: Background of Study

1.1 Introduction

Soil acidification is a critical global challenge that restricts agricultural productivity and disrupts soil ecosystem balance (Chaudhari et al., 2019). Driven by intensive nitrogen fertilization, acid rain, and mineral weathering, acidification decreases soil pH, limits nutrient availability, increases toxic aluminum and manganese concentrations, and suppresses beneficial microbial activity (Ameyu, 2019). Reversing these effects is vital for food security and environmental sustainability (Neina, 2019).

Wood ash, a byproduct of biomass combustion, represents a sustainable and cost-effective amendment for soil management. Its high alkalinity, derived from calcium oxide and potassium carbonate, makes it a promising alternative to conventional lime for neutralizing acidity while supplying essential nutrients such as phosphorus, potassium, calcium, and magnesium (Demeyer et al., 2001; Escudey et al., 2010). Applying wood ash also supports circular bioeconomy principles by recycling waste materials and reducing landfill disposal. However, its efficacy and safety depend strongly on appropriate dosage and soil characteristics (Baloch et al., 2024).

Accurate determination of soil buffering capacity—the soil's ability to resist pH change—is essential for safe wood ash application. Over-liming can lead to nutrient imbalances and microbial disruption (Ké & Dihé, 2024), emphasizing the importance of dose adjustment based on buffering capacity (Woodard & Bly, 2010; Gupta et al., 2019). The interaction between wood ash and soil organic matter (SOM) also influences nutrient cycling and carbon sequestration, varying with soil type, ash source, and environmental conditions (Chimdessa & Sori, 2020). Maintaining an optimal pH is essential for nutrient availability and microbial functioning (Kendawang et al., 2004).

This study aims to determine optimal wood ash application rates based on soil buffering capacity and to evaluate their effects on SOM and liming requirements. Building upon recent review papers (Baloch et al., 2024), it synthesizes scientific and practical insights on the use of wood ash and related organic amendments for improving soil health and managing acidity in sustainable agricultural systems.

1.2 Literature Review

1.2.1 Wood Ash as a Soil Amendment

Wood ash, the residue of burned wood, contains essential minerals such as calcium, potassium, magnesium, and phosphorus, contributing to its liming and fertilizing properties (Rolka et al., 2023). Its alkalinity (pH 10–12) effectively neutralizes soil acidity and enhances nutrient availability (Adotey et al., 2018; Luna & Larrea, 2024). The potassium content supports strong root and reproductive growth (Jian et al., 2025). However, excessive application can raise pH beyond optimal levels, leading to micronutrient deficiencies and salt stress in sensitive species (Rumpf et al., 2001; 'Plant Growth-Promoting Rhizospheric Microbes for Remediation of Saline Soils', 2019). Soil testing prior to application is therefore essential for safe and effective use (Jian et al., 2025).

1.2.2 Chemical Composition and Variability of Wood Ash

WThe chemical composition of wood ash depends on wood type, combustion conditions, and storage, with variable levels of oxides, carbonates, and nutrients (Ké & Dihé, 2024; Van Lith et al., 2008; Arshad et al., 2012). While offering a sustainable nutrient source, inconsistencies in composition present challenges due to potential heavy metals or uneven nutrient content (Baloch et al., 2024; Jalajakshi et al., 2024). Thus, detailed characterization and standardization are vital for its safe agricultural use.

1.2.3 Soil pH and Buffering Capacity

Soil pH is a major determinant of nutrient availability and microbial activity (Zhang et al., 2019; Cox & Koenig, 2010; Barrow & Hartemink, 2023; Breugem et al., 2024). Buffering capacity—the soil's ability to resist pH change—depends on clay minerals, organic matter, and carbonates ('Buffering Capacity of Soils in Mining Areas and Mitigation of Acid Mine Drainage Formation', 2023a, 2023b). Soils rich in clay and organic matter buffer pH changes more effectively, whereas sandy soils are more reactive. Understanding buffering capacity is essential for determining appropriate wood ash application rates (Liyanage et al., 2012).

1.2.4 Liming Needs and Alternatives

Liming neutralizes acidity to maintain optimal pH and nutrient balance (Abdi, 2024; Hayes et al., 2022; Enesi et al., 2023). Traditional lime sources include calcium and magnesium carbonates and hydroxides (Li et al., 2019). Alternatives such as wood ash ('Possible Use of Wood Ash and Compost for Improving Acid Tropical Soils', 2011; Lama & Sain, 2021), compost, biochar (Akmal et al., 2019), and industrial byproducts like basic slag (Rathoure, 2019) provide sustainable options. Gypsum can also improve soil structure and calcium supply without major pH changes (Anderson et al., 2020).

1.2.5 Effects of Wood Ash on Soil pH and Buffering Capacity

Wood ash increases soil pH through alkaline oxides and carbonates (Füzesi et al., 2015; Arshad et al., 2012). Moderate applications enhance nutrient availability and reduce aluminum toxicity (Bonfim-Silva et al., 2019; Paramisparam et al., 2021), but excessive rates risk over-alkalinization (Melese & Yli-Halla, 2016). Its carbonate reserves also strengthen buffering capacity, stabilizing soil pH against acidifying processes (Jian et al., 2025; Hamidi et al., 2021).

1.2.6 Wood Ash as a Lime Substitute for Soil Liming

Wood ash effectively substitutes lime due to its calcium and magnesium carbonates, with a neutralizing value of 25–60% compared to pure calcium carbonate (Manirakiza et al., 2025). It also supplies additional nutrients such as potassium and phosphorus (Bachmaier et al., 2021). However, composition variability and potential metal contamination (Neina et al., 2020; Wiklund, 2017; Barbosa et al., 2009) necessitate careful testing and standardized application (Scussel et al., 2022).

1.2.7 Impacts of Wood Ash on Soil Organic Matter and Microbial Activity

Wood ash affects SOM and microbial dynamics primarily through pH modification and nutrient enrichment (Baloch et al., 2024; Błońska et al., 2023). Moderate ash application enhances bacterial activity and decomposition rates (Bang-Andreasen et al., 2017a), though effects on organic carbon vary (Zhao et al., 2022; Bougnom et al., 2020). High application rates may reduce microbial diversity and favor alkaliphilic taxa (Bang-Andreasen et al., 2017b; Noyce et al., 2016; Cruz-Paredes et al., 2021).

1.2.8 Environmental Considerations and Application Guidelines

While wood ash from untreated wood typically contains low metal concentrations, composition varies with feedstock and combustion conditions (Maresca et al., 2018; Pitman, 2006). Over-application can cause heavy metal accumulation and leaching (Beauchemin et al., 2015; Dědina et al., 2022; Romdhane et al., 2021). Only ash from untreated wood should be used (Yanitch et al., 2020). Safe application requires comprehensive soil and ash analysis (ASH, 2013; Kamal & Mahmood, 2024) and adherence to recommended rates and handling practices to prevent runoff or contamination (Baloch et al., 2024; James et al., 2012).

1.3 Research Objectives and Knowledge Gaps

This study aims to evaluate integrated approaches to soil management, crop resilience, and sustainable agriculture by synthesizing evidence across chemical, organic, biological, and molecular strategies. While wood ash is a central focus for its liming effect and nutrient contributions, the thesis also incorporates complementary practices such as crop residue management, biochar application, microbial innovations, and nucleic acid–based tools. Together, these approaches are assessed for their potential to improve soil fertility, strengthen crop resilience, and reduce dependence on chemical inputs.

- To evaluate the effectiveness of wood ash as a soil amendment for acidity management, fertility enhancement, and sustainable nutrient supply.
- To examine the role of crop residues and biochar in enriching soil organic matter, improving soil structure, and enhancing soil nutrient cycling.
- To explore microbial innovations, particularly rhizobacterial volatile organic compounds (VOCs), in supporting soil health and nutrient dynamics.
- To assess nucleic acid-based molecular tools for improving crop resilience under climate variability.
- To integrate chemical, organic, biological, and molecular strategies into a comprehensive soil management framework for long-term sustainability.

Knowledge Gaps Identified

- Limited research on site-specific integration of soil amendments (wood ash, biochar, residues) tailored to soil buffering capacity and fertility needs.
- Insufficient long-term studies on combined impacts of organic inputs and microbial processes on soil organic matter stability and nutrient cycling.
- Lack of standardized guidelines for safe and effective wood ash application across diverse soil types.

- Few comparative evaluations of integrated soil management strategies that combine chemical, biological, and molecular approaches.
- Limited application of modern molecular tools in practical field-based soil management frameworks.

Chapter 2: Methodology

2.1 Literature Search and Selection

This thesis adopts a comprehensive literature review approach, combined with the author's contributions to several peer-reviewed review articles and collaborative research studies. The purpose of the methodology was to systematically collect, analyze, and synthesize existing scientific evidence on the role of wood ash and complementary soil amendments in improving soil fertility, reducing soil acidity, and enhancing agricultural productivity. Relevant publications were identified through searches in major international databases, including ScienceDirect, Web of Science, Scopus, and Google Scholar. A combination of keywords was used, such as wood ash, soil amendment, soil acidity, liming effect, crop productivity, soil organic matter, biochar, rhizosphere, and sustainable agriculture.

2.2 Inclusion criteria were as follows:

- Peer-reviewed articles, review papers, and book chapters published in English.
- Studies reporting chemical, physical, or biological effects of wood ash and related amendments.
- Comparative studies where wood ash was evaluated against lime or other soil improvement strategies.
- Both short-term and long-term field or experimental studies relevant to soil fertility and sustainability.
- Priority was given to recent publications and those from high-impact journals

2.3 Organization of the Review

The selected literature was organized into thematic areas to highlight key aspects of soil management:

- Wood ash application for fertility enhancement and acidity management.
- Crop residue management and contributions to soil health.
- Soil organic matter (SOM) dynamics and evaluation methods.
- Rhizosphere engineering and microbial innovations for crop resilience.
- Biochar and other amendments for sustainable soil improvement.

2.4 Integration of Published Papers

This thesis is closely linked to published review papers and book chapters in which the author actively contributed. These publications form the foundation of Chapter 3 (Results and Discussion). Each paper followed a structured review or synthesis approach with a specific thematic focus:

1 Baloch et al. (2024), Chemosphere: Reviewed wood ash application for crop production, soil acidity reduction, and contaminated soil remediation. Methodology included systematic collection of experimental and field studies and comparative analysis with lime and other amendments.

2 Baloch et al. (2024), Heliyon: Focused on rhizobacterial volatile organic compounds (VOCs) and their role in nutrient cycling and soil health. Literature was screened to summarize microbial contributions to agricultural sustainability.

3 Murindangabo et al. (2023), Agronomy: Applied quantitative approaches to review and evaluate methods for assessing SOM dynamics. Methodology emphasized studies testing SOM measurement models and their applications.

4 Saeed et al. (2024), International Journal of Biological Macromolecules: Reviewed nucleic acid innovations for rhizosphere engineering and crop resilience under climate change. Literature synthesis included recent molecular advances and applied case studies.

5 Ali et al. (2024), IntechOpen Book Chapter: Reviewed biochar applications for improving soil quality and sustainability, drawing from experimental and field-based studies in diverse soils and cropping systems.

2.5 Synthesis and Critical Analysis

All selected literature and the above publications were critically analyzed to:

- Assess the benefits and challenges of using wood ash and complementary amendments.
- Compare findings across different soils, climates, and management practices.
- Highlight environmental considerations, such as heavy metal accumulation and nutrient leaching.
- Identify persistent knowledge gaps and directions for future research.

Chapter 3: Results and Conclusions

This dissertation integrates six peer-reviewed studies that collectively address sustainable soil management through chemical, biological, and molecular innovations. The primary focus lies on the evaluation of wood ash as an alternative to lime in acidic soils, supplemented by complementary research on crop residues, microbial interactions, soil organic matter dynamics, biochar, and nucleic acid-based approaches for improving soil fertility and crop resilience.

The first-author study on wood ash demonstrated its significant potential to neutralize soil acidity and enhance crop productivity through its high calcium, potassium, and magnesium content. Comparative analyses revealed that while wood ash effectively raised soil pH and improved nutrient availability, its variable composition and possible trace metal content necessitate site-specific assessment and cautious application. The study emphasized that integrating wood ash into sustainable management frameworks could reduce dependence on conventional liming materials while promoting circular bioeconomy practices by utilizing agricultural and forestry by-products.

The second paper on crop residue management highlighted the central role of organic recycling in restoring soil organic matter and improving physical structure. Residue retention and incorporation were shown to enhance microbial activity, nutrient cycling, and soil aggregation, thereby strengthening the foundation of long-term soil fertility. When combined with biochar or compost, crop residues provided synergistic benefits, supporting sustainable productivity and minimizing environmental degradation.

The third study explored rhizobacterial volatile organic compounds (VOCs) and their contribution to soil health. The review confirmed that specific VOCs stimulate plant growth, improve nutrient uptake, and suppress soil-borne pathogens, underscoring the importance of microbial-mediated nutrient cycling. These findings support the integration of microbiological insights into soil improvement strategies, bridging the gap between traditional soil amendments and next-generation biotechnologies.

The fourth study applied quantitative models to assess soil organic matter (SOM) dynamics, identifying key indicators for sustainable soil monitoring. It emphasized the necessity of harmonized analytical methods and long-term data to understand carbon stabilization and nutrient turnover under diverse management regimes. Complementarily, the fifth study on nucleic acid-based innovations illustrated how DNA and RNA technologies can be used to engineer rhizosphere function and enhance crop tolerance to abiotic stress. Such molecular advancements present promising pathways for climate-adaptive agriculture and precision soil management.

Finally, the book chapter on biochar demonstrated its broad applications in improving soil structure, increasing nutrient retention, and mitigating greenhouse gas emissions. Evidence across field and laboratory studies confirmed biochar's role as a multifunctional amendment, capable of enhancing both soil quality and ecosystem sustainability when used in combination with other organic inputs.

Collectively, the results affirm that sustainable soil management cannot depend on a single amendment or technology. Instead, the integration of chemical (wood ash, biochar), biological (microbial VOCs), and molecular (nucleic acid innovations) approaches provides the most effective path toward resilient agroecosystems. These findings underscore that restoring soil fertility and maintaining productivity require multidisciplinary strategies grounded in both traditional and modern scientific practices.

This thesis contributes to advancing the scientific and practical understanding of sustainable soil management. It confirms the value of wood ash as a low-cost liming alternative, highlights the role of organic and microbial processes in nutrient cycling, and points toward molecular tools as future drivers of innovation. Together, these approaches establish a holistic framework for improving soil health, reducing reliance on synthetic inputs, and supporting global food security within environmentally responsible agricultural systems.

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