

Chapter 1

Introduction

1.1 Overview

The increasing accumulation of organic waste, particularly floral waste (FW) and agricultural residues like rice straw (RS), has become a pressing environmental concern. With growing urbanization and intensified agricultural practices, the improper disposal of these organic materials exacerbates problems such as landfill overloading, greenhouse gas emissions, and air pollution [1]. Traditional methods of handling FW and RS, including landfilling, open dumping, and burning, are environmentally damaging and waste valuable organic matter that could be recycled back into the ecosystem. This has led to a growing interest in sustainable alternatives, with composting emerging as a scientifically supported solution for organic waste management [2].

1.2 Floral waste and its environmental impact

FW constitutes a substantial portion of organic waste, particularly in countries with vibrant cultural and religious practices where flowers play an important role in ceremonies, festivals, and offerings. FW typically consists of discarded flowers, leaves, stems, and other plant-based materials from temples, markets, and households [3]. Despite its biodegradable nature, the majority of this waste ends up in landfills or is incinerated, contributing to methane emissions when decomposed anaerobically and adding to air pollution through open burning. These practices not only exacerbate climate change but also lead to the loss of valuable nutrients that could otherwise be cycled back into the soil through composting [4].

FW is rich in organic compounds, making it an excellent material for composting, where microbial activity can break down the waste and produce nutrient-rich compost. However, FW poses specific challenges during the composting process, primarily because of its high moisture content. Excess moisture can limit the amount of oxygen available within the compost pile, creating wet, compacted zones where air cannot circulate freely [5]. This lack of oxygen promotes anaerobic conditions, which are undesirable in composting as they slow down decomposition and can lead to the production of foul odors and greenhouse gases like methane [5].

In addition to this physical challenge, there is also a biological complexity. Although FW is rich in organic matter and nutrients, making it an excellent raw material for composting, the microbial communities that drive the breakdown of this material are not yet fully understood [6]. These microorganisms play a critical role in efficiently converting organic waste into stable, nutrient-rich compost. However, due to the diversity and dynamic nature of microbial populations involved—especially under varying composting conditions—there are still significant gaps in scientific knowledge. This limited understanding makes it difficult to fine-tune composting parameters (such as temperature, aeration, and moisture control) to maximize efficiency and ensure the consistent production of high-quality compost [1].

1.3 Rice straw and the challenge of agricultural residue management

In agricultural settings, RS is a significant byproduct of rice cultivation, especially in regions where rice is a staple crop. After harvesting, farmers are often left with large quantities of RS, which is commonly burned in the fields to clear land for the next planting season [7]. However, rice straw itself poses a number of challenges. It is bulky, difficult to handle, and has low nutritional value for livestock, making it less useful as animal feed. Additionally, its high silica content makes it slow to decompose, which complicates efforts to incorporate it back into the soil as organic matter. With limited access to machinery for straw collection or alternative uses

such as composting or bioenergy, many farmers feel they have little choice but to burn it [8]. Unfortunately, this practice, while convenient, results in the release of large amounts of carbon dioxide (CO₂), methane (CH₄), and particulate matter into the atmosphere. These emissions contribute not only to regional air pollution and public health issues but also to global greenhouse gas emissions, creating long-term environmental concerns [8]. RS, composed largely of cellulose, hemicellulose, and lignin, is relatively resistant to microbial degradation, making its natural decomposition slow and inefficient. As a result, finding more sustainable alternatives to its disposal is crucial [7]. Composting offers a promising solution for managing RS by converting it into a valuable soil amendment that can enhance soil fertility and structure. However, due to its complex composition, composting RS requires specific microbial communities that can effectively break down its tough fibers. Selecting the right inoculant to introduce the necessary microbial activity is key to speeding up the process and improving the quality of the resulting compost [7].

1.4 Integrated perspective on floral waste and rice straw composting

FW and RS may derive from distinct sectors — namely, urban cultural practices and rural agriculture, respectively — but they share the problem of being significant contributors to unmanaged organic waste, which is an enormous burden on the environment. Both are regularly disposed of in environmentally harmful ways, including open dumping or field burning, resulting in greenhouse gases, air pollution, and nutrient loss. While FW is high in moisture and salts compared to RS, which is lignocellulosic and structurally recalcitrant, both have a slender prospect of valorization via composting [3]. Composting is a scientifically proven approach to treat these types of biomasses by transforming them into soil improvers full of nutrients. Using an integrated approach, this study delves into the process of FW and RS composting, focusing on the microbial dynamics and the potential of inorganic ADS and CD inoculants to improve FW compost maturity and quality [7]. Using parallel experiments on

both FW and RS for microbial diversity, compost performance but also the effect of emerging contaminants like the MPs which often reach the compost through floral packaging materials, the research aims to establish the best use of FW and for what beneficial purpose. The biological functionalities of these microorganisms are essential as they either affect the microbial communities or delay compost maturation and reduce compost quality itself; thus, investigating them in real-world decentralized composting systems is essential. The study underscores the importance of addressing waste types together as tailored microbial strategies, inoculant choices, and treatment have the potential to optimize composting within specific categories whilst highlighting common issues, including contamination and inefficient degradation across these substrates. The integrated framework therefore affords a more comprehensive view of organic waste recycling and a more realistic basis for practical implications in both agriculture and waste management policy. The reason for mixing floral waste and rice straw is to treat two of the most abundant streams of organic waste generated in India, from the floral waste (due to our rich religious and cultural practices) and rice straw (being burnt) one of the main culprits of seasonal air pollution problem due to open-field burning, particularly in the northern part of the country (Delhi, Punjab, etc.). Rice straw is also an excellent source of bulking agent in composting. Although floral waste composting is undertaken in different forms throughout India, it has not been widely studied under controlled scientific conditions especially with the use of diverse inocula such as ADS. Further, the application of advanced molecular methods, including metagenomics and flow cytometry, to monitor microbial community changes during composting has been low. Mechanistically, the impact of varying inocula on microbial dynamics occurs at the microbial and molecular levels. ADS and cow dung present unique microbial consortia that instigate distinct paths of organic matter degradation. Cow dung often provides aerobic, thermotolerant, and mesophilic microbial populations to encourage cellulose breakdown and compost stabilization. ADS, on

the other hand, engenders a wave of facultative anaerobes and anaerobic microbes that can modify community dynamics, affect pH oscillations, and instigate early-stage fermentation. Flow cytometry and metagenomics were used to understand the dynamics with which microbial interactions and succession patterns play out with respect to functional group dynamics and the microbial stress tolerance phenomena due to microplastic contamination. This means combining flower waste with rice straw had several goals. It aimed to balance the carbon-to-nitrogen ratio and boost compost quality. It also set out to examine how microbes adapt in a real-world relevant waste management situation. Both these waste types are common in India during festivals and when crops are harvested. Mixing these materials offers an eco-friendly approach to composting. As a result, it helps to enhance waste management methods in India.

1.5 Anaerobic digestate slurry as a composting inoculant

Anaerobic digestate slurry (ADS) is a nutrient-rich byproduct of the anaerobic digestion process, where organic waste is broken down in the absence of oxygen to produce biogas. After the digestion process, ADS contains a diverse microbial community and a significant amount of residual organic matter, which can be further degraded under aerobic conditions [9]. This suggests that ADS represents a possible composite inoculant, introducing a multitude of microorganisms that enhance decomposition and improve the quality of compost [9]. *Bacillus*, *Pseudomonas*, *Clostridium*, and *Streptomyces*, all components of AD's anaerobic biological community are facultative anaerobes and can survive in conditions that are rich in oxygen. Consequently, ADS can be used effectively in aerobic composting. The ADS produced during the anaerobic digestion of complex biomass have partially stabilized organic matter that has bioavailable substrates for aerobic microbes that can benefit the process of composting [10]. Moreover, ADS is rich in important constituents, including nitrogen, phosphorus, and micronutrients, which help in microbial activity and enhance the quality of compost. If

managed appropriately by using controlled aeration, bulking agents for adjusting the carbon-to-nitrogen ratio, and ongoing monitoring of properties and conditions, ADS can help achieve aerobic composting effectively. ADS can effectively achieve decomposition rates to meet or exceed those achieved by traditional composting practices, and it is an environmentally sustainable alternative to traditional composting by utilizing biogas byproducts as a valuable soil amendment in accordance with the principles of the circular economy. However, despite its potential, the specific role of ADS in composting FW and RS remains underexplored. Unlike traditional inoculants such as CD, which are sourced from aerobic environments, ADS originates from an anaerobic setting, which may influence the microbial dynamics during composting in ways that are not yet fully understood [10]. Understanding how ADS interacts with different organic wastes and how it influences the microbial communities involved in composting is crucial for optimizing its use.

1.6 The problem statement

Both FW and RS represent significant organic waste streams that, if not managed properly, contribute to environmental degradation through greenhouse gas emissions, air pollution, and the depletion of soil nutrients. While composting has been identified as a viable solution for managing these organic wastes, several challenges remain. One of the most critical challenges is the selection of appropriate inoculants to enhance microbial activity and accelerate the composting process, particularly for organic materials like FW and RS that have unique physical and chemical characteristics. ADS has shown potential as an inoculant for composting, offering benefits such as increased microbial diversity, enhanced nutrient availability, and faster compost maturation [11]. However, its effectiveness compared to more traditional inoculants like CD in the composting of FW and RS has not been comprehensively studied. Additionally, the influence of ADS on microbial community structure, compost quality, and the overall efficiency of the composting process in these contexts remains unclear. This knowledge

gap represents a significant barrier to optimizing composting practices and improving the sustainability of waste management systems. Therefore, this research aims to address these gaps by investigating the role of ADS in the composting of FW and RS. By comparing the effects of ADS and CD as inoculants, the study seeks to understand how each influences microbial dynamics, compost maturation, and nutrient content. The findings of this research contribute to the development of more efficient composting techniques, enhance compost quality, and help reduce the environmental impacts of floral waste and rice straw disposal.

1.7 Significance and scope of this study

This study comprehensively investigates the composting of FW and RS by exploring key biological, chemical, and economic aspects that influence the efficiency and sustainability of organic waste management. A central focus is on understanding the role of ADS, a nutrient-rich byproduct of the anaerobic digestion process, as a microbial inoculant in composting. ADS holds particular significance due to its diverse microbial population and its potential to accelerate composting processes by enhancing microbial activity and nutrient cycling. By comparing ADS with CD, the study evaluates their effects on microbial diversity, nutrient availability, and overall compost quality, offering insights into the most effective composting strategies. The use of RS as a bulking agent in FW composting is another critical area of investigation. Given the high moisture content of FW, RS helps improve aeration, balance the carbon-to-nitrogen ratio, and optimize compost conditions. The study assesses the physicochemical properties of compost produced with this combination, focusing on microbial dynamics and compost maturity. The objectives of this research include exploring the mechanistic basis of the differences in microbial community composition that occur during composting. Specifically, this research assesses how the source of inocula (ADS and CD) and the nature of the carbon source (FW and RS) influence microbial populations during composting. Temporal changes in community composition during composting are evaluated to

assess microbial succession and adaptive dynamics. Links between changes in community composition and key physicochemical parameters of the composting process, such as temperature, pH, and nutrient availability, are established. Its overall aim is to enhance our understanding of microbial dynamics and design strategies to optimize the composting of different organic waste streams. Additionally, the influence of microplastics (MPs) on microbial communities when composting with RS has been investigated. Polyethylene terephthalate (PET) and polystyrene (PS) were chosen for this study, as they are common materials, such as beverage bottles (PET) and disposable food containers, foam packaging, and other items made with thermocol (PS), that can enter the organic waste stream due to improper disposal as well as waste not being separated. The persistence of polystyrene (PS) and polyethylene terephthalate (PET) in compost may create serious issues as they limit microbial activity, prolong compost maturation time, and affect compost quality. Beyond the biological aspects, a techno-economic analysis has been conducted to evaluate the feasibility and economic viability of RS composting. This analysis might provide insights into the operational costs, potential profitability, and scalability of composting as a waste management solution. By integrating microbial ecology, compost chemistry, and economic assessments, the study aims to develop sustainable and economically viable composting practices that address the challenges of FW and RS disposal, enhance soil fertility, and reduce environmental pollution. This research contributes valuable knowledge for optimizing composting processes, particularly in regions where FW and RS are abundant, and supports the broader adoption of composting in agriculture and waste management.

1.8 Research objectives

The present study encompasses the investigation of critical aspects of composting systems, focusing on microbial dynamics, substrate interactions, and system feasibility. The research has the following key objectives:

1. Explore the core microbiome diversity in digested versus raw manure and its impact on rice straw composting
2. Evaluating the impact of digestate and raw manure on physicochemical conditions and microbiome dynamics during floral waste composting
3. Investigate the effect of polyethylene terephthalate and polystyrene microplastics on microbiome dynamics during rice straw composting
4. Conduct a techno-economic analysis of rice straw composting, evaluating its technical feasibility and economic viability

Addressing these objectives, the study contributes insights to enhance composting practices, support better waste management, and promote sustainable agriculture.

1.9 Thesis organization

This thesis has been organized into eight chapters, each designed to systematically address the research objectives and provide a comprehensive analysis of microbial, environmental, and economic aspects of composting systems.

Chapter 1: This chapter highlights the environmental challenges of rice straw and floral waste mismanagement and introduces composting as a sustainable solution. It presents the rationale for evaluating co-substrates and microplastics and outlines the research problem, objectives, significance, scope, and thesis structure.

Chapter 2: This chapter reviews composting fundamentals, including types, key process parameters, and monitoring methods. It covers analytical techniques, the role of bacterial

communities in decomposition, and the agricultural and environmental benefits of compost application.

Chapter 3: This chapter outlines the materials and methodologies employed in the study. It details the physicochemical analysis of compost parameters, metagenomic sequencing for microbial profiling, flow cytometry for microbial viability, scanning electron microscopy for structural insights, and Fourier-transform infrared spectroscopy for chemical characterization.

Chapter 4: This chapter explores the core microbiome diversity in digested and raw manure and examines its influence on the composting of lignocellulosic waste. It highlights differences in microbial communities in organic matter degradation, emphasizing their impact on composting efficiency and process dynamics.

Chapter 5: This chapter focuses on the role of digestate and raw manure as co-substrates in floral waste composting, evaluating their effects on physicochemical conditions and microbial succession. The findings highlight their influence on compost quality and process performance.

Chapter 6: This chapter investigates the effects of polyethylene terephthalate and polystyrene microplastics on microbial dynamics during rice straw composting. It assesses how these synthetic contaminants alter microbial community structure, activity, and composting outcomes.

Chapter 7: This chapter presents a techno-economic analysis of rice straw composting, evaluating its technical feasibility, cost factors, and economic potential. The assessment provides insights into the sustainability and scalability of composting as a viable waste management strategy.

Chapter 8: This chapter concludes the study by summarizing key findings related to microbial communities, substrate influence, and microplastic impacts. It also provides practical recommendations and identifies future research directions to further advance sustainable composting practices.