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Presented by :
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Monitoring physicochemical and biological characteristics of date palm waste compost

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Dedication and Acknowledgements

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Introduction

Introduction

In recent years, the world population's surge, has led to increase in anthropogenic activities such as urbanization, industrialization, expansion and intensive agriculture to meet modern demands (Azis *et al.*, 2022 ; Gupta, 2019 ; Kumar, 2016). Consequently, these actions have led to significant negative environmental impacts, including rising amounts of waste (Azis *et al.*, 2022 ; Dong et Lee, 2009), climate change, land degradation, pollution, resources depletion, biodiversity loss, persistent accumulation of harmful chemicals, and other issues that have made the planet increasingly uninhabitable for many species (Arora *et al.*, 2018). In addition, the world's population is expected to continue growing with projections indicating that it will hit 9.7 billion by 2050 and a potential peak of nearly 10.4 billion in mid 2080s; the majority of this population growth is expected to occur in Africa and at a rapid rate, accounting for more than half of the global increase by 2050 (UN, 2022), which will create increased strain on the environment and natural resources to fulfil human needs, posing a threat to humanity and potentially jeopardizing civilized life (Escobar *et al.*, 2009).

Talking about agriculture, the oldest and most prevalent industry in humankind *(Nath et al., 2023)* and the main supplier of food, by 97% (Gupta, 2019). It has long been a crucial part of human civilization (Gomiero, 2018) and remains today, sustaining the livelihoods of millions of people around the world, and contributes significantly to economic growth and developing, making up 4% of the global Gross Domestic Product (GDP) and up to 25% in some less developed nations (Dethier et Effenberger, 2012 ; WB, 2023). In the 20th century, agricultural production shifted to intensive industrial methods, with mechanization, fertilizers, pesticides, and herbicides leading to intensified and concentrated production, altering output volume, composition, and quality (Seadi et Holm-Nielsen, 2004); All of which generally results in the depletion of soil fertility, erosion, pollution of water, compaction of soil, and decrease in organic matter content (Muktadirul Bari Chowdhury *et al.*, 2013). Moreover, agricultural productivity still struggles to meet the high demand for food (Haouas *et al.*, 2021), and as the world's population continues to grow, meeting its increasing food demands requires a 25 to 100% boost in productivity by 2050 (Hossain *et al.*, 2020 ; Hunter *et al.*, 2017 ; Tscharntke *et al.*, 2012), which will put more pressure on the environment and natural resources (Srinadh et Neelancherry, 2023).

INTRODUCTION

The role of agriculture, particularly soil, extends beyond being the primary source of food to encompass other vital services, include: Provisioning services (primary materials, and infrastructure support); Regulating services (flood control, nutrient filtering, carbon storage, waste recycling, and pest regulation); Cultural services (recreation, aesthetics, heritage values, and cultural identity) (Kopittke *et al.*, 2019); Ecosystem services (water supply, climate change mitigation, biodiversity conservation, and carbon sequestration)(Gupta, 2019). Despite all of that, the agricultural sector has received less attention compared to other policy objectives like economic and social growth , as policymakers deemed it to be self-sustaining (Godfray et Garnett, 2014). Studies indicate that a large portion of land is unsuitable for farming (Borrelli *et al.*, 2017), and although 38% of the Earth's land surface is used for food production (Foley *et al.*, 2011), 60% of it has undergone significant degradation due to direct or indirect human influence in recent years (Chalise *et al.*, 2019 ; Hossain *et al.*, 2020), with 2 to 9% of it expected to disappear in the coming decades (Haouas *et al.*, 2021). This has led scientists to strive for a balance between intensifying agriculture and environmental conservation through what is known as sustainable intensification (Davis *et al.*, 2016 ; Godfray et Garnett, 2014 ; Hunter *et al.*, 2017).

To provide the world's dietary requirements, the agriculture activities involves crop cultivation, animal and fishery husbandry (Kesavan et Swaminathan, 2008). However, it also generates a significant amount of waste each year, i.e., Agricultural waste, also known as agro-waste, estimated at 140 billion metric tons per year (Srinadh et Neelancherry, 2023) and still gaining momentum (Nguyen *et al.*, 2019); consists of livestock waste, food production waste, crop waste, hazardous and toxic agricultural waste (fertilisers, pesticides…) (Hamda *et al.*, 2023 ; Lakshmi *et al.*, 2017 ; Nath *et al.*, 2023), and comes in various physical states (solid, liquid, or slurry) (Kumar *et al.*, 2023). Most agricultural waste is organic (80%) (Nguyen *et al.*, 2019) include semicrystalline lignocellulosic components such as cellulose, lignin, hemicellulose and organic fertilizing molecules such as N, P, K, and C, etc. (Nath *et al.*, 2023), which can be used to generate value-added commodities if utilized adequately (Fu *et al.*, 2021 ; Huang *et al.*, 2017). Indeed, the majority of agricultural waste can be highly valuable assets that should be recycled and utilized for energy recovery and industrial purposes (Seadi et Holm-Nielsen, 2004), therefore, they should be seen as a promising asset instead of useless remains in order to avert pollution and prevent the spread of dangerous substances (Obi *et al.*, 2016). Nevertheless, since most farmers are unaware of the benefits and economic opportunities of waste recycling (Hamda *et al.*, 2023), along with the increasing challenges and cost of collecting, transporting, and processing these waste (Nguyen *et al.*, 2019 ; Srilatha *et al.*, 2019) (Obi *et al.*, 2016), they are often left unused or simply burned in fields, leading to significant environmental problems (Srilatha *et al.*, 2019) such as the generation of greenhouse gases (GHGs) (Koul *et al.*, 2022); the main cause of the climate change (Satterthwaite, 2009), and/or triggering an upsurge in the population of insects and weeds, which requires the implementation of management techniques like chemical-based pesticides or fungicides that may cause further environmental problems (Abas *et al.*, 2018), and poses risks to human and animal health (Lakshmi *et al.*, 2017 ; Obi *et al.*, 2016 ; Seadi et Holm-Nielsen, 2004). Thus, the rising demand for agricultural products will lead to a more rapid generation of agricultural waste than degradation and processing rate, emphasizing the need for sustainable and efficient agricultural practices to ensure food security without harming the environment (Koul *et al.*, 2022), making agricultural waste management an inevitable goal in global sustainable strategies today (Seadi et Holm-Nielsen, 2004).

Globally, waste management such Argo-Waste is a huge issue that could have serious implications if not solved (Azis *et al.*, 2022). This has put the spotlight on the Agricultural Waste Management Systems (AWMS) for ecological agriculture and sustainable development (Hamda *et al.*, 2023 ; Obi *et al.*, 2016), which is an elaborate framework that controls and utilizes agricultural waste to sustain or improve environmental resources (USDA, 2011). The system comprises six fundamental operations that can be adjusted as needed: production, collection, storage, treatment, transfer, and utilization (Obi *et al.*, 2016 ; USDA, 2011). The new waste management hierarchy system (WMHS) is a set of rules that categorize waste treatment methods and strategies from most suitable to least environmentally friendly (Vu *et al.*, 2022), in a hierarchical order, it consist of waste reduction, recovery, reuse, and recycling, as well as the disposal of waste with and without energy recovery (Hamda *et al.*, 2023 ; Vu *et al.*, 2022). This guidelines (WMHS) is widely accepted by governments, academics, environmental groups, and companies for its ability to evaluate the environmental, social, and economic impacts of a community's waste management system (Doaemo *et al.*, 2021).

In agricultural waste management system, waste disposal is the least favourable method, while waste avoidance is the most effective approach (Doaemo *et al.*, 2021 ; Hamda *et al.*, 2023). Therefore, several strategies have been adopted to reduce the amount of waste sent for disposal, such as the 3R strategy that aims to avoid or reduce the amount of waste sent for disposal arranged hierarchically by reducing, reusing, and recycling wastes (Awasthi *et al.*, 2016 ; Obi *et al.*, 2016); the Zero Waste strategy also focuses on direct waste recycling at the household and workplace levels to reduce the burden of waste collection and transportation, which is one of the main challenges in waste management (Neugebauer, 2018). Thus, landfills are considered a poor solution due to their numerous negative effects on the environment (Ioannou *et al.*, 2015), including the generation of compounds that emit greenhouse gases (CO2 and CH4), as well as the generation of Odors and explosion hazards (Da Silva *et al.*, 2020), along a requirement for extensive land that could be repurposed for other uses (Kauser et Khwairakpam, 2022). Other treatment technologies focused on recycling and waste recovery include thermal treatments such as combustion, gasification, pyrolysis, and refuse-derived fuel (RDF); However, most of these solutions either necessitate advanced technology and incur high costs, or they are uncommercialized and still in the early stages of development (Awasthi *et al.*, 2016). The selection of waste management technology is contingent upon the size of the waste and particular characteristics (Ebrahimi *et al.*, 2012), which vary based on the specific agricultural system and type of cultivation practiced (Lakshmi *et al.*, 2017 ; Srinadh et Neelancherry, 2023).

In arid and semi-arid regions such as North Africa and the Middle East, the date palm (Phoenix dactylifera L.) is one of the oldest and most vital horticultural crops (Abul-Soad *et al.*, 2017 ; Aydeniz-Güneşer, 2022), due to its many uses, particularly the production of dates fruit, which is considered a valuable commodity globally, both as a high-end confectionery product and as a vital food source in desert regions (Chandrasekaran et Bahkali, 2013 ; Johnson *et al.*, 2015a). It is considered to be the most socioeconomically significant tree both domestically and globally (Abid et Ammar, 2022 ; Bouguedoura *et al.*, 2015), where it has always been essential to the economic and social well-being of the local population (Agoudjil *et al.*, 2011). Recent data indicates approximately 120 million date palm trees are cultivated globally, with 90% situated in the Middle East and North Africa (MENA) region (Makkawi *et al.*, 2019). Each year, these trees produce 2.8 million tons of waste, which is ultimately dumped in landfills (Awad et al., 2020).

Algeria, a North African nation renowned for its rich phoenicicolous heritage, is a major producer of date palm fruit, ranking sixth globally and first in the Maghreb region, with nearly 800 distinct varieties, contributing approximately 6% to the world's date production (Aberlenc-Bertossi, 2010 ; Jaradat, 2015). Additionally, it is the home of the foremost valuable and sought-after date plantations in the world's marketplace, Deglet Noor cultivar; As a consequence, the country has established an electricity grids and stimulated novel water supplies, particularly in Adrar, El Oued, Biskra, Ouargla, and Ghardaïa, in order to boost date production, satisfy local demand, and raise exports (Bouguedoura *et al.*, 2015). Indeed, from 2015 to 2019, the number of cultivated palm trees increased by approximately 458,173, resulting in a total of 19,063,249 trees across 169,785.71 hectares; The annual yield of dates from these trees is estimated at approximately 11,360,248 million tonnes (TIDSA, 2022), with Biskra, ranks first, contributing about 42% of national production and occupying 26% of the total area, with 62% committed to Deglet Noor cultivation; then followed by El Oued and Ouargla (Bouguedoura *et al.*, 2015 ; TIDSA, 2022). In Biskra, the waste produced in 2019 is estimated to be about 3.8 to 7.6 million quintals per year (Ouali et Hiouani, 2024). Hence, as production rates rise due to increasing demand and government efforts to address it, there is an expansion of palm plantation areas, resulting in greater waste and byproducts during processing (Aydeniz-Güneşer, 2022).

Considering the discussed factors, including population growth, economic expansion, increased agricultural demand, food security, waste generation, and environmental challenges and etc...; Identifying effective treatment methods for reducing and reusing biowaste from date palm trees is essential to mitigate environmental pollution and support sustainable food and energy sources (Aydeniz-Güneşer, 2022).

One of the most effective biowaste treatment technologies is composting, which is commercially accessible (Garg *et al.*, 2009), safe, environmentally friendly (Jain *et al.*, 2020), since it emits less hazardous gases (Azis *et al.*, 2022), with low capital and operating costs, simple operation, minimal labour requirement, and exceptional treatment efficiency compared to other treatments (Chen *et al.*, 2019b ; Seng *et al.*, 2016). Composting is becoming increasingly popular as a highly efficient strategy for enhancing sustainable agricultural productivity (Karanja *et al.*, 2019). It involves recycling and valorising organic waste by reclaiming their nutrients and converting them into safe and beneficial products, i.e. compost, that can then be used as a soil amendment or/and even reintegrated into the economic system as a valuable resource (Bernal *et al.*, 2009 ; Maheshwari, 2014 ; Reyes-Torres *et al.*, 2018 ; Scotti *et al.*, 2016). Compost serves as a natural fertiliser to enhance soil fertility and boost crop productivity (Muktadirul Bari Chowdhury *et al.*, 2013), by enhancing soil water retention and aggregate stability, facilitating cation exchange, stimulating microbial diversity and activity, supporting the decomposition of pesticides and other synthetic organic chemicals, and suppressing soil-borne pathogens (Karanja *et al.*, 2019 ; Muktadirul Bari Chowdhury *et al.*, 2013 ; Scotti *et al.*, 2016). Nevertheless, composting is renowned for its time-consuming nature, taking several months or even years to produce complete stable and mature compost

(Azis *et al.*, 2022). In particular, the composting of lignocellulosic wastes such as date palms, which have a very sluggish rate of decomposition (Jain *et al.*, 2018b ; Reyes-Torres *et al.*, 2018 ; Rynk *et al.*, 2022b), thereby shifting the focus towards accelerating the process while enhancing the quality of the compost (Reyes-Torres *et al.*, 2018). Composting technologies such as windrows and aerated static piles are not recommended in arid regions owing to water scarcity and substantial daily water evaporation; On the other hand, the in-vessel system has been proposed as a more rational alternative (Alkoaik, 2019) , as it is superior in managing process emissions, occupies less space, and operates more swiftly (EU, 2008). It has proven effective in improving soil properties, including conductivity, stabilization, erosion resistance, fertility, and plant nourishment (Kauser et Khwairakpam, 2022).

In light of the above, it is crucial to adopt a zero-waste strategy by encouraging farmers to participate in on-farm composting and avoiding the disposal of waste in landfills or burning. On-farm composting approaches enables the recycling of raw agricultural wastes and enhanced byproducts from agricultural chains back into the farm (De Corato, 2020), using in-vessel systems (Alkoaik *et al.*, 2019b).

Generally, prioritizing on-farm composting (in-site composting) is recommended over decentralized composting plants, followed by centralized composting (Ghosh, 2019). Indeed, establishing multiple small composting plants is more effective than constructing a single large-scale facility to process the region's waste (Kalamdhad et Kazmi, 2008). In 2014, the quantity of processed date palm waste was estimated at 43,758 tonnes, derived from around 2,917,186 palm trees in the Biskra region alone, where it is projected that 88 manufacturing plants would need to be established to compost this waste, assuming a productivity of 500 tonnes each (TIDSA, 2022). This approach not only offers a solution to waste disposal problems, especially in transportation and reducing waste management costs, but also aims to eliminate the need for chemical-based products by providing farmers with a self-supply of high-quality compost, which will enhance and rehabilitate soil quality, foster plant health, and protect the environment (Abid et Ammar, 2022 ; De Corato, 2020 ; Scotti *et al.*, 2016 ; Wang *et al.*, 2021).

The rotary drum bioreactor is a straightforward and economical in-vessel system, that simplifies agitation, aeration, and mixing of the compost, resulting in a homogeneous and uniform end product (Kalamdhad et Kazmi, 2009b) and encouraging On-farm composting (decentralize system) (Scotti *et al.*, 2016), especially for smaller communities or projects that need a fast and closed pathogen destruction process (Jain et Kalamdhad, 2019 ; Kalamdhad et

Kazmi, 2008, 2009a). It has received considerable acceptance for its sophisticated characteristics and potential, which include producing a stable end-product with enhanced nutritional properties within a 20-day timeframe (Jain et Kalamdhad, 2019 ; Kalamdhad et Kazmi, 2008, 2009a ; Rashwan *et al.*, 2021), by effectively managing key factors, such as temperature, pH (Gao *et al.*, 2010) most importantly, the C:N ratio, oxygen, and moisture content of the initial composting mixture to successfully initiate the process (Calisti *et al.*, 2020).

The current investigation is focused on monitoring the alterations in the physico-chemical and biological characteristics of date palm waste mixed with different additives throughout the composting process, with specific sub-objectives including:

- Promoting the recycling and valuation of agricultural waste among farmers through methods that are accessible, straightforward, and non-intrusive.
- Accelerate the composting process for date palm waste and lignocellulosic waste in general.

The thesis comprises four primary chapters:

Chapter 1 discusses the date palm tree, exploring its origins and structure, as well as its value, chronology, worldwide distribution, production, and waste generation.

Chapter 2 delves into the composting process, examining its historical context, influencing variables, significance, unique methods and techniques, and evaluating the maturity and stability of the final product.

Chapter 3 covers the approach employed in the design of the composter, the reasons for choosing additives, their incorporation with palm wastes, and the methods used to perform analyses.

Chapter 4 addresses date palm waste composting and each of the chemical and physical alterations that occur during the process, along with their interpretation and recommendations for suitable adjustments.

Chapter 01 :
Date Palm
(Phoenix dactylifera L.)

Chapter 01: Date Palm (Phoenix dactylifera L.)

I. Date Palm (Phoenix dactylifera L.) Classification:

The date palm (Phoenix dactylifera L.) is a monocot angiosperm diploid plant belongs to the Arecaceae family, known as Palmae in the monocotyledon order, encompassing approximately 200 genera and 2,600 species, a part of the Coryphoideae subfamily, the only member of Phoeniceae tribe, then the Phoenix genus (Figure 1) (Al-Yahyai et Manickavasagan, 2012 ; Gros-Balthazard *et al.*, 2021 ; Jaradat, 2015 ; Johnson, 2011 ; Zaid et De Wet, 1999a).

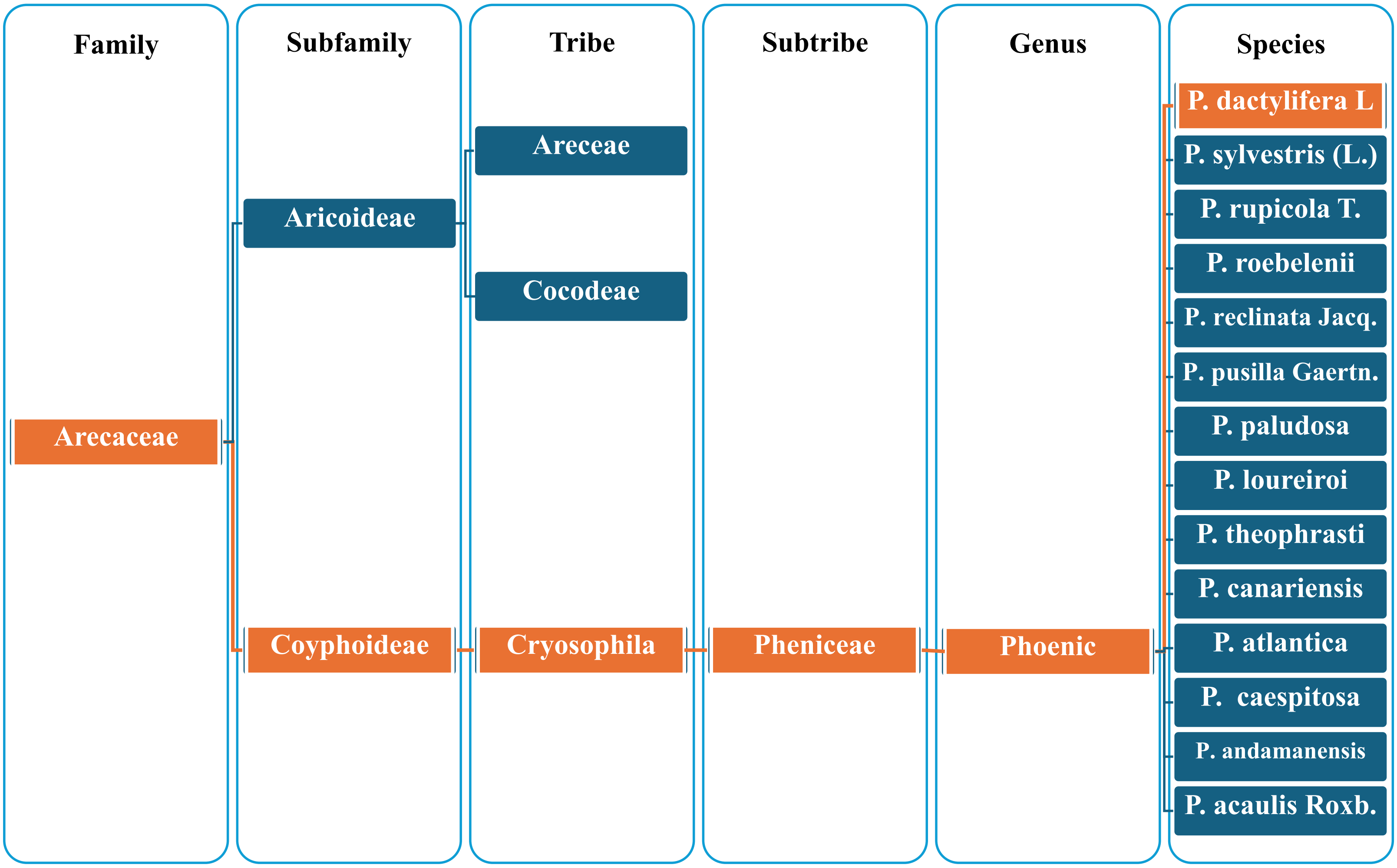

Figure 1: Taxonomy of the date palm (Phoenix dactylifera L.) *(after Gros-Balthazard et al., 2021 ; Krueger, 2021 ; Zaid et De Wet, 1999a).*

The genus Phoenix includes 27 species; nonetheless, most taxonomic classifications acknowledge around 14 species, among which is Phoenix dactylifera (Gros-Balthazard *et al.*, 2021 ; Johnson, 2011 ; Krueger, 2021), Many of these species are recognized as decorative trees, such as canariensis chabeaud (Zaid et De Wet, 1999a),. It is linked to the Cretan date palm (P. theophrasti Greu.) from the Eastern Mediterranean, the Canary Islands date palm (P. canariensis Chab.) endemic to that archipelago, and the sugar date palm (P. sylvestris (L.) Roxb.) native to South Asia (Johnson *et al.*, 2015b) as shown in Figure 1.

II. Etymologically:

The taxonomy of the date palm, Phoenix dactylifera, is obtained from the Greek word "Phoenix," which denotes purple or red, pointing to the colour of the dates, while "dactylifera" or "daktylos" translates to "fingers," concerning their date shapes; meaning purple or red fingers (Abid et Ammar, 2022 ; Ghnimi *et al.*, 2017 ; Jaradat, 2015 ; Zaid et De Wet, 1999a). Some relate the etymology of its name to Egyptian roots, associating it with the Egyptian bird "Phoenix" due to its capacity for regeneration after incineration, while "dactylifera" derives from the Hebrew term "dashil," which describes the fruit's shape (Zaid et De Wet, 1999a).

III. History:

The precise origin of the date palm remains mired in uncertainty; nonetheless, it can be traced to the Mesopotamian region (southern Iraq), and the Nile Valley in Egypt, dating back to 4000-3000 BC (Abid et Ammar, 2022 ; Aydeniz-Güneşer, 2022 ; Chao et Krueger, 2007) , as indicated archaeologically by the art and artefacts of ancient civilizations, including the Sumerians, Assyrians, Babylonians, Egyptians, and later the Greeks and Romans in the Mediterranean basin, where it was utilized in the building of the moon god's temple, and symbolized a year in hieroglyphics and its frond represented a month (Al-Yahyai et Manickavasagan, 2012 ; Zaid et De Wet, 1999b). Additionally, the Egyptians esteemed it as a sacred symbol of fertility; the Carthaginians depicted it on their coins and memorials, while the Greeks and Latinos incorporated it as a decoration in their victorious festivities (Abid et Ammar, 2022).

Moreover, the Date Palm holds significant religious importance in the three major world religions, where it is referenced 21 times in the Holy Quran and 300 times in the Hadith, establishing it as the most frequently mentioned plant in Islam; As well, it is revered in Christianity and Judaism, associated with various religious events, including Passover and Palm Sunday (Al-Yahyai et Manickavasagan, 2012).

The propagation of date cultivation extended over the Arabian Peninsula and the Middle East, eventually reaching North Africa by the time of the Phoenician conquest and Spain through Islamic expansions (Chao et Krueger, 2007 ; El-Sharabasy *et al.*, 2021 ; Hamza *et al.*, 2015). Figure 2 illustrates the chronology of key events in the cultivation of date palms.

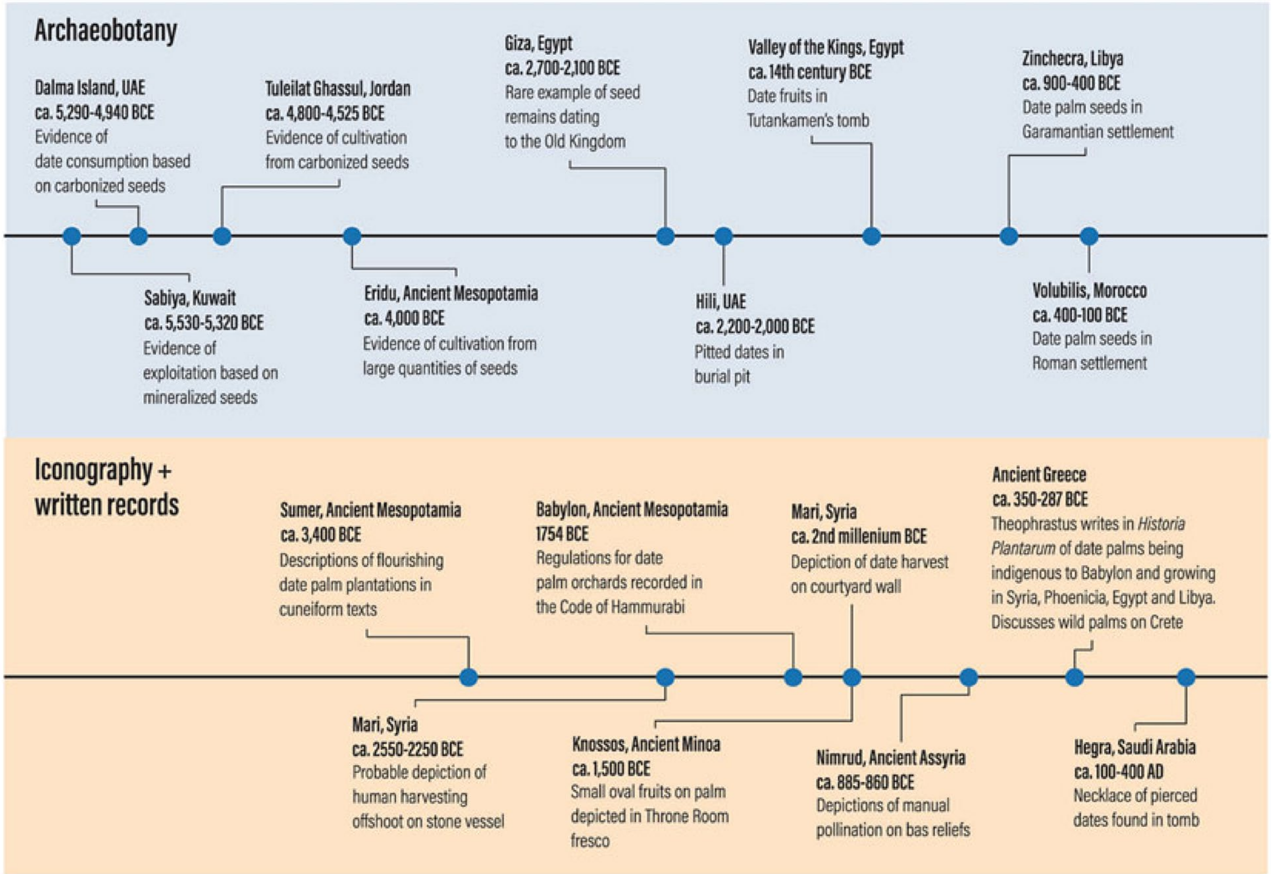

Figure 2: chronology of key events in the cultivation of date palms (Gros-Balthazard et Flowers, 2021).

IV. Distribution and Production:

The date palm (Phoenix dactylifera L.) is well-known as a xerophytic plant species and one of the oldest vital crops cultivated in the hot and arid regions of Afro-Eurasia, especially in the Arabian Peninsula, North Africa, and the Middle East region (MENA); subsequently it was introduced over three millennia to various regions, due to its many advantages, including the United States, Europe, particularly Spain, along with North America (Mexico, Argentina), Australia, India, and Pakistan (Abid et Ammar, 2022 ; Aydeniz-Güneşer, 2022 ; Chao et Krueger, 2007 ; Harkat *et al.*, 2022 ; Jaradat, 2015 ; Krueger, 2021 ; Zaid et De Wet, 1999a).

In general, the geographic distribution of date palms in both hemispheres ranges from 10°N (Somalia) to 39°N (Elche/Spain or Turkmenistan), with optimal regions located between 24° and 34°N in Morocco, Algeria, Tunisia, Libya, Egypt, Iraq, Iran, and Pakistan (Abul-Soad *et al.*, 2017). Currently, approximately 100 to 120 million date palm trees are cultivated globally, with an estimated 70 to 90 % situated in the Middle East and North Africa (MENA) region (Ghnimi *et al.*, 2017 ; Makkawi *et al.*, 2019). Thus, the most prominent date production regions are the Middle East, Northern Africa, as well as Pakistan, with minor contributions from various areas in North America and Southern Europe (Figure 3) (Abul-Soad *et al.*, 2017).

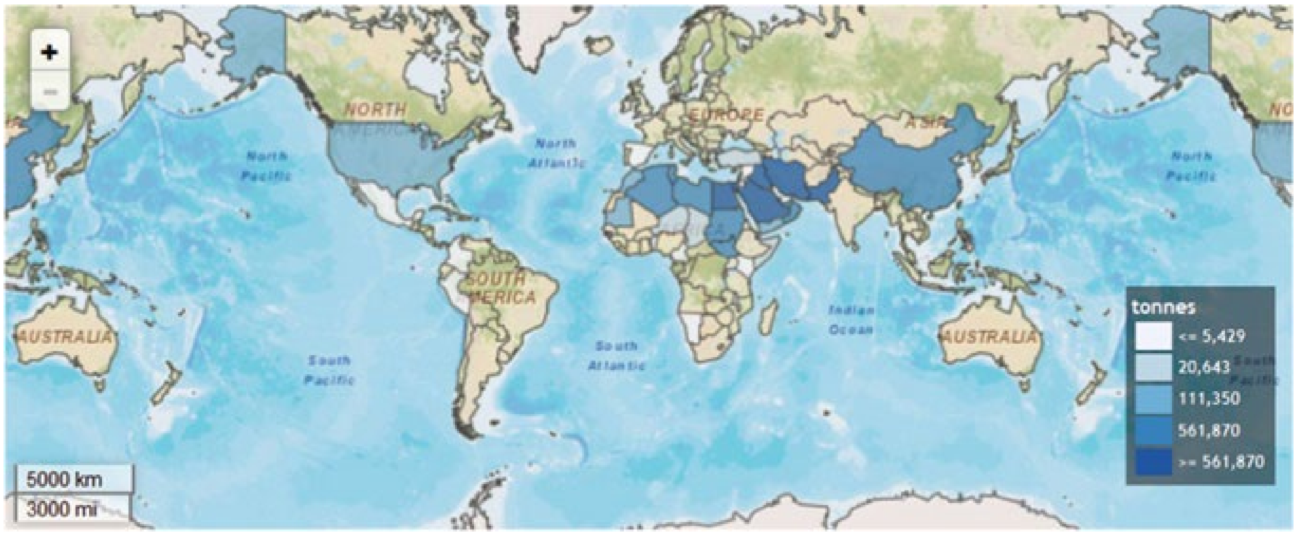

Figure 3: Geographical distribution of date palms (Phoenix dactylifera L.) worldwide (Abul-Soad et al., 2017).

Furthermore, the cultivation of date palms is experiencing significant growth globally, attributed to its various applications, and is anticipated to persist as a prominent crop (Aydeniz-Güneşer, 2022 ; Martis *et al.*, 2020). In 2010, the estimated cultivated area for date palm was 1,281,957 hectares, yielding an annual production of approximately 7,527,764.57 tonnes; As of 2021, the cultivated area reached 1,301,979 hectares, with annual production increasing to approximately 9,656,377.75 tonnes (FAO, 2022), with Egypt, Saudi Arabia, Iran, Algeria, and Iraq are the leading countries in the production of dates (Abid et Ammar, 2022).

V. Botanical Description:

The genus Phoenix is monotypic with Phoenix dactylifera being the tallest species, reaching heights of up to 30 meters (Jaradat, 2015 ; Johnson *et al.*, 2015b) and an average age of 40–50 years, although some individuals may live for as long as 150 years (Abid et Ammar, 2022 ; Krueger, 2021).

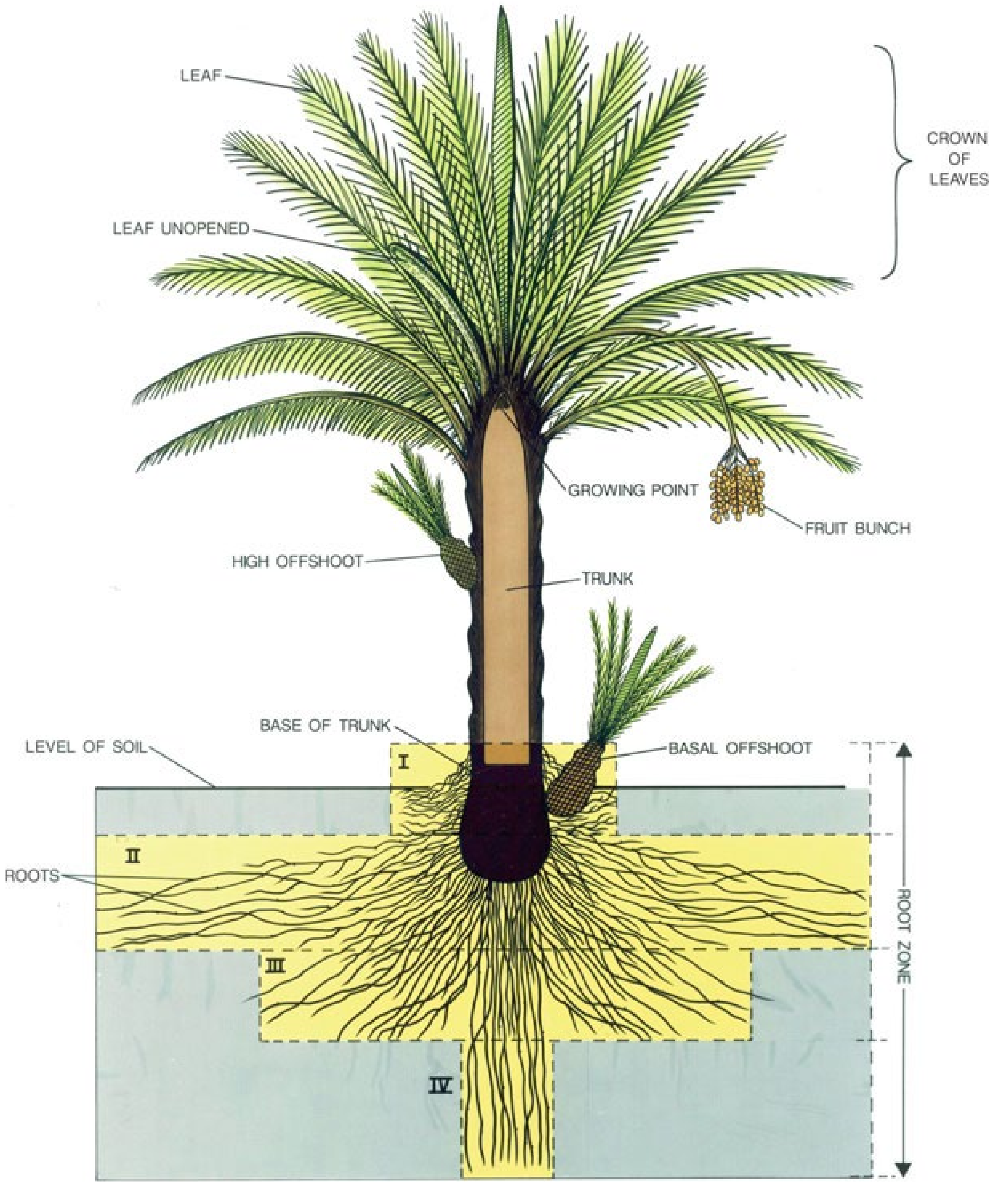

Figure 4: Diagrammatic representation of the Date Palm Tree (Krueger, 2021).

V.1. Rhizosphere:

The date palm, classified as a monocotyledon, can extend its root system to depths exceeding 10 meters, influenced by external factors including soil properties, groundwater availability, agricultural methods, and exhibits a fibrous root system free of a tap, containing pneumatodes to aerate subterranean roots, which can be split into four distinct zones (Figure 4): Zone I, the respiratory zone, comprising primary and secondary roots; Zone II, the nutritional zone, is characterized by primary roots that make up the majority of the tree's root volume; Zone III, the absorbing zone, primarily consists of primary roots with dropping density from top to bottom; and Zone IV, the most submerged zone, signifies the largest portion and uses subterranean water (Krueger, 2021 ; Zaid et De Wet, 1999a), Additional information is provided in Table 1.

Table 1: Morphology and distribution of date palm rhizome (Zaid et De Wet, 1999a).

Roots Order	Origin	Form	Average length (m)	Average diameter (mm)	Characteristics
Primary	Trunk base	Cylinder	4 (up to 10)	9.5 (7-12.5)	- vertical - adventitious - no root hair - conic tip - called auxirhyzes and also main roots
Secondary	Primary roots	Similar to primary roots	0.20 - 0.25	3.5	- called mesorhyzes
Tertiary	Secondary roots	Similar to secondary roots but thin	0.02-0.1	0.3 - 1.5	- Low growth - short and - abundant called brachyrhizes

V.2. Trunk:

The trunk of the date palm, referred to as the stem or stipe, is characterized by its vertical, cylindrical, and columnar form, maintaining a consistent diameter with an average circumference of approximately 1 to 1.10 m throughout its height; This structure results from a fascicular cambium that eventually ceases to function, leading to exclusively vertical growth of the stem thereafter, and the development of new aerial stems, known as offshoots or offsets (Figure 4) (Johnson *et al.*, 2015b ; Krueger, 2021 ; Zaid et De Wet, 1999a) . Occasionally, it can exhibits branching, which may arise from dichotomy, axillary bud development, polyembryony, or disease; and can yield as much fruits as a single-headed palm (Zaid et De Wet, 1999a).

V.3. Leaves:

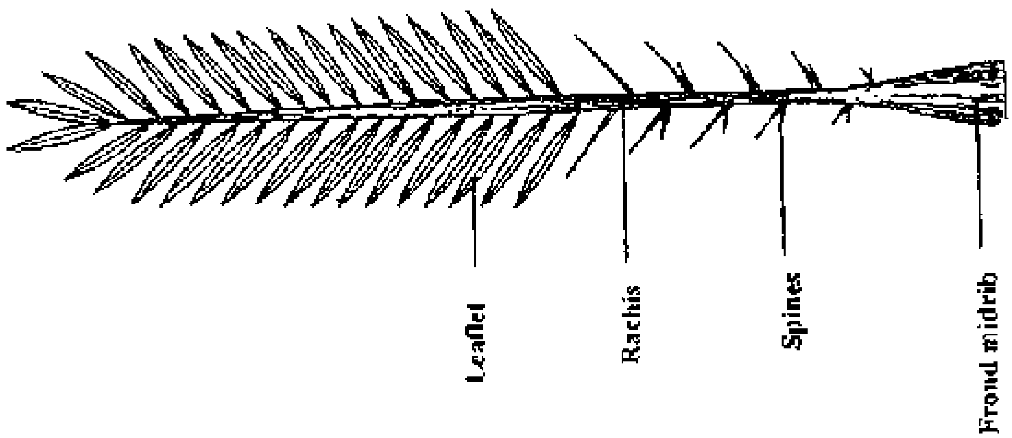

Figure 5: Date palm leaf (Zaid et De Wet, 1999a).

The leaves of the date palm exhibit an irregular feathery structure (pinnate), characterized by an axis (petiole) on which there is 4% acanthophylls (spines) and 62% leaflets on each side, along with terminal leaflets shaping V (Abid et Ammar, 2022 ; Zaid et De Wet, 1999a), as shown in Figure 5.

Petiole or midrib range from 3 to 6 meters in length, contingent on age and variety, exhibiting a wide base that reaches 0.5 meters before tapering swiftly towards the leaf tip (Zaid et De Wet, 1999a). Leaflets measure 15–100 cm in length and 1–6 cm in width based on age and variety, characterized by sharp tips and a V-shaped, induplicate folding in most varieties; which is a distinctive structure of the genus Phoenix and other restricted group of Caryotoid palms (Gros-Balthazard *et al.*, 2021 ; Krueger, 2021).

A grow date palm possesses 60–180 green leaves that form a crown, with an annual production of 10–25 leaves (Krueger, 2021), with lifetime of 3 to 7 years (Johnson *et al.*, 2015b). Each leaf is held up by a cylindrical mesh mat made of resilient, fibrous material at its base (Abid et Ammar, 2022).

The date palm's crown consists of three types of leaves: 40% are immature leaves exhibit white coloration and lack photosynthetic activity, 10% are green young leaves, and 50% are green mature leaves that participate in photosynthesis at a modest rate, where the photosynthetic rate of leaves diminishes with age (Krueger, 2021).

V.4. Fruit:

The date palm is dioecious, with distinct female (pistillate) and male (staminate) trees (Johnson *et al.*, 2015b ; Krueger, 2021); Nonetheless, occurrences of hermaphroditic trees and male trees exhibiting feminine features have been occasionally, documented (Chao et Krueger, 2007 ; Krueger, 2021). Male and female flowers exhibit distinct morphological differences; Male flowers are characterized by a sweet scent, typically possessing six stamens composed of two small pollen sacs, and are surrounded by white waxy, scale-like petals and sepals (three each), whereas, female flowers feature fundamental yellowish stamens and three closely pressed carpels, with a superior ovary (hypogynous) that has the potential to blossom into fruit (date) on a stalk or strands (Zaid et De Wet, 1999a). Dates flower when the ambient temperature exceeds 18 °C and develop fruit at temperatures above 25 °C (Chao et Krueger, 2007), progressing through three maturation stages :Khalal or Bisr, Rutab (semi-ripe), and Tamr stages (Aydeniz-Güneşer, 2022 ; Ghnimi *et al.*, 2017).

Generally, the production rates of dates (yield) exhibit significant variability, ranging from 20 to 100 kg per adult tree, determined by age, cultivation practices , environmental conditions, and cultivar (Johnson *et al.*, 2015b). Although, the exact number of cultivars is indeterminate, affected by the widespread occurrence of synonyms and homonyms both internationally and domestically, along with the translation of Arabic names into other languages complicates the matter, since there are generally numerous transliterations of a single Arabic name (Chao et Krueger, 2007), for example approximately 400 varieties exist in Iran, 370 in Iraq, 250 in Tunisia, and 244 in Morocco, along with numerous additional varieties in other significant date-producing countries (Zaid et De Wet, 1999a); there are approximately 5,000 date cultivars globally, exhibiting variations in fruit colour, flavour, shape, dimension, pulp, and ripening time (Bekheet et El-Sharabasy, 2015).

Approximately 75% of worldwide production is derived from just 10 varieties of dates (Abid et Ammar, 2022), including ‘Deglet Noor’, which originates from the Algerian Sahara and is a prominent cultivar in North Africa and California; ‘Barhee’, ‘Khadrawy’, and ‘Zahidi’ are high-quality soft dates originating from Iraq; ‘Medjool’ and ‘Halawy’ are thought to have originated in the Tafilalt region of Morocco; while ‘Hayany’ is a substantial, early-ripening date hailing from southern Egypt (Chao et Krueger, 2007).

VI. Benefits:

The date palm (Phoenix dactylifera L.) is a highly valued domesticated fruit tree due to its religious significance, health benefits, productivity in harsh semiarid and arid environments, and the variety of subsistence products derived from its fruits and other parts (Johnson *et al.*, 2015b). It has served as a crucial food security crop in the Middle East and North Africa (MENA) for the past 5000 years, earning titles such as the sacred tree, the tree of life, and the bread of the desert due to its valued fruits (Ghnimi *et al.*, 2017), its superior tolerance to harsh conditions compared to other fruit crop species (Harkat *et al.*, 2022), its applications in wood, craft items, and traditional medicine (Gros-Balthazard *et al.*, 2021). Thus, the absence of date palms would have precluded the sustenance of large human populations in these regions (MENA), desert regions generally, as they exhibit greater tolerance to high temperatures, drought, and salinity compared to other fruit crops (Bekheet et El-Sharabasy, 2015).

The date palm holds significant social, economic, and traditional importance for the local community; Beyond its nutritional value, the fruit can be processed into various by-products such as paste, flour, syrup, vinegar, alcohol, yeast, and sweets; Additionally, its leftovers, including leaves and roots, can be utilized in the construction of houses and tools, while the seeds can serve as animal feed (Bouguedoura *et al.*, 2015 ; El Hadrami et Al-Khayri, 2012). Furthermore, it mitigates sand encroachment and offers shade, protecting underlying crops such as fruit trees, vegetables, and cereals from excessive solar radiation, while also supporting diverse animal and plant species vital for the survival of local communities (BOUGUEDOURA *et al.*, 2010).

VII. Date Palm Waste:

The cultivation of date palms generates significant quantities of waste (Aydeniz-Güneşer, 2022) , with estimates indicating that a single palm tree produces around 20–40 kg of waste annually, primarily as a result of harvesting and pruning activities (Mallaki et Fatehi, 2014 ; Martis *et al.*, 2020). According to Abid et Ammar, (2022), Date palm trees have the potential to yield 20 kg of dry leaves annually, along with approximately 35 kg of waste biomass, which comprises roughly 35% midribs, 30% leaflets, 27% spadix stems, and 8% mesh and other waste materials.

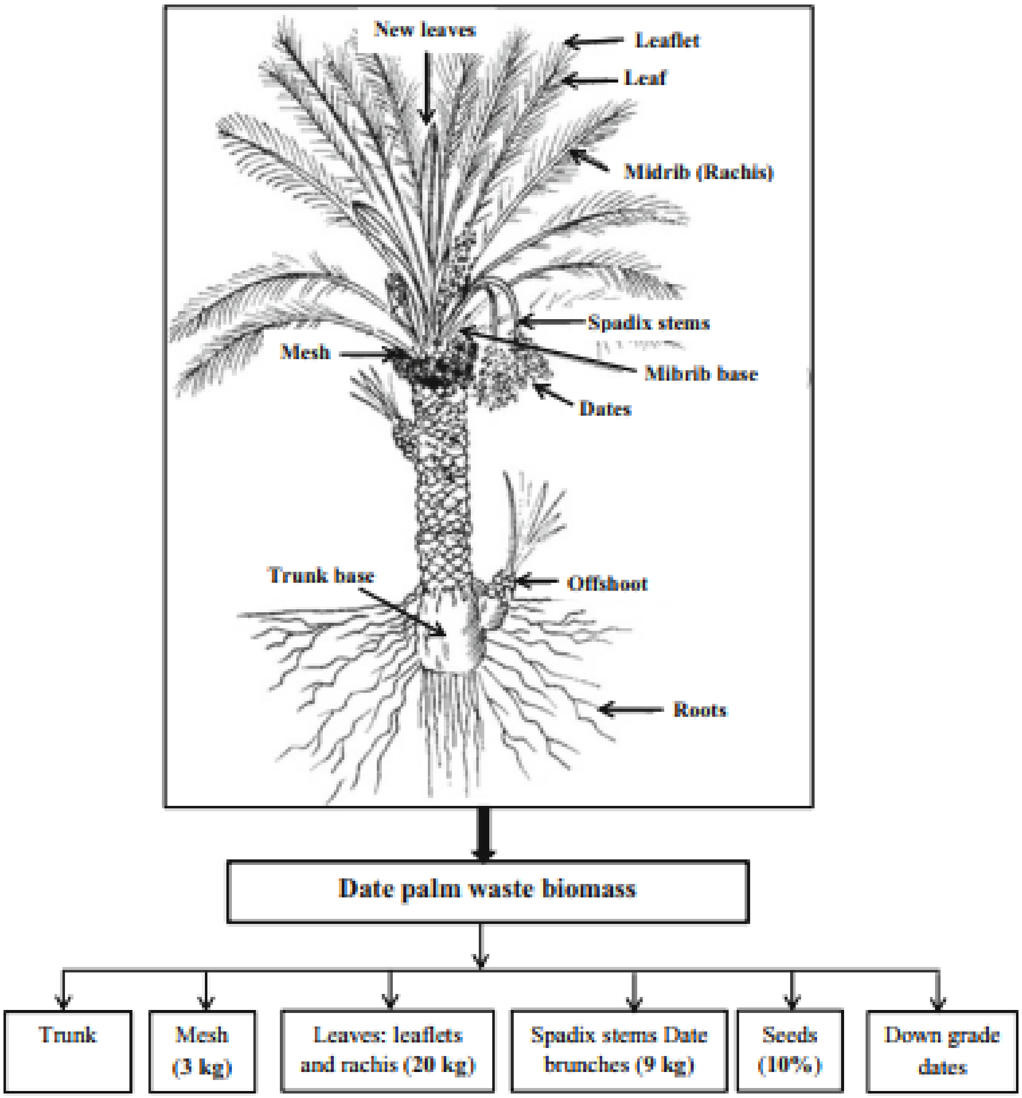

Figure 6: Components of the date palm tree and annual waste production *(Abid et Ammar, 2022)*.

In the MENA region, home to 75% of date palms, between 2.6 and 2.8 million tonnes of waste are generated each year, eventually disposed of in landfills (Abid et Ammar, 2022 ; Awad *et al.*, 2021) or incinerated on farms, posing a significant environmental concern; Even though they consist of cellulose, hemicelluloses, lignin, and other chemicals desired in many biological activities (Chandrasekaran et Bahkali, 2013).

Chapter 02:
Composting Process

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I. History:

Although the origin of Composting is unknown (Haug, 1993), it is a practice that has been used for centuries to improve soil quality and enrich lands for cultivation that may date back to Neolithic era and Early Civilizations in regions such as South America, India, China, and Japan, where early farmers used to put different residues (agricultural, animal and human) in pits or piles and let them undergo prolonged decomposition resulting in compost production (Diaz et De Bertoldi, 2007 ; Epstein, 1997 ; Stewart, 2022), where the ancient Egyptians found that fresh animal manure has a smaller influence on the ground and can potentially harm it compared to manure mixed with silt or vegetation (Ivankin *et al.*, 2014). Generally, the concept of composting has ancient origins; nevertheless, its contemporary development is largely credited to British botanist and organic farming pioneer Sir Albert Howard (1873–1947), who is recognized as a foundational figure in pre-World War II composting and organic agriculture due to his Indore composting system, which represented as the first scientific approach to large-scale composting (Epstein, 1997 ; Haug, 2020 ; Veeresh et Veeresh, 2006).

II. Generality:

During biotransformation, decomposer microorganisms play a crucial role in breaking down organic substances through intricate microbial metabolic processes that include biodegradation (mineralization, depolymerisation…) and biosynthesis (humification, polymerization…), ultimately converting it into a more complex and stable substance referred to as humus (Lignoproteins); This process occurs continuously and gradually in nature, when moist organic materials are gathered, therefore, by exploiting this phenomenon and managing microbial activity, it is possible to produce a stable and high-quality humified OM within a shorter timeframe (Figure 7) (Bernal *et al.*, 2009 ; Ceglie et Abdelrahman, 2014 ; Ceustermans *et al.*, 2010 ; Insam *et al.*, 2010 ; Insam et De Bertoldi, 2007 ; Oshins *et al.*, 2022 ; Raza et Ahmad, 2016 ; Stewart, 2022). This approach known as composting and has no formally accepted definition (Haug, 1993). However, it can be defined as an exothermic biotechnological process involving the biodegradation, sanitization, and stabilization of biologically degradable materials; in controlled conditions, essentially aerobic, in order to produce a stable, pathogen-free, plant-seed-free, humus-like end product called compost that can improve and fertilizes soils (Alkoaik *et al.*, 2019a ; Bernal *et al.*, 2009 ; Ceglie et Abdelrahman, 2014 ; Ghosh, 2019 ; Haug, 1993 ; Pergola *et al.*, 2018 ; Rechcigl et MacKinnon, 1997 ; Rynk *et al.*, 2022a). In brief, it differs from natural rotting or putrefaction (Ceglie et Abdelrahman, 2014) as it is a controlled biodegradation process designed to sanitize and expedite the production of humified OM.

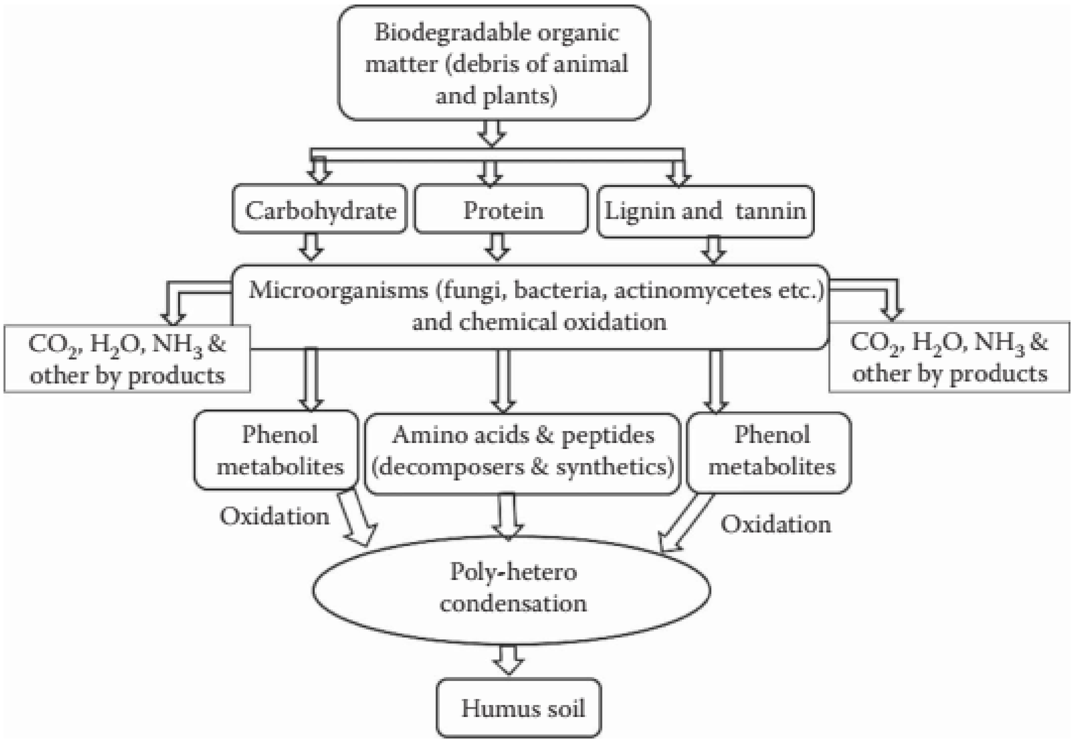


Figure 7: Natural humus soil synthesis from plant and animal waste (Singh et Kalamdhad, 2019).

The term composting originates from the Latin word 'Compostium', which means mixture, and refers to a mixture of substrates that are biodegraded by diverse microbial populations under solid-state and oxygen-rich conditions (Insam et De Bertoldi, 2007 ; Majeed *et al.*, 2021). While, co-composting indicates the simultaneous composting of diverse organic residue materials (Petric *et al.*, 2012) such as: date palm waste with poultry manure (Ouali et Hiouani, 2024).

Far from its metaphorical roots and from the perspective of an agriculturist, compost is an archaic English term that originally meant "decomposed organic wastes" signifying organic matter that has undergone decomposition and subsequent recycling for the purpose of fertilisation and soil amendment (Stewart, 2022). In other word, compost is the outcome of a composting process (Ceglie et Abdelrahman, 2014 ; Majeed *et al.*, 2021), encompassing various compost that vary in quality parameters, initial mixtures, and composting technologies (Ceglie et Abdelrahman, 2014). It is characterized as a matured and stabilized organic matter that is naturally enriched by hydrophobic carbon-rich molecules referred to as humic substances, which can be divided into three subfractions: humic acids, fulvic acids, and humin (De Corato, 2020). Although compost is frequently referred to as "humus," it is different from soil humus, which is a stable amalgamation of organic compounds formed over time through continuous decomposition and biological activity, while compost contains humic compounds that are not identical to soil humus and are still undergoing the transformation into humus (Rynk *et al.*, 2022a).

III. Composting technologies:

At first, the process was anaerobic; however, it was later adapted to an aerobic technique (Epstein, 1997 ; Veeresh et Veeresh, 2006) and researchers have continued to explore composting, enhance the original technology, and innovate on it, making composting technologies more well-developed (Zhou *et al.*, 2023). Particularly, after discovering that the performance of the composting process is decided by the contribution of varies microorganisms and their activity (Ivankin *et al.*, 2014).

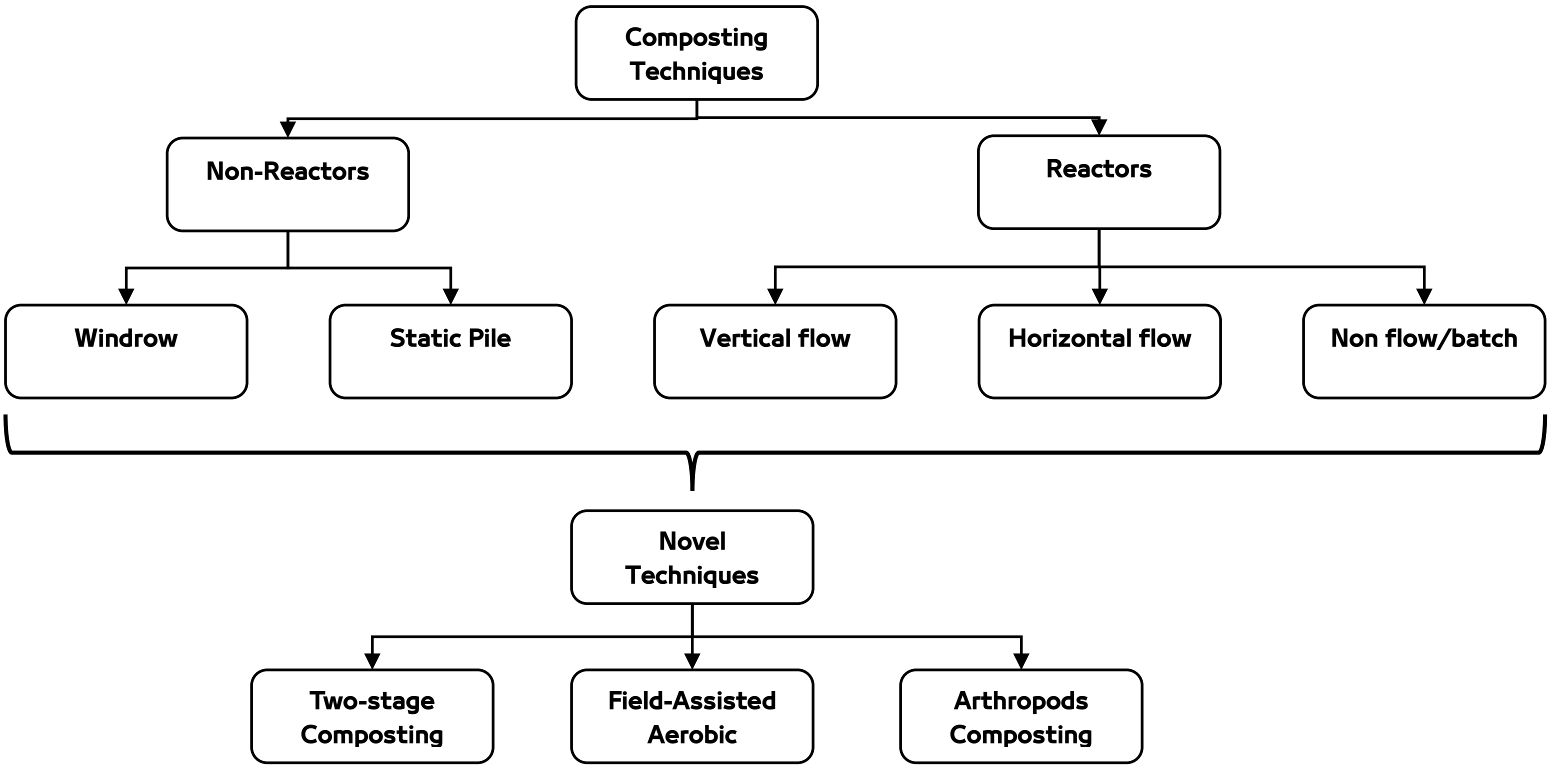


Figure 8: Different composting techniques.

Nowadays, Composting systems and technologies exhibit considerable variability due to many factors influencing the composting process and can be categorized into open or/and Non-reactor systems, and enclosed, also termed "mechanical", "Reactor", or "in-vessel" systems (Haug, 1993 ; Onwosi *et al.*, 2020), which can be split based on the flow of solids into three types: vertical flow reactors, horizontal flow reactors, and non-flow reactors (Figure 8)(Haug, 1993 ; Singh et Kalamdhad, 2019). Furthermore, it can be classified into various types according to the aeration procedures, which include static, turning, and forced aeration composting (Tong *et al.*, 2019). Generally, four primary composting methods are widely employed: windrow, aerated static pile, in-vessel in all its forms, and vermicomposting (Lim L.Y. *et al.*, 2017 ; Mandpe *et al.*, 2020 ; Sayara *et al.*, 2020), along with novel composting techniques such as electric field-assisted aerobic composting (EAC), that applies a 2 V direct current to enhance conventional aerobic processes (Fu *et al.*, 2021), two-stage composting, which combines distinct technologies to improve the final product quality (Lim L.Y. *et al.*, 2017 ; Zhang et Sun, 2016), Composting using arthropods for reprocessing and transforming vegetative waste (Mandpe *et al.*, 2020), and etc…

The Windrow and Static Pile, , whether maintained in open, covered, semi-covered, or windrow form, exemplify non-reactor systems; where, the windrow systems utilizes an agitated solids bed reliant on turning for aeration, while the Static Pile systems employs a static solids bed that depends on forced aeration (Singh et Kalamdhad, 2019). They require a vast area and a long composting duration, typically ranging from 1 to 2 years (Ajmal *et al.*, 2022), resulting in the adoption of a turning or forced aeration system to expedite the process and enhance its efficiency (Tong *et al.*, 2019).

On the other hand, the in-vessel system entails the decomposition of the organic waste fraction within a sealed container or vessel, utilising controlled conditions (Mandpe *et al.*, 2020) and employing fixed, agitated, or rotating bioreactors for composting (Ajmal *et al.*, 2022), with reliance on mechanization through regular turning or active aeration, whether completely or partially (Ajmal *et al.*, 2022 ; Lohri *et al.*, 2017). Additionally, various composting technologies employing in-vessel systems are available, including agitated solid bed and packed bed (silo reactor) for vertical flow reactors, as well as the rotary drum bio-reactor, which exemplifies horizontal flow reactors (Haug, 1993 ; Singh et Kalamdhad, 2019). The rotary drum bio-reactor (Figure 9) represents an exciting advancement in composting systems, recognized globally for its sophisticated and beneficial features (Rashwan *et al.*, 2021).

Figure 9: rotary drum bio-reactor *(Kauser et Khwairakpam, 2022)*.

Moreover, the different composting systems can be divided according to their volume (V) or/and surface area-to-volume ratio (Sv) into laboratory scale ($V < 0.1$ m³; Sv = 10-88), pilot scale (V = 0.1-2 m³; Sv = 4-10), both of which are referred to as small scale, and full-commercial scale ($V > 2$ m³; Sv = 0.2-4), i.e. large scale (Alkoaik *et al.*, 2019a).

The choice of composting approach is contingent upon capital expenditure, labour expenses, time constraints, land availability, and other factors (Sayara *et al.*, 2020)

IV. Compostable materials:

Composting technology is currently being recommended as a viable alternative approach for managing and valorising solid waste materials (Sayara *et al.*, 2020), including yard waste (branches, leaves, grass), food waste, agricultural waste, manure, septage, sewage biosolids, industrial sludges, garbage, wood and paper products, human feces, petroleum sludges, explosives, and other diverse mixed materials (Lohri *et al.*, 2017 ; Rechcigl et MacKinnon, 1997 ; Rynk *et al.*, 2022a). Indeed, the number of substrates potentially suitable for composting, i.e. Compostable materials, is substantial (Haug, 1993), particularly the organic waste, which is rich in microorganisms and nutrients that support their growth, and other resources in the form of organic matter, energy, and minerals… (Hamda *et al.*, 2023 ; Insam et De Bertoldi, 2007 ; Rynk *et al.*, 2022b). These compostable materials become soil-enhancing products that usually have value that possess greater value than their original form, i.e., compost, through composting (Rynk *et al.*, 2022b).

V. Composting Advantages:

Composting serves as the apex of waste recycling and is one of the most eco-effective and suitable Waste Biotreatment/bio-management approaches used worldwide (Cáceres *et al.*, 2015 ; Epstein, 1997 ; EU, 2008 ; Maheshwari, 2014). It is becoming increasingly trendy compared to other methodologies such as bio digestion, incineration, RDF conversion, and landfill, owing to its ease of implementation, low labour and operational costs, practical, environmentally friendly ,safe, and sustainable way that effectively maintains resources, preserve the environment and adds value to materials deemed unused or harmful by recycling and converting /reintroducing them into the economic framework as organic substrates and/or amendments (Compost)(Jain *et al.*, 2020 ; Maheshwari, 2014 ; Rechcigl et MacKinnon, 1997 ; Reyes-Torres *et al.*, 2018 ; Rynk *et al.*, 2022a ; Seng *et al.*, 2016).

VI. Compost benefits:

According to different researches (Ceglie et Abdelrahman, 2014 ; Ceustermans *et al.*, 2010 ; Gao *et al.*, 2010 ; Karanja *et al.*, 2019 ; Muktadirul Bari Chowdhury *et al.*, 2013 ; Scotti *et al.*, 2016), applying compost has beneficial effects on various aspects of soil health including:

1. improving soil physical characteristics such as structure stability, water-holding capacity, porosity and lowers soil bulk density;
2. enhancing soil chemical properties like cation exchange capacity, the quantity and quality of soil organic matter (SOM), enrich the soils of nutrients such as nitrogen, potassium, calcium, and phosphorus, necessary for the plant's growth;
3. influencing soil biochemical and biological properties, improvements in global microbial biomass and soil enzyme activities, reduce the load of soil-borne pathogens on plants by enhancing competition between native soil microorganisms and those derived from compost. Furthermore, reducing the severity of soil-borne diseases has been documented.

Hence, compost can serve as a fertilizer and/or soil amendment, while providing a sustainable solution to mitigate the negative environmental impacts associated with waste management, supporting the circular economy through by-product recycling (Ceglie et Abdelrahman, 2014 ; Finore *et al.*, 2023).

VII. Maturation and Stabilisation:

Nonetheless, the compost must be fully mature and stable; otherwise, its application on the soils may result in negative effects, including a lack of nitrogen in plants due to competition between plants and microorganisms for inorganic N , Intense microbial activity can also alter the degradation of soil organic matter, resulting in an accelerated decomposition of indigenous organic matter, phytotoxic effects from ammonia and other low molecular weight organic acids, as well as the presence of pathogens (Benito *et al.*, 2005 ; Gao *et al.*, 2010). Thus, the main criteria for the safe agricultural and environmental application of compost is its degree of stability and maturity (Benito *et al.*, 2003 ; Ceustermans *et al.*, 2010), which, in turn, reflect its quality and suitability as a product that is beneficial for plants, soil, environment, and social responsibility (Baffi *et al.*, 2007). In fact, compost production is regulated by guidelines, regulations, and national laws (De Corato, 2020).

Table 2: Maturity and Stability Indices *(Antil* et al.*, 2014)*.

Maturity Indices	Stability Indices
C:N ratio	**Temperature**
C_w /N_{org}	**pH**
HA/FA ratio	**EC**
HI	**WSC**
CEC	**Total organic carbon/OM loss**
CEC/TOC ratio	**Microbial diversity population/activity**
NH4 and NO3	**Enzyme activity**
Germination index	**O_2 and CO_2 respiratory**

Maturity and stability are terms frequently employed to characterize the decomposition level of organic matter throughout the composting process (Eggen et Vethe, 2001). The first one, i.e. Maturity, denotes the amount of phytotoxic compounds that may inhibit plant growth in the compost, alongside the level of their decomposition throughout the active composting period, as well as indicates the absence of pathogens and active weed seeds (Benito *et al.*, 2005 ; Gao *et al.*, 2010 ; Lončarić *et al.*, 2024). It can be evaluated using many physical, chemical, and biological characteristics, including the carbon-to-nitrogen ratio, cation exchange capacity, and, most notably, seed germination tests and plant growth bioassays (Antil *et al.*, 2014 ; Gao *et al.*, 2010). Consequently, it is optimal to estimate maturity by evaluating two or more compost parameters (Antil *et al.*, 2014); Table 2 categories indicators by maturity and stability. On the other hand, stability has a significant correlation with biomass microbial activity in compost, which reflects the resistance of its organic matter to further decomposition, i.e. bioavailability. that could lead to the generation of odorous volatile compounds (Eggen et Vethe, 2001 ; Gao *et al.*, 2010 ; Lončarić *et al.*, 2024). Its evaluations can be conducted through various respirometric measurements, including O_2 uptake rate, CO_2 production rate, or by assessing the heat released due to microbial activity, as well as by examining the transformations in the chemical properties of compost organic matter (Benito *et al.*, 2003 ; Gao *et al.*, 2010). Indeed, the quality of the product is contingent upon the success of composting (Jouraiphy *et al.*, 2005).

VIII. Factors:

In order to achieve a fully mature and stable compost in short time-frame, it is crucial to control and establish favourable conditions for microorganisms during the entire process, because unfavourable conditions can not only compromise the compost quality but also lead to environmental pollution (Ceustermans *et al.*, 2010 ; Liu *et al.*, 2020 ; Sundh et Rönn, 2002). Generally, numerous studies indicate that the success and rate of composting depend on several variables (Ceglie et Abdelrahman, 2014 ; Gaspar *et al.*, 2022 ; Oshins *et al.*, 2022 ; Sołowiej *et al.*, 2021 ; Xie *et al.*, 2023), including :

- The physical, chemical, and biological characteristics of the feedstocks, especially their biodegradability, particle sizes and morphology, porosity, free air space (FAS), permeability, structure, and bulk density, which all are interdependent.
- Bioavailability of nutrients, encompassing a balanced provision of carbon and nitrogen (C:N ratio) and moisture., which can be attained through the proportions of ingredients in the initial mixture, i.e., the composting recipe.
- The conditions during composting, including oxygen availability, moisture content, pH, temperature, and the mass being composted.
- The composting technique employed and the process duration.

Several variables interact with one another and collaboratively influence the rate of decomposition (Oshins *et al.*, 2022).

To further clarify the distinction of these variables, they can be classified into two categories: internal factors, which pertain to the composition of the composting mixture and include the carbon-to-nitrogen ratio (C/N), moisture content, pH, and particle size, and exogenous factors, which relate to process management and encompass aeration, oxygen supply, temperature and other external additives (Bernal *et al.*, 2009 ; Xie *et al.*, 2023).

Although the composting process might appear straightforward at first glance, an in-depth assessment of the intricate interactions among physical and chemical factors, along with the highly complex biological mechanisms involved in it, reveals that it is, in fact, a complex system (Ajmal *et al.*, 2022 ; Seng *et al.*, 2016).

Various vital factors influence the composting process; Hence, optimising factors is essential for reducing time and costs while enhancing the quality of final product (Patchaye *et al.*, 2018). Generally, the following factors are usually recognised as the principal determinants influencing the composting process:

VIII.1. Aeration:

Composting is basically an aerobic process that requires oxygen at its different stages in order to regulate and enhance the process (Gaspar *et al.*, 2022 ; Onwosi *et al.*, 2020), mainly, because aerobic decomposition occurs rapidly, generating less harmful products and unpleasant smells , releasing significant amount of energy, which results in higher temperatures (Awasthi *et al.*, 2016). Generally, aeration serves two main purposes: First, it supplies sufficient oxygen for microorganisms and remove CO_2 since the aerobic microbes dominate the medium, thereby ensuring their survival, maintain their metabolism activity, and enhancing the decomposition rate (Gaspar *et al.*, 2022 ; Xie *et al.*, 2023). The other purpose relates to its influence on temperature and moisture distribution, where high aeration rate promotes rapid cooling and drying of the pile by increasing the evaporation rate; whereas low aeration rate leads to reduced moisture and heat loss, resulting in the formation of anaerobic zones, thereby affecting the fermentation process and the final product's quality (Gaspar *et al.*, 2022 ; Onwosi *et al.*, 2020 ; Xie *et al.*, 2023)

Composting performance depends on the aeration rate, which correlates directly with microbial dynamics (Onwosi *et al.*, 2020) ; therefore, sufficient oxygen must be provided during periods of height microbial activity ,at the beginning and high-temperature period, where microbes oblige high oxygen consumption rate (Patchaye *et al.*, 2018 ; Xie *et al.*, 2023). Thus, aeration is considered as an essential aspect in various composting technologies, as it facilitates the maintenance of aerobic conditions, which offers significant benefits (Awasthi *et al.*, 2016). According to Bernal *et al.*, (2009) and Awasthi *et al.*, (2016) the optimum oxygen supply required for effective operation falls within the range of approximately 10% to 30%. This optimum aeration rate during composting can be achieved through natural (static), turning and its frequency, and/or forced aeration procedures (Onwosi *et al.*, 2020 ; Tong *et al.*, 2019 ; Zein *et al.*, 2015). Furthermore, aeration is influenced by several factors, with particle size and its distribution being the most significant as it subsequently impacts the structure, texture and porosity of the composting matrix (Wang, 2003).

Particle size, Free Air Space and Bulk Density:

The characteristics of particles, including their geometry, dimension, and arrangement, influence their settling behaviour, which in turn impacts the porosity and density of the matrix (Azim *et al.*, 2018), along with the availability of the compost's substrate for microorganism's metabolism, specifically the surface area of the particles for microbial growth (Bernal *et al.*, 2009 ; Wang, 2003). The composting matrix consists of an interconnected system of solid materials that have voids and gaps of various dimensions, referred to as pores or porosity (the ratio of void volume to total volume), which can hold air, water, or both, thereby it can be split into two sections: an air-filled space (TAS), which encompasses Free Air Space (the inter-particle air space) and micro-pores (the open and closed air pores space within particles), and a water-filled space (Wang, 2003), as shown in Figure 10.

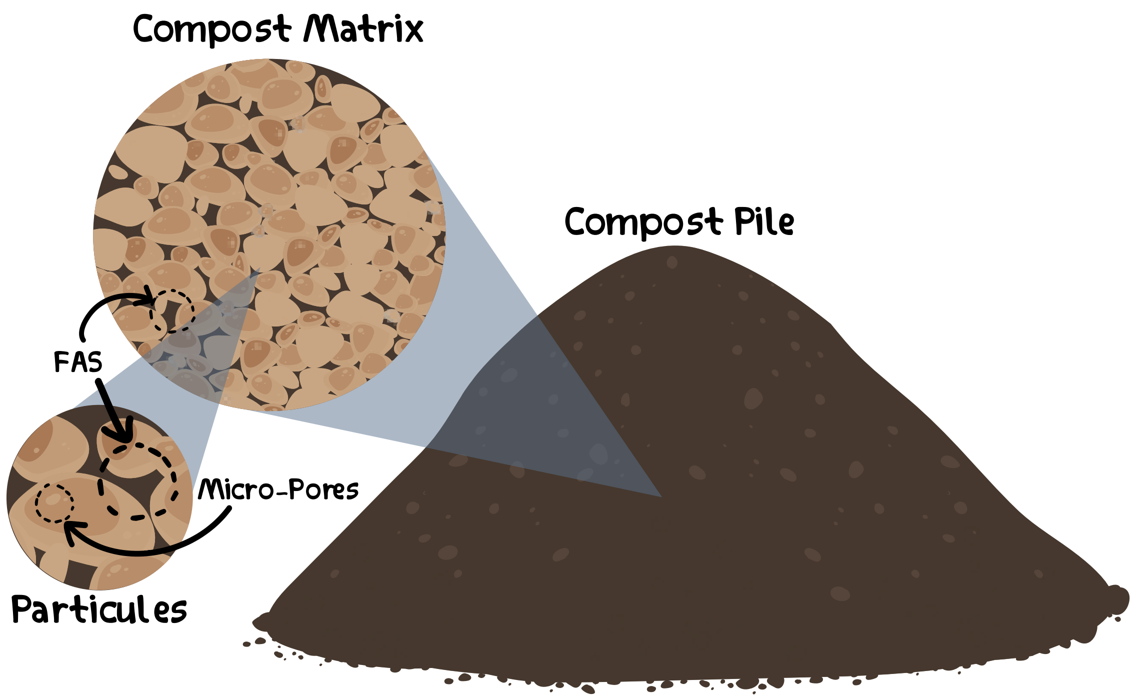


Figure 10: Compost Matrix and the Pore Space (after Wang, 2003).

Free Air Space (FAS) is a vital metric that assesses the volume and airflow inside the composting mixture, impacts heat and mass transfer processes, which in turn impacts microbial kinetics, and must be greater than 30% to provide sufficient aeration during the composting process (Jain *et al.*, 2018a, 2019a). Bulk density indicates the mass of substances that occupies a specific volume (Azim *et al.*, 2018), and influences numerous mechanical qualities, including strength, ease of compaction and porosity (Jain *et al.*, 2019a).

As particle size increases, the surface area to mass ratio diminishes, leading to an increase in porosity, particularly the free air space; a reduction in bulk density and water retention, with improving in air flow/ Air permeability; However, this also hinders microbial accessibility to the substance, thereby reducing material decomposition; and vice versa (Azim *et al.*, 2018 ; Bernal *et al.*, 2009 ; Jain *et al.*, 2018a, 2019a ; Wang, 2003). Furthermore, porosity and bulk density, specifically particle size, are influenced by various factors, including Bulking Agents ,the strength of compounds like fibrous materials that have high lignin and moisture content, particularly, where it can form an impermeable film on the surfaces of particles, filling the pores with water and consequently reducing the available air space, or weaken the structural integrity of fragile materials, making them appear plastic-like , thereby leading to anaerobic conditions (Bernal *et al.*, 2009 ; Jain *et al.*, 2018a ; Wang, 2003). Throughout the composting process, degradation results in a reduction of particle size and an increase in matrix dry bulk density, which consequently leads to a decrease in total porosity. (Richard *et al.*, 2002).

VIII.2. Temperature:

The composting is an exothermic process that generates heat energy , resulting in the formation of a high-temperature phase during the process (Insam *et al.*, 2010), which is a crucial phase in order to establish the sanitization conditions required for killing pathogenic microbes (Chen *et al.*, 2014). In aerobic conditions, the breakdown of carbon bonds in the biodegradation process (microbial work) generates significant amounts of heat energy (Azim *et al.*, 2018 ; Epstein, 1997 ; Insam *et al.*, 2010 ; Vinnerås *et al.*, 2010). For example, the heat produced during the complete oxidation of a fatty acid molecule and a glucose molecule is presented in equations (1) and (2), respectively (Vinnerås *et al.*, 2010).

$$C_{16}H_{32}O_2 + 23O_2 \rightarrow 16CO_2 + 16H_2O \qquad \Delta H = -39.2\ MJ/Kg \tag{1}$$

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O \qquad \Delta H = -15.7\ MJ/Kg \tag{2}$$

Microorganisms can capture a small portion of this energy (40–50%) for synthesizing ATP, however the majority of it is lost to the surrounding, triggering an increase within the composting mass temperature , which may approach 70-90℃ (Diaz et Savage, 2007). Therefore, it could be concluded that Temperature plays a dual role in the process, both as an effect and a factor. It affects the rate of microbial activity and its corresponding impact on the process, while also being a consequence of the bioactivity itself (Ceustermans *et al.*, 2010 ; Oshins *et al.*, 2022).

High temperatures accelerate biochemical reactions, leading to faster decomposition, increased heat production, higher oxygen demand, material sanitization, and greater evaporation of volatile compounds and water. On the other hand, lower temperatures slow down decomposition, which preserves nutrients and slows organic matter degradation, and emits fewer odors and volatile compounds (Oshins *et al.*, 2022). Often, microbial activity produces very high temperatures that may inhibit their growth and lead to their eventual death, in what can be called "microbial suicide", thereby limiting the biodegradation process of organic substances (Diaz et Savage, 2007).

According to Stentiford, (1996), the sanitation process requires temperatures above 55 degrees Celsius to eliminate any possible pathogens in the mixture. On the other hand, the most effective rates of biodegradation occur at temperatures ranging from 45-55°C; while low temperatures between 35-40°C ensure the greatest microbial diversity within the mixture, all of which is essential for rapid stabilization. Generally, the optimum temperature range for achieving necessary sanitization conditions without inhibiting microorganisms during high-temperature phase is 45-65℃ i.e. (thermophilic) for 3 days (Sudharsan Varma et Kalamdhad, 2015). Optimal temperatures refer to the degrees that effectively accomplish the desired objectives, including sanitization, fast mineralisation and humification i.e., stabilization (Azim *et al.*, 2018). However, as was stated, ensuring the optimal temperature during the process is insufficient to meet the essential sanitization conditions, it must be maintained for a minimum period, especially in large-scale composting, in order to ensure near-total destruction of pathogens (Oshins *et al.*, 2022), Therefore, the composting process is commonly presented as a function of a time-temperature relationship (Epstein, 1997), which is typically influenced by various aspects, including the composting system used, the characteristics of the feedstocks and the weed species, and finally the ultimate temperature (Oshins *et al.*, 2022).

According to the Process to Further Reduce Pathogens (PFRP) standards set by the US EPA, in sewage sludge composting, the temperature must exceed 55 degrees for at least 3 days using in-vessel or static aerated pile systems and 15 days with 5 turnings if using windrow (EPA, 2003 ; Epstein, 1997). In addition to the US, several countries have established their compost sanitation standards based on the time-temperature factor, as shown in Table 3

Table 3: Sanitation standards for composting in different countries (Neugebauer, 2018).

Country	Composting method	Temperature/Pathogens
Australia	**All methods**	**> 55 °C for at least 3 days, with a margin for variations and lower temperatures**
Germany	**Open windrow**	**> 55 °C for 2 weeks, or > 65 °C for 1 week**
	Closed/In vessel	**> 60 °C for 1 week**
	In all new facilities, absence of the following in 25 g:	**Human/Veterinary Hygiene: S. senftenberg W775**
	Elimination of added:	**Phyto-hygiene: Tobacco-mosaic Virus (TMV) & Plasmodiophora brassicae**
Austria	**All compost**	**> 60 °C for 6 days, or > 65 °C for 3 days**
Switzerland		**> 55 °C for 3 weeks, or > 60 °C for 1 week, or proven time-temperature relationship**
Denmark	**All compost**	**> 55 °C for 2 weeks**

Generally, the variations in temperature are a direct result of the exchange of heat energy between the various components of the thermal balance, which comprise the generation of heat mainly through aerobic metabolism alongside other ways of heat loss via convection, conduction, evaporation, and radiation (Ahn *et al.*, 2009), in addition to insulation capacity of the feedstocks, i.e. thermal conductivity (Oshins *et al.*, 2022). In the composting process, the fundamental components of thermal balance typically consist of biological heat generation, sensible heat of the mixture and composter system, sensible heat of the airflow, conductive and convective losses through the composter wall, radiation losses and the enthalpy of vaporization (Seng *et al.*, 2016 ; Wang *et al.*, 2014, 2016b):

$$\boldsymbol{E_{bio}} = \Delta \boldsymbol{U_{air}} + \Delta \boldsymbol{U_{c}} + \Delta \boldsymbol{U_{r}} + \Delta \boldsymbol{U_{lat}} + \Delta \boldsymbol{U_{wall}} \quad \textbf{(3)}$$

where $\boldsymbol{E_{bio}}$ is the biological heat production from degradation (kJ/h); $\Delta \boldsymbol{U_{air}}$ is internal energy accumulation of inlet air (kJ/h); $\Delta \boldsymbol{U_{c}}$ is internal energy accumulation of compost (kJ/h); $\Delta \boldsymbol{U_{r}}$ is internal energy accumulation of reactor (kJ/h); $\Delta \boldsymbol{U_{lat}}$is latent heat of water evaporation (kJ/h); $\Delta \boldsymbol{U_{wall}}$ is the conductive and convective heat losses through reactor wall (kJ/h).

Temperature variation serves as a key element in controlling composting progress (Vico *et al.*, 2018). Thus, the temperature control process can be achieved by either reducing heat loss or providing favourable conditions to increase the microbial heat generation. (Bernal *et al.*, 2009) listed several strategies to remove excess heat include controlling compost size and form, improving cooling through turning, and implementing temperature feedback-controlled ventilation.

Microorganisms exhibit sensitivity to temperature fluctuations (Ghanney *et al.*, 2023). Therefore, scientists have categorized and labelled three temperature ranges based on microorganisms' optimum conditions: mesophilic, approximately 20-45°C, thermophilic, 45-75°C , and psychrophilic (Oshins *et al.*, 2022). The composting process involves a temperature shift resulting from the biological activity of microorganisms (Gaspar *et al.*, 2022).

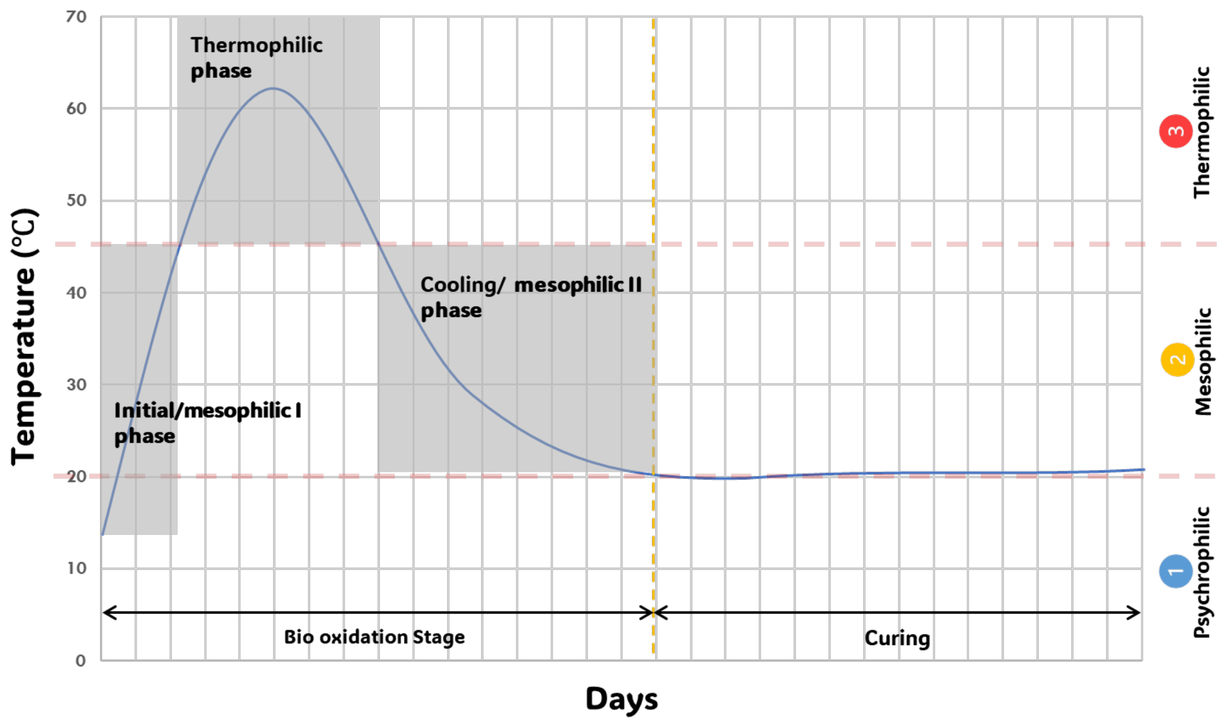


Figure 11: Patterns of temperature and Composting phases.

Typically, four microbiologically distinct composting phases can be characterized based on temperature kinetics (Oudart *et al.*, 2012 ; Sołowiej *et al.*, 2021) :

I. An initial or first mesophilic phase (20-45°C):

As suggested by the term itself, this phase marks the beginning of the process and takes place at a moderate temperature that is in proximity to the ambient temperature. This phase contains abundant energy, readily degradable carbohydrates, and various other bioresources (Polprasert et Koottatep, 2017). Once all the triggering factors of the composting process are present, particularly adequate aeration, moisture content, and nutrient balance (Azim *et al.*, 2018), the mesophilic microorganism, which outnumber thermophilic species by three orders of magnitude, initiates the bio-oxidation of the organic substance, releasing heat energy as byproduct which accumulates and raises the mixture temperature (Bernal *et al.*, 2009 ; Insam et De Bertoldi, 2007).

Under the abundance of labile substrates, such as sugars, amino acids, proteins, and microbial optimal conditions, competition occurs among the various microbes within the mixture such as fungi, actinomycetes, and bacteria, generally referred to as primary decomposer, which leads to rapid bio oxidation of substances that causes rapid self-heating of the mixture (Bernal *et al.*, 2009 ; Insam *et al.*, 2010 ; Sayara *et al.*, 2020). The temperature rapidly rises, shifting from the mesophilic phase (25–45°C) to the thermophilic phase (over 45°C) (Sayara *et al.*, 2020).

II. A thermophilic phase (45–70°C):

The thermophilic phase is marked by high temperatures ranging from 45 to 70°C, and in some cases even 90°C. The high temperature during this phase is crucial for eliminating pathogens agents, weed seeds, and insect larvae in the composting materials (Sayara *et al.*, 2020). Essentially, the thermophilic phase, is paramount for successful composting; during which, high temperature promote the biodegradation of recalcitrant components, such as fats, cellulose, hemicellulose and a fraction of lignin, leading to weight loss due to high water vapor and CO_2 emission; additionally, its function goes beyond simply destroying pathogenic microbes, but also degrading chemical contaminants such as antibiotics, pesticides, hormones, and drug residues (Bernal *et al.*, 2009 ; Rich *et al.*, 2018 ; Sołowiej *et al.*, 2021).

At the onset of the thermophilic phase, high temperatures give thermophilic organisms an upper hand over their competitor, mesophiles; Over time, the once-growing mesophilic organisms become inactive and gradually decompose by the thermophilic organisms, together with the Labile Substrates that remains from the initial phase and the recalcitrant components (Insam *et al.*, 2010 ; Insam et De Bertoldi, 2007). The optimal temperature for most thermophilic microorganisms is 60°C (Grantina-Ievina et Rodze, 2020), while temperatures from 40°C to 58°C eliminated numerous mesophilic bacteria (Epstein, 1997). According to Insam *et al.*, (2010), the decomposition rate increases proportionately with the temperature until it reaches 62 °C. It was stated also that the temperature may rise beyond 80°C due to abiotic exothermic reactions, which could involve temperature-stable enzymes of actinobacteria. However, temperatures above 65°C are not recommended as they can limit the decomposition rate by eliminating many microbes, mostly mesophilic, which may cause a delay in recovery after the temperature peak and extend the composting process (Insam et De Bertoldi, 2007 ; Sayara *et al.*, 2020 ; Sołowiej *et al.*, 2021).

The duration of the thermophilic phase can vary from days to months (Grantina-Ievina et Rodze, 2020), depending on factors such as feedstocks characteristics, composting facility scale, and environmental conditions (Finore *et al.*, 2023).

III. A second mesophilic phase or cooling phase:

Gradually, the temperature begins to decrease until it reaches the ambient degree (cooling), resulting in the reestablishment of a second mesophilic phase (>45°C). As the labile substrates become more scarce, the activity of thermophiles decreases, leading to a drop in temperature and the restoration of mesophilic conditions, which assists in the re-domination of the mesophiles, which, over time, begin to decompose any remaining sugars, cellulose, and hemicellulose (Bernal *et al.*, 2009 ; Grantina-Ievina et Rodze, 2020 ; Sayara *et al.*, 2020). It is important to note that these new mesophiles include both the surviving organisms and those that have been externally inoculated or spread from protected micro niches, which they are complex-decomposing organisms, in contrast to the initial stage mesophiles, which primarily consisted of sugar-decomposing species (Grantina-Ievina et Rodze, 2020 ; Insam *et al.*, 2010).

The previous phases can be referred to as the bio-oxidative period, which is considered the most active stage, followed by the maturity stage (Song *et al.*, 2015).

IV. A maturation, curing or stabilization phase:

At this stage, complex-decomposing organisms, especially fungi (Ascomycota, Basidiomycota, etc.), support the transformation of complex organics into humic colloids, ultimately ending in the formation of low readily degradable organic matter known as humus (Polprasert et Koottatep, 2017 ; Zhao *et al.*, 2023). This secondary fermentation decomposes slowly organic molecules using specific extracellular enzymes, producing side-chain oxidation, aromatic-ring substitution, alongside a large number of HS precursors like amino acids, sugars, polyphenols, and phenolic derivatives, which are used to synthesise humus through condensation and/or polymerisation, i.e., humification (Zhao *et al.*, 2023).

VIII.3. Moisture Content:

The moisture content is a critical factor that plays an immense effect on microbial activities, and the physical structure of the compost (Chen *et al.*, 2019a ; Kim *et al.*, 2015), thus has a central influence on the organic matter decomposition and humification (Ghanney *et al.*, 2023). It exerts a much greater influence on microbial activity than temperature (Liang et al., 2003), where, it performs several crucial roles: allowing the dissolution and transportation of minerals and nutrients through leaching; playing as a solvent in oxidation-reduction reactions; breaking down complex organic compounds, i.e., Hydrolysis; softening materials and providing an optimal environment for microorganisms to navigate and metabolize organic matter (Ghanney *et al.*, 2023 ; Li *et al.*, 2022 ; Oshins *et al.*, 2022 ; Xie *et al.*, 2023). Moreover, it may even be considered the primary driver of the impact of other factors (Ghanney *et al.*, 2021).

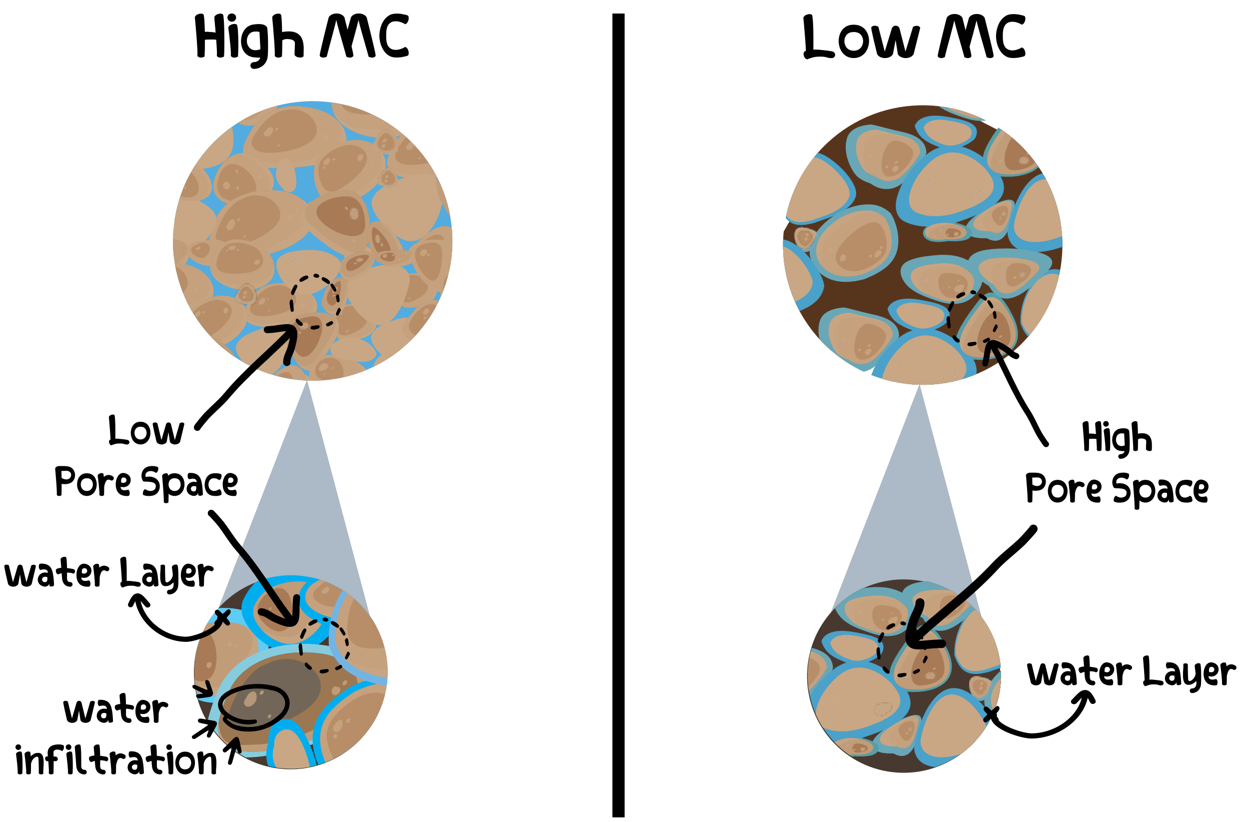


Figure 12: moisture content inside the compost matrix.

At high moisture content (> 70%), the material structure and/or liquid coating surrounding solid particles thickens and fill the pores spaces between particles, decreasing oxygen airflow, leading to anaerobic conditions (Figure 12), which will trigger anaerobic metabolism and reduce the decomposition rate, resulting in the formation of methane (CH_4) instead of carbon dioxide (CO_2); the generation of organic acids due to incomplete bio-decomposition, which, in turn, leads to a decrease in compost pH and leaching of salts; significant nitrogen loss due to N_2O accumulation and volatilisation; as well as a large amount of unpleasant odour (H_2S) (Ghanney *et al.*, 2023 ; Li *et al.*, 2021 ; Oshins *et al.*, 2022 ; Rich *et al.*, 2018 ; Wang *et al.*, 2015). Additionally, high moisture content may hinder heating as water has a higher specific heat capacity than microbial activity, which causes lacking heat generation (Li *et al.*, 2022). On the other hand, low moisture content (< 40%) can impede or halt biological activity, which is crucial for decomposing organic molecules, leading to unstable and immature compost; This makes moisture content the most crucial element in the composting process after the feedstocks (Kim *et al.*, 2015 ; Oshins *et al.*, 2022 ; Shen *et al.*, 2015). Therefore, it is vital to ensure the correct amount of moisture throughout the composting process (Jain *et al.*, 2018a), by rewetting the composting mixture (Bernal *et al.*, 2009 ; Trémier *et al.*, 2009) and/or using dry bulking agent (BA) (Trémier *et al.*, 2009). This stimulates a rise in temperature, promoting the invasion and decomposition of organic materials by heat-tolerant microbes (Ghanney *et al.*, 2023).

There is no universally optimum moisture content owing to the feedstock's distinct physical, chemical, and biological properties of each composting material (Chen *et al.*, 2019a). It depends on physicochemical and biological factors , such as particle size, porosity, absorption, and ash or mineral content (Guo *et al.*, 2012 ; Oshins *et al.*, 2022), and most importantly , material structural strength, where, fibrous materials, including wood chips and straws, preserve their structure and porosity after absorbing a lot of water; in contrast to vegetable trimmings (Wang *et al.*, 2015). It was stated that the composting material's properties change over time; therefore, fulfilling the optimal moisture content initially can't ensure its preservation during composting. Therefore, optimal moisture content should be determined for the desired material and throughout the composting process (Kim *et al.*, 2015 ; Wang *et al.*, 2015). However, according to most studies, the optimal moisture content is typically considered to be between 50% and 70% (Chen *et al.*, 2019a ; Kim *et al.*, 2015 ; Singh et Kalamdhad, 2019).

Monitoring and adjusting moisture content throughout composting is challenging and costly; thus, it's fundamental to establish the optimal moisture content from the very beginning (Debertoldi *et al.*, 1983). Generally, initial moisture content of around 60% is a basic requirement at the start of the process (Alkoaik, 2019 ; Calisti *et al.*, 2020), where insufficient initial moisture content may cause early dehydration during composting, impede microbial activity and promote heat loss due to high porosity, ultimately producing an unstable product (Debertoldi *et al.*, 1983 ; Li *et al.*, 2021).

Generally, the movement of water includes four primary processes: evaporation, diffusion, and percolation (liquid and vapor diffusion) , as well as water generation resulting from biological activities (Seng *et al.*, 2016). Additionally, the material Water Holding Capacity helps control the moisture content loss during the process (Rich *et al.*, 2018). Thus, higher temperatures are expected to lead to a significant decrease in moisture content (Kalamdhad *et al.*, 2009), which serves as an indicator of the extent of organic matter breakdown (Sudharsan Varma et Kalamdhad, 2015), and an index of composition rate (Rich *et al.*, 2018).

According to Shen *et al.*, (2015), in organic matter, there are two basic states of water: free water (entrapped and capillary water) and bound water (multiple-molecular-layer and monolayer water); During composting, most of the change in moisture content occurs only at the level of free water.

VIII.4. potential of Hydrogen (pH):

The pH is a key abiotic factor that significantly impacts microbial and enzymatic activities in different capacities during composting and serves as an essential measure of the compost's acidity or alkalinity (Ma *et al.*, 2019 ; Voběrková *et al.*, 2020 ; Zhao *et al.*, 2023). It can affect microorganisms' development ability, where different microorganisms thrive at different pH levels; For example, bacteria prefer neutral pH, while fungi develop better in slightly acidic conditions; Thus, microorganisms can be categorized as acidophiles (pH 2-3), alkalophiles (pH 7-12), or neutrophiles (Debertoldi *et al.*, 1983 ; Diaz et Savage, 2007 ; Epstein, 1997). This pH sensitivity of microorganisms is mostly an indirect outcome of the multiple enzymatic reactions responsible for their metabolism (Haug, 2020), which affect nutrient bioavailability and mineral solubility (Habchi *et al.*, 2022). Therefore, unsuitable pH conditions may restrict or impede microbial activity, leading to slow composting performance (Zhao *et al.*, 2023).

According to different studies, the optimal pH for the composting process should range between 6.7 and 9. This range enhances microbial activity, sustains high temperatures, reduces emission rates, and minimizes nitrogen loss (Bernal *et al.*, 2017 ; Cao *et al.*, 2020 ; Diaz et Savage, 2007 ; Rich *et al.*, 2018). Regardless, the composting process's capacity to auto-correct or buffer permits it to perform within a broader range, from 5.5 to 9.0 (Ceustermans *et al.*, 2010); However, the process may be slower at pH this range than at a neutral pH (Oshins *et al.*, 2022).

During composting, the pH level fluctuates, depending on the materials and process conditions (Oshins *et al.*, 2022 ; Xie *et al.*, 2023). Generally, the pH can change in three ways:

1. **Reduction**, where it can occur due to the formation of low-molecular weight fatty acids such as acetate, propionate, and butyrate, which are intermediate products of the incomplete decomposition of nitrogenous matter by acid-forming bacteria in anaerobic conditions (Diaz et Savage, 2007 ; Oshins *et al.*, 2022 ; Rich *et al.*, 2018); nitrification or/and volatilization; During nitrification (Eq. 4 and 5)(at low temperatures) , ammoniacal nitrogen is converted into nitrate by nitrifying bacteria, whereas In volatilization (at Hight temperatures), it is converted into a gas and volatilizes, releasing hydrogen ions (H+) (Bernal *et al.*, 2017 ; Cao *et al.*, 2020 ; Kalamdhad et Kazmi, 2009b ; Oshins *et al.*, 2022 ; Petric et Selimbašić, 2008).

$$2NH_4^+ + 3O_2 \rightarrow 2NO_2^- + 2H_2O + 4H^+ \quad (4)$$

$$2NO_2^- + O_2 \rightarrow 2NO_3^- \quad (5)$$

2. **Increase**, it can occur due to the bio-oxidation of organic acids, mainly by fungi, or/and through The ammonification process, where proteolytic bacteria oxidase nitrogenous compounds, leading to the formation of ammoniacal nitrogen (Ammonium, ammonia), which can interact with hydrogen ions (H^+) and is characterized, mainly NH_4^+, by a high pKa of 8 to 9.3 (Eq 6) (Bernal *et al.*, 2017 ; Ghanney *et al.*, 2023 ; Haug, 1993 ; Oshins *et al.*, 2022 ; Rich *et al.*, 2018).

$$NH_3 + H_2O \rightarrow NH_4^+ + OH^- \qquad pK_a = 9.3 \quad (6)$$

3. **Stabilization**, often occurs due to an abundance of a buffering agent such as humus and calcium (Diaz et Savage, 2007 ; Rich *et al.*, 2018).

As the majority of compounds are within this pH range, pH is rarely a concern in composting; however it is significant for managing nitrogen losses due to ammonia volatilization, especially at pH levels exceeding 7.5 (Bernal *et al.*, 2009).

VIII.5. Electrical Conductivity (EC):

As a measure of the compost's saltiness and its potential plant-growing compatibility, electrical conductivity (EC) is often monitored throughout the composting process (Singh et Kalamdhad, 2013). It is an essential metric in composting, serving as an indicator of the dissolved salts concentrations in compost, i.e. salinity; thereby, its potential phytotoxicity effects on plant development when it is applied to soil (Antil *et al.*, 2014 ; Cao *et al.*, 2020 ; Ghanney *et al.*, 2021 ; Petric et Selimbašić, 2008). Electrical conductivity (EC) is an essential metric in composting, serving as an indicator of the dissolved salts concentrations in compost, i.e. salinity; thereby, its potential phytotoxicity effects on plant development when it is applied to soil (Antil *et al.*, 2014 ; Cao *et al.*, 2020 ; Ghanney *et al.*, 2021 ; Petric et Selimbašić, 2008)

In compost, the feedstocks are the main source of salts (Rynk *et al.*, 2022b). During composting, microorganisms break down organic matter, releasing different compounds such as soluble salts (ammonium, phosphate, sodium, chloride, magnesium…) and organic acids into the compost; The soluble salts (ions) have electrical charges that can conduct electricity, increasing the EC of the compost; Conversely, Organic acids, Moisture, and pH can directly or indirectly impact the electrical conductivity, where, High Moisture can neutralize salt charge or/and transport it out of the compost through leaching, as well as organic acids; High pH can boost the ammonia volatilization, whereas low Moisture can cause salt precipitation, which ultimately causes a decrease in EC (Cao *et al.*, 2020 ; Ghanney *et al.*, 2021, 2023 ; Singh et Kalamdhad, 2013 ; Stehouwer *et al.*, 2022). The decrease in EC may also be related to microorganisms metabolizing salts (Fu *et al.*, 2021). Additionally, the organic matter biodegradability (Ghanney *et al.*, 2023) and the matter cation exchange capacity (Chan *et al.*, 2016) both play a key role in the EC alteration during the process.

The compost EC can vary significantly, usually between 0.2 to 16 dS/m in an extract of 1:5 (compost: water) (Stehouwer *et al.*, 2022). Although salts often provide the main nutrients for root absorption, The application of compost with EC values higher than 4 dS/m to the soil can restrict water and nutrient absorption due to significant osmotic potential (Chen *et al.*, 2019a ; Rynk *et al.*, 2022b ; Singh et Kalamdhad, 2013 ; Stehouwer *et al.*, 2022). According to (Kauser *et al.*, 2020), a compost with an electrical conductivity (EC) higher than 4 dS/m can still be applied to agricultural soil. However, it is advantageous to adjust the EC of the compost prior to its application or even avoid utilizing feedstocks with a high salt content in composting (Rynk *et al.*, 2022b).

It is interesting to note additional approaches, such as soaking in water, for reducing feedstock EC before utilization (Abid *et al.*, 2020), and/or enhancing ion retention and regulating their release utilizing phosphate-rich materials (Haouas *et al.*, 2021).

VIII.6. Organic Matter decomposition and biodegradability:

The composted materials could vary from homogeneous waste to a mix of diverse and non-uniform waste substances (Onwosi *et al.*, 2020). Overall, composted materials exhibit enormous heterogeneity in terms of their composition, physical and chemical characteristics (Vinnerås *et al.*, 2010). However, they can be mainly divided into 3 phases: gas, liquid, and solid phases. The latter consists of a diverse microbial community and a range of organic compounds, encompassing water-soluble organic substances such as sugars, soluble carbohydrates, organic acids, amino acids and proteins, and insoluble organic substances that incorporate polymers such as cellulose, hemicellulose, lignin (the main components of plant matter), fats, aromatic compounds, and chitin, along with inert substrate that composts with little or no alteration (Figure 13) (Bernal *et al.*, 2017 ; Oshins *et al.*, 2022 ; Seng *et al.*, 2016 ; Vinnerås *et al.*, 2010).

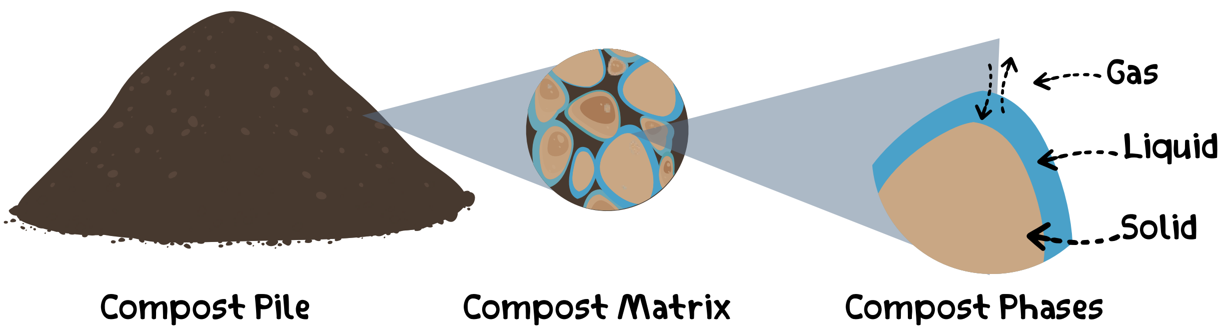


Figure 13: Composting's three stages (gas, liquid, solid) and interacts (after Oudart, 2013).

The composting process initiates by prioritizing the mineralization and metabolization of easily biodegradable substances by different decomposers that already exist on the surfaces of each particle, producing carbon dioxide or/and methane (depending on oxygen levels), water, novel microorganisms, and thermal energy. (Kulikowska et Klimiuk, 2011 ; Oshins *et al.*, 2022 ; Seng *et al.*, 2016). After depleting easily biodegradable substances, decomposers become less active and shift to microorganism populations with greater ability for metabolizing recalcitrant components (Oshins *et al.*, 2022). These materials, along with dead microorganisms, decompose and hydrolyse into simpler compounds that are either metabolize by microbes or polymerize and condensate as fundamental components for the synthesis of stable organic matter called humus, in other words, the prevailing of humification process (Bernal *et al.*, 2009 ; Kulikowska et Klimiuk, 2011 ; Muktadirul Bari Chowdhury *et al.*, 2013 ; Oshins *et al.*, 2022 ; Seng *et al.*, 2016). According to Insam *et al.*, (2010), approximately 50% of biodegradable waste converts into CO_2, H_2O, minerals, and energy via effective composting; 30% of the remaining organic matter is broken down into their structural units by aerobic and/or anaerobic processes, with about 20% undergoes intricate metabolic transformations that produce compounds resembling humic substances.

As composting progresses, the loss of biodegradable organic material, principally as CO_2 and water vapour, decreases gradually as carbon sources are exhausted and new complex organic compounds are formed, leading to a reduction in mass and C:N ratio (Bernal *et al.*, 2009 ; Gibbs *et al.*, 2002). In composting, organic matter (OM) serves as a crucial carbon and energy source, as well as a significant indication of microbial activity and compost quality (Xu et al., 2019), which can be measured by OM loss, or organic carbon loss (Muktadirul Bari Chowdhury *et al.*, 2013). Thus, the OM reduction during the process can be influenced by the rate of microbial decomposition, resulting in an increased concentration of CO_2 and consequently higher temperatures due to the evaporation of excess water vapor, i.e. Higher decomposition rate (Gibbs *et al.*, 2002). On the other hand, the process of converting composted material depends on the biodegradability of organic matter (OM), which in turn affects decomposition rate, gas emissions, process duration, and oxygen needs (Bernal *et al.*, 2009). Therefore, composting agricultural waste poses a significant challenge due to the difficult biodegradation of lignocellulose caused by its chemical and physical characteristics (Jain *et al.*, 2018b ; Reyes-Torres *et al.*, 2018 ; Rynk *et al.*, 2022b).

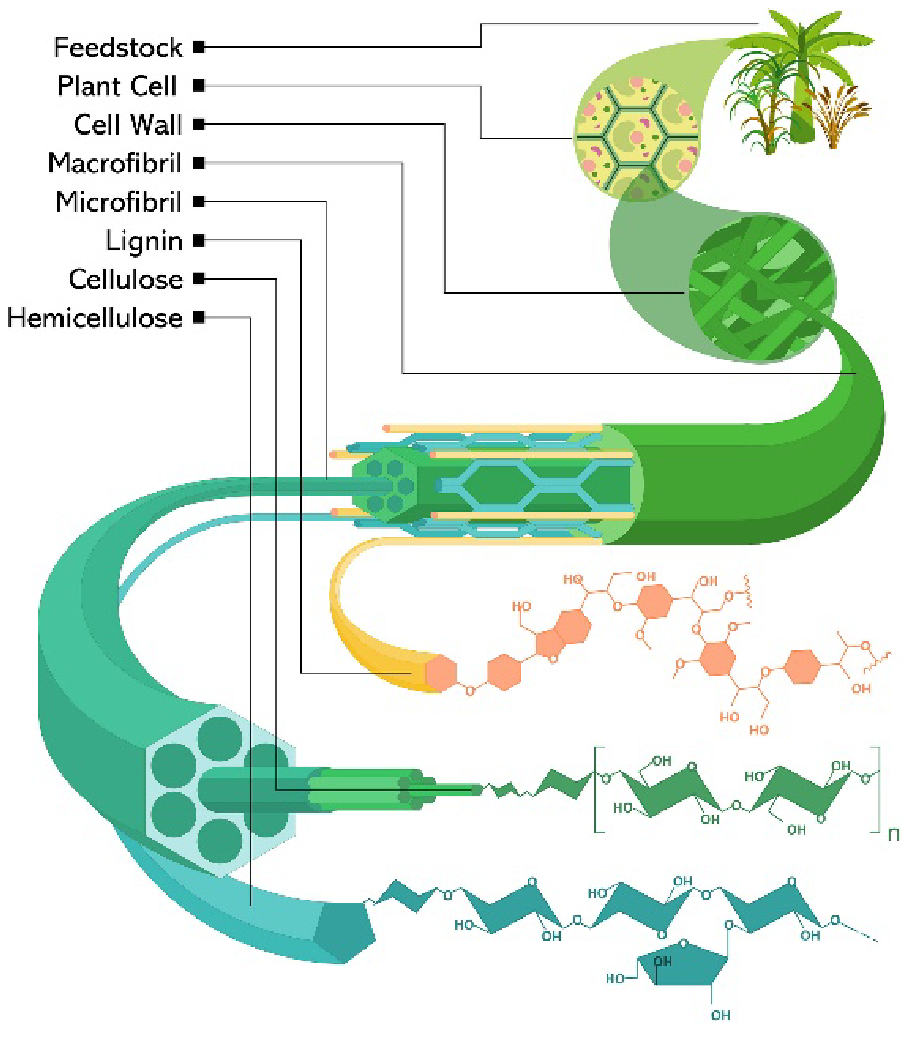


Figure 14: lignocellulosic biomass structure *(Magalhães* et al.*, 2019)*.

The lignocellulose content in agricultural wastes typically accounts for 50%–90% of the total organic matter, and its physical structure varies among different types of biomass (Bernal *et al.*, 2017). Generally, it consist of cellulose fibrils packed into microfibrils, which are further wrapped by hemicellulose and then lignin (Haug, 1993), as illustrated in Figure 14. All three substances have low biodegradability (carbohydrates > hemicellulose > cellulose > chitin > lignin), with lignin, a complex polyphenolic, aromatic, three-dimensional polymer.

polymer, being the most difficult to degrade by microorganisms. (Muktadirul Bari Chowdhury *et al.*, 2013). It acts as a protective barrier for the microfibrils, shielding them from degradation by biological and chemical agents (Haug, 1993), thereby limiting the breakdown of cellulose and hemicellulose (Varma *et al.*, 2017). Those features enable it to be the ideal indicator of the decomposition rate of composted materials and can be calculated using the Eq. 7 (Rynk *et al.*, 2022b), where, the initial lignin concentration has an inverse effect on organic matter degradation (Bernal *et al.*, 2017).

$$\boldsymbol{Biodegradability}\ (\%\ \boldsymbol{of\ volatile\ Solids}) = \mathbf{0.83}\ \times \boldsymbol{Lignin}\ \%\ \boldsymbol{of\ volatile\ Solids} \quad \textbf{(7)}$$

In the composting process, various populations of bacteria, actinomycetes, and fungi contribute to the degradation of organic matter through distinct rates of oxidation (Oudart *et al.*, 2012). However, a few species, particularly fungi, have evolved enzymes capable of breaking lignin mainly under aerobic conditions (Rynk *et al.*, 2022b). The decomposers involved in composting vary depending on several variables during the process, where Bacteria are the major contributors in the initial stages, whereas fungi and Actinomycetes sp. dominate the maturation phase due to their ability to break down strong polymers (Muktadirul Bari Chowdhury *et al.*, 2013). Moreover, the decomposition of lignin, along with polysaccharides and nitrogenous compounds , leads to the production of basic phenols that are metabolized or used during polymerization processes, resulting in the formation of humidified and stable end products (Muktadirul Bari Chowdhury *et al.*, 2013 ; Patchaye *et al.*, 2018). Consequently, the quality of compost can be affected by the concentrations of lignin and other resilient compounds (Oshins *et al.*, 2022).

VIII.7. Nutrients and C/N ratio:

The molecular composition of feedstock includes organic substances such as carbon (C), hydrogen (H), oxygen (O), sulfur (S), nitrogen (N), phosphorus (P), potassium (K), sodium (Na), calcium (Ca), magnesium (Mg), sulfur (S), zinc (Zn), and etc , which significantly influence the quality and applicability of compost products (Bernal *et al.*, 2017 ; Rynk *et al.*, 2022b). Mature composts consist of essential elements for plant growth (macro- , microelements, trace elements, and organic matter …) in different concentrations depending on the feedstocks' nutrients, and thus it can be used as a fertilizer/amendment to enhance soil physical and biological qualities, limiting the requirement for commercial fertilizers and pesticides (Gao *et al.*, 2023 ; Muktadirul Bari Chowdhury *et al.*, 2013 ; Rynk *et al.*, 2022a).

In contrast to commercial fertilizers and raw manure, the nutrients in compost, particularly nitrogen (N), are less soluble in water (Rynk *et al.*, 2022a). This phenomenon occurs because mature composts are stable and rich in humus-like, which requires mineralization before nutrients can be available/released (AyanfeOluwa *et al.*, 2017) , thereby contributes to the mitigation of nutrients loss via leaching and drainage (Rynk *et al.*, 2022a). Additionally, the mineralization rate in soil can be influenced by Several factors, such as climate, moisture, soil type, and raw material content, as well as compost maturity and the composting method (AyanfeOluwa *et al.*, 2017).

In the composting process, microorganisms break down the organic matter in the feedstock to release essential nutrients, i.e. mineralization process, and energy for their metabolism (Onwosi *et al.*, 2020). Therefore, nutrient supplies, along with other factors/ biochemical processes, play a major role in influencing interactions among functional microorganism groups (Verkhovtseva *et al.*, 2002).

Among the key nutrients required for boosting composting microorganisms in order to improve their metabolic rate are carbon, nitrogen, phosphorus, and potassium (Onwosi *et al.*, 2020). Nitrogen and Carbon, in particular, have a major effect on the process and the outcome (Epstein, 1997, 2011), where microorganisms use biodegradable organic carbon as a source of energy and nitrogen for their growth and metabolism (Bernal *et al.*, 2009 ; Reyes-Torres *et al.*, 2018). In contrast to most nutrients, which are typically preserved during composting, resulting in an increase in their concentration, both carbon and nitrogen undergo substantial loss due to their degradable nature, particularly nitrogenous compounds, with the exception of more resistant components (Onwosi *et al.*, 2020 ; Rynk *et al.*, 2022b). According to Tiquia, (2002), roughly 20-70% of the initial nitrogen content in the feedstock can be lost during composting due to ammonia volatilization, leaching, and drainage. This not only diminishes the composted product's value as a nitrogen-based fertilizer, but it further raises a substantial threat of environmental pollution (Bernal *et al.*, 2009 ; Tiquia, 2002). Thus, controlling nitrogen loss during composting is a major challenge (Onwosi *et al.*, 2020).

During composting, nitrogen experiences a range of metabolic reactions (volatilization, ammonification, immobilization, nitrification, and denitrification), with the dominating reaction influenced by the substrate as well as certain factors (Meng *et al.*, 2016). Several methods to reduce nitrogen loss have been studied, including adjusting the moisture content, aeration rate, incorporating additives, and most importantly, the C/N ratio (Tong *et al.*, 2019), which serves as a crucial parameter for determining the nutritional balance, and estimating the bioavailability of nutrients, as well as the stability and maturity of compost (Huang *et al.*, 2016 ; Singh et Kalamdhad, 2019). In order to achieve an efficient composting rate, a mature product with high nutritional content, while limiting nitrogen loss during the process, the initial carbon-to-nitrogen ratio should range from 20:1 to 40:1, with 30:1 being the most optimal value based on research findings (Alkoaik *et al.*, 2019b ; Bernal *et al.*, 2017 ; Jain *et al.*, 2019b ; Oshins *et al.*, 2022), where it is speculated that microorganisms require 30 parts of carbon per unit of nitrogen (Bernal *et al.*, 2017 ; Muktadirul Bari Chowdhury *et al.*, 2013).

High C: N ratios (> 40) indicate a low nitrogen concentration per unit of carbon, which can deplete the nitrogen supply before a complete breakdown occurs, hence extending the composting process needed to stabilize organic waste; Conversely, a low C: N ratios (< 20) suggests an excess of nitrogen beyond the essential needs of microbial metabolism compared to the required quantity for the degradable carbon unit, which can be lost as inorganic nitrogen through NH_3 volatilization (at elevated pH and temperature conditions), nitrous oxide (N_2O), and dinitrogen (N_2) emissions (Alkoaik *et al.*, 2019b ; Antil *et al.*, 2014 ; Bernal *et al.*, 2017 ; Patchaye *et al.*, 2018 ; Singh et Kalamdhad, 2019).

Wet green materials like manures, sewage sludge, biosolids, and leaves have more are nitrogen -rich (low C/N ratio) , while dry brown materials like straw, sawdust, and paper are carbon-rich (low C/N ratio) and not suitable for composting (Bernal *et al.*, 2017 ; Patchaye *et al.*, 2018).

Adjusting the initial carbon-to-nitrogen ratio can often be achieved by combining carbonaceous and nitrogenous materials prior to composting (Bernal *et al.*, 2017).

Chapter 03: Materials and Methods

Chapter 03: Materials and Methods

I. Objectives:

The main focus of this research study is to monitor changes in the physical, chemical, and biological properties of date palm waste across the composting process, including Temperature, Particle Size Distribution (PSD), Bulk density (BD) and Free Air Space (FAS), Moisture Content (MC), potential of Hydrogen (pH), Electrical Conductivity (EC), Organic Matter (OM) decomposition, Total Kjeldahl Nitrogen (TNK), C:N ratio, Germination Index (GI), Sensory Analysis.

Furthermore, a supplementary goal was to utilize straightforward, cost-effective, and accessible approaches to motivate farmers to compost their waste while enhancing process efficiency.

II. Study's site:

The research was carried out in the city of Bou Saada during 2023/2024, particularly in El-Maader region which is encompasses an area of 2,984 hectares in the northeastern region and constitutes 80% of the total agricultural land in the municipality of Bou Saada (A.S.B, 2018).

Generally, Bou Saada is one of the oldest oases in Algeria; Located in the southeastern region of northern Algeria, it is located 250 km from Algiers and spans an area of 225 km² (N35° 26' 07,9"; E004°20'52,8"), at an altitude of about 398 m above sea, acting as an important intersection between the Mediterranean and the Sahara. It is located in the southern region of the Wilaya of M'sila, surrounded to the north by Ouled Sidi Brahim, to the southeast by Oultem and El-Hamel, to the northeast by Maarif, to the east by Houamed, and to the west by Tamsa (A.S.B, 2018 ; Ouzir *et al.*, 2021). It is situated in a semi-arid region, and marked by a pronounced dryness, as precipitation is infrequent and irregular during winter, spring, and autumn, averaging 178.95 mm per year (Ouzir *et al.*, 2021).

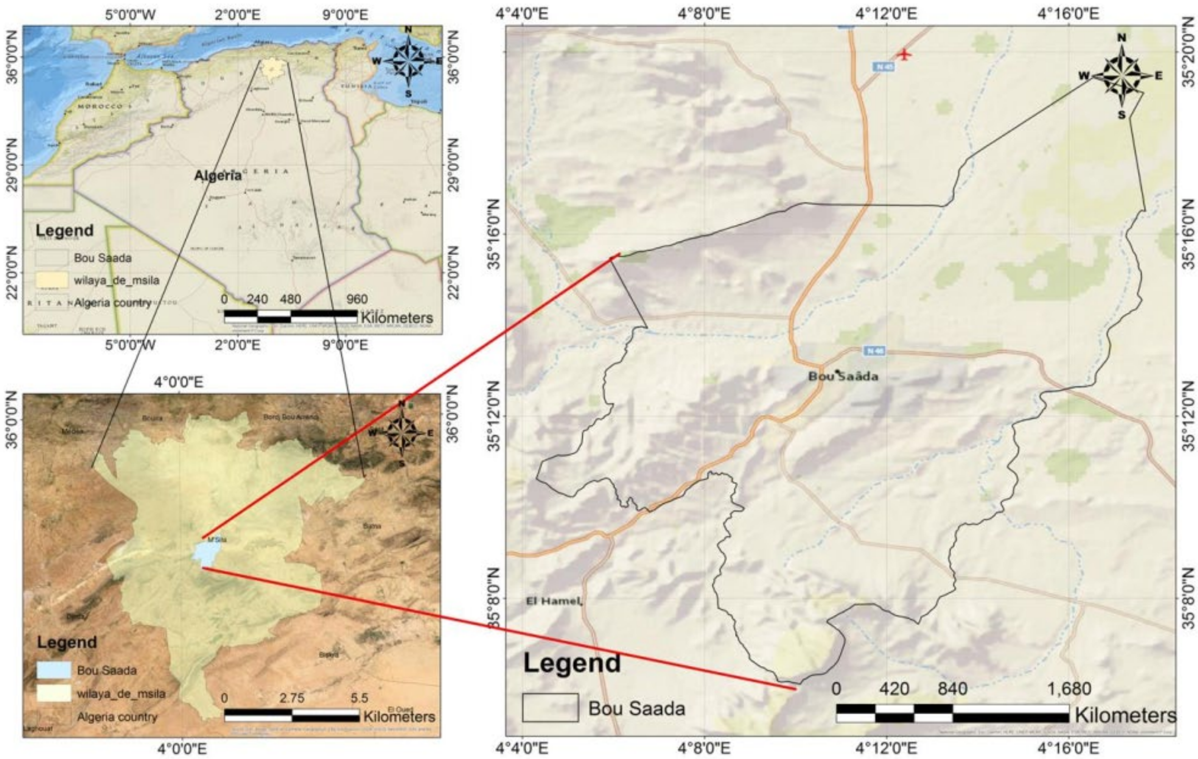


Figure 15: The location of the city of Bou Saada (Ouzir *et al*., 2021).

III. Feedstocks Collection and Recipe preparation Techniques:

The main feedstock in this study was the date palm wastes (DPW), which consists mainly of leaves and fronds collected from various farmers in Biskra region during trimming season, about 170 km away, where the experiments were carried out (Figure 15). According to Alkoaik *et al.*, (2019b), to improve aeration, moisture distribution, and microbial degradation, date palm waste should have a particle size of 1–2 cm. In this study, a particle size larger than the generally recommended range for agricultural waste (2.5-7.5 cm)(Singh et Kalamdhad, 2019) was applied instead, mainly due to grinder availability. The waste was mechanically chopped into 3 to 10-cm pieces in diameter at a nearby composting facility (Figure 16).

Figure 16: the feedstock used in recipe composition (a: date palm waste, b: poultry manure, c sheep manure, d: chicken litter).

Moreover, due to the date palm waste's high C:N ratio (67.95) (Table 4), direct composting is not feasible. Therefore, in order to adjust the initial C:N ratio of the mixture, additives with a high nitrogen concentration must be implemented, such as animal manure, which is widely available and frequently used as a natural fertilizer in the area.

Although animal manure is an important resource rich in nutrients such as nitrogen, phosphorus, and organic compounds, its direct application as a natural fertilizer can lead to environmental problems owing to inadequate biodegradation and hazardous components for plants (Li *et al.*, 2021). Therefore, the co-composting of date palm waste with animal manure as additives serves two purposes: adjusting the initial C:N ratio of the mixture along with treating the manure through pathogen eradication and stabilization of its nutrients and organic matter (Petric *et al.*, 2012).

In this study, 3 types of animal manure were used, namely Sheep, Poultry, and Chicken Litter (Figure 16). These additives were either collected or bought from various farms in Bou Saada region. The characteristics of the gathered feedstocks are illustrated in Table 4.

Table 4: The initial properties of the feedstocks.

	Unite	DPW (Carbone Source)	Animal Manure (Nitrogen Source)			Water (Moisture Source)
			Poultry Manure	Sheep Manure	Chicken Litter	
Moisture	%	5.07 ± 3.87	8.9 ± 0.55	0.99 ± 0.17	7.7 ± 2.75	100
TOC	%	50.28 ± 1.09	46.66 ± 0.52	37.33 ± 1.46	32.75 ± 3.2	0.00033 ± 0.05
TKN	%	0.74 ± 0.12	3 ± 0.3	1.36 ± 0.5	2.01 ± 0.02	0.0056 ± 0.03
C:N ratio	-	67.95	15.55	27.45	16.29	0.06
pH	-	5.46 ± 0.06	8.99 ± 0.02	8.11 ± 0.03	7.06 ± 0.07	7.45 ± 0.05
EC	dS/m	7.41 ± 0.31	7.02 ± 0.01	8.95 ± 0.01	5.42 ± 0.01	2.07 ± 0.03
WHC	%	14.68 ± 2.17	35.78 ± 2.67	27.77 ± 3.47	31.14 ± 4	-

It's noteworthy that the carbon concentration in poultry manure was unexpectedly higher than in chicken litter (Table 4), typically consists of a heterogeneous mix of manure, bedding, feathers, spilled feed, soil, and minerals; this result may be due to the presence of a less combustible mass that reduces mass loss during decomposition, the use of a low temperature of 550 °C, over a short period of 2 hours, and/or sample size (Heiri *et al.*, 2001).

III.1. The compost recipe preparation:

In this study, a total of four recipes were prepared, two of them were particularly designed to achieve the optimum initiating moisture content (60%), which is a vital triggering factor of the process as already explained, while the other two also address the initial C:N ratio.

Two fundamental approaches were used in the formulation of the compost recipe. The first one was arbitrary. It aims to achieve an optimal initial moisture content by applying a simple ratio of 2:2:6 (DPW: Additives: Water), using Sheep Manure (ShP2) or Poultry Manure (PM1) as additives, while assuming that the feedstocks are completely dry. The second was a mathematical approach, through a mathematically balancing moisture - C:N ratio method, which has often been the main method used to generate composting recipes (Rynk *et al.*, 2022b). This method takes into account the C:N ratio and moisture content of the feedstocks to achieve a well-balanced recipe with a desired initial moisture content and C:N ratio (Table 5).

The calculation were performed based on the equations (8) and (9) (Alkoaik *et al.*, 2019b ; Rynk *et al.*, 2022b), using Chicken Litter as an additive to produce a compost mixture (CkS : DPW : Water) with an optimum moisture content (60%) ,along with a C:N ratio of 30 (CkS30) as recommended in most of the study and 25 (CkS25) as recommended by Sudharsan Varma & Kalamdhad, (2014) for a rotary drum composting.

$$\boldsymbol{MC}(\%) = \frac{(\boldsymbol{MC01} \times \boldsymbol{Wt01}) + (\boldsymbol{MC02} \times \boldsymbol{Wt02}) + (\boldsymbol{MC03} \times \boldsymbol{Wt03})}{\boldsymbol{Wt01} + \boldsymbol{Wt02} + \mathbf{Wt03}} \quad \textbf{(8)}$$

$$\mathbf{C{:}\,N\ ratio} = \frac{[\mathbf{C01} \times \mathbf{Wt01} \times (\mathbf{100} - \mathbf{MC01})] + [\mathbf{C02} \times \mathbf{Wt02} \times (\mathbf{100} - \mathbf{MC02})] + [\mathbf{C03} \times \mathbf{Wt03} \times (\mathbf{100} - \mathbf{MC03})]}{[\mathbf{N01} \times \mathbf{Wt01} \times (\mathbf{100} - \mathbf{MC01})] + [\mathbf{N02} \times \mathbf{Wt02} \times (\mathbf{100} - \mathbf{MC02})] + [\mathbf{N03} \times \mathbf{Wt03} \times (\mathbf{100} - \mathbf{MC03})]} \quad \textbf{(9)}$$

where: Wt is the total weight, MC is the moisture content, N is the total nitrogen and C is the total carbon of feedstocks 01,02, and 03 (Date Palm Waste, Additive, Water).

Additionally, the lack of sufficient mathematical knowledge among most farmers was taken into account, therefore, an easy-to-use GUI application with multilingual interface was created, i.e. compost recipe calculator (Figure 17)(Ouali, 2024). The C:N ratios and moisture content were measured in the laboratory following the mixing of the calculated proportions, as detailed in Table 4.

Table 5: The proportions of feedstocks in each recipe and their total weight.

FEEDSTOCKS	PM1 ShP2	CkS25	CkS30
RECIPE	2:2:6		
DATE PALM	32.6	20.47	28
ADDITIVE	32.6	35.49	25.8
WATER	97.8	73.35	76.2
TOTAL	163	129.3	129.9

Figure 17: the compost recipe calculator UI (Ouali, 2024).

IV. Bioreactor selection and design:

There are several models and designs of the bioreactors, each focusing on controlling one or more of the composting factors, but in general, they can be divided into manual, semi-manual, or fully automated (Azis *et al.*, 2022). As the innovation level progresses from manual to the fully automated, the efficiency of the process increases, along with the complexity and manufacturing cost.

Generally, the bioreactors systems are capable of handling a significant amount of waste (depending on the scale) within a small area, while efficiently managing environmental factors such as temperature, moisture content, and aeration (Alkoaik *et al.*, 2018). Additionally, in order to minimize manufacturing costs while retaining control over crucial process factors such as aeration without relying on energy consumption, a simple and highly efficient manual pilot-scale bioreactor has been implemented, i.e. Rotary Drum Bioreactor.

The design of Rotary Drum Bioreactor was based on the outline provided by Kalamdhad et Kazmi, (2008), which consists of two main parts (Figure 18).

- The first part is the drum, a container with a capacity of 628 L (1.25 m long and 0.8 m in diameter), built using 3mm thick galvanized sheet metal. It features two half-side doors for aeration and loading, as well as two 10cm drainage holes with grids at the top, and longitudinally welded 40mm angles to help with mixing, agitation, and aeration. Additionally, tow side handles and metal frames have been added to facilitate the rotation process.
- The second part is a metal table with four rollers installed on top of it to support the drum and facilitate the manual rotation.

Figure 18: The rotary drum bioreactor.

V. Experimental Setup:

In addition to initial C:N ratio and moisture content, temperature and oxygen levels are key factors in the composting process and can be directed by controlling factors such as aeration, and turning frequency (Zein *et al.*, 2015), thereby providing enough oxygen and bioavailable nutrient for aerobic microorganisms to decompose waste rapidly (Alkoaik *et al.*, 2019b).

In the rotary drum bioreactors, the Aerobic conditions were maintained naturally by keeping the half-side doors open and only closed during the rotation process. As for the tuning frequency, twenty-four-hour time intervals were adopted based on (Kalamdhad et Kazmi, 2009a)'s study on the rotary drum composting of organic waste (cattle manure, green vegetable and sawdust), which led to longer thermophilic phases, higher peak temperatures, lower electrical conductivity, lower phytotoxicity, and higher mineralization compared to other intervals. Thus, in order to achieve an effective mixing of the compost during the process with little labour from the farmer, four rotations were implemented every 24 hours. Additionally, the experiments were conducted at different times of the year. For PM1 and ShP2, which were carried out during the low-temperature seasons, the drum was filled to 75% of its total capacity (164 Kg), mainly to reduce the rate of heat loss. In contrast, the drum was filled to 50% of its total capacity (129.3 Kg) for CkS30 and CkS25 to control the maximum temperature value, as both experiments were conducted during high-temperature seasons.

The four trials can be divided into two parts:

1- Investigating the effectiveness of the rotary drum co-composting of date palm with different additives (Sheep and Poultry manure) over a 60-day timeframe (PM1 and ShP2).
2- Evaluating the impact of applying the recommended parameters for the initial C:N ratio and moisture content on the rate of date palm rotary drum composting over a 20-day period, as indicated by most studies (CkS30 and CkS25), using chicken litter as additive for adjusting the C:N ratio.

VI. Sampling, physicochemical and biological Analysis:

Representative samples of the mixture were taken every 2 days during the bio-oxidation stage (mainly the first 20 days) and every 10 days during the maturation stage for analysis and measurement of the following parameters:

VI.1. Temperature:

During the composting process, ambient temperatures, as well as temperatures from the centre and both ends of each composter, were monitored daily on-site every six hours using DHT 22 sensor (Aosong Electronics, China; accuracy ±0.5 °C for temperature and ± 2–5% for humidity) and DS18B20 digital thermometer (Maxim Integrated, USA; accuracy ± 0.5 °C within –10 to +85 °C and ± 2 °C within –55 to +125 °C) connected to a computer via Arduino, which automatically logged data to a CSV file. A digital sensor was employed at various times to check all sensors' functionality.

The time-temperature relationship was calculated using Eq. (10) given by Epstein, (1997):

$$\mathbf{D} = \frac{\mathbf{131700000}}{\mathbf{10^{0.14t}}} \qquad \mathbf{(10)}$$

Where D is the time in days, and t is the temperature in degrees Celsius.

VI.2. Moisture Content:

A fresh sample was over-dried at 105°C for 24 hours to assess Moisture Content (MC) and then estimated using Eq. (11) (Jain *et al.*, 2020):

$$\mathbf{MC}\ (\%) = \frac{\mathbf{Wf - Ws}}{\mathbf{Wf}} \times \mathbf{100} \qquad \mathbf{(11)}$$

Where W_f is the weight of the fresh sample (g), and W_s is the weight of the over-dried sample (g).

VI.3. Water Holding Capacity:

The evaluation of Water Holding Capacity (WHC) was conducted following the approach outlined by Singh & Kalamdhad, (2019). After a 2-day immersion of a sample with defined moisture content (MC) and initial weight (Wi) in water, the excess water was removed by filtration through Whatman No 2-filter paper. The sample was subsequently reweighed (Wf), and Eq (12) was employed to determine the water holding capacity (WHC):

$$\mathbf{WHC} = \frac{[(\mathbf{Wf - Wi}) + \mathbf{MC \times Wi}]}{[(\mathbf{1 - MC}) \times \mathbf{Wi}} \qquad \mathbf{(12)}$$

where W_i is the initial weight of sample (g), W_f is the final weight of sample (g), and MC is the initial moisture content of sample (decimal).

VI.4. potential of Hydrogen (pH) and Electrical Conductivity (EC):

Despite the pH measurement being straightforward, various compost-to-water ratios used may lead to significant differences (Epstein, 1997). It is recommended to use ratio of 1:50 compost : water for pH and EC measurement, but 1:10 also is used (Epstein, 1997 ; Stehouwer *et al.*, 2022). In this study, pH and EC values were measured by agitating a sample at an extraction ratio of 1:10 for a duration of 2 hours (Jain *et al.*, 2018b ; Singh et Kalamdhad, 2019), using Hach HQ440D Laboratory Multi-Meter.

VI.5. Total Kjeldahl Nitrogen (TKN):

The Kjeldahl method was used to estimate total nitrogen (Ouali *et al.*, 2025). A 0.2 g sample was initially digested with 20 ml of concentrated sulfuric acid (H_2SO_4) and a 1 g catalyst mixture (composed of 20% $CuSO_4$ and 80% K_2SO_4) at 400 °C until a colourless solution was obtained. After cooling the solution and diluting it to a total volume of 100 ml, a 25 ml aliquot was subjected to distillation using 6 N sodium hydroxide (NaOH) and 2% boric acid (H_3BO_3). The total nitrogen content (TKN) was measured by titration with 0.1 N sulfuric acid, utilizing Tashiro's indicator. The results were calculated according to Eq (13).

$$\mathbf{TKN} = \frac{(V_s - V_b) \times V_t \times 0.1 \times 1.4}{V_a \times P} \quad \mathbf{(13)}$$

In this equation V_s represents the titration volume of the sample (in ml), V_b indicates the titration volume of a blank (in ml), V_t refers to the total volume of digestion (100 ml), V_a denotes the volume of the aliquot used for distillation (25 ml), P is the weight of the sample (0.2 g), 0.1 is the normality of sulfuric acid, and 1.4 is the nitrogen conversion factor.

VI.6. Organic Matter (OM), Total Organic Carbon (TOC) and Biodegradability:

The organic matter (OM) and total organic carbon (TOC) were determined using the loss on ignition (LOI) method, which involved heating a dry sample in a muffle furnace at 550 °C for a duration of 2 hours. The ash content was calculated from the weight loss as per Eq. (14), while Eqs. (15) and (16) were employed to estimate OM and TOC, respectively (Nayak et Kalamdhad, 2015 ; Rynk *et al.*, 2022b):

$$\mathbf{ASH}(\%) = \frac{\mathbf{Wi} - \mathbf{Wf}}{\mathbf{Wi}} \quad \mathbf{(14)}$$

$$\mathbf{OM}(\%) = \mathbf{100} - \mathbf{ASH} \quad \mathbf{(15)}$$

$$\mathbf{TOC}(\%) = \frac{\mathbf{OM}}{\mathbf{1.8}} \quad \mathbf{(16)}$$

where W_i is the initial weight of sample (g), W_f is the final weight of sample (g), 1/1.8 represents the portion of Carbone in the OM.

The calculation of organic matter biodegradability was performed using the initial and final organic matter contents, as outlined in the following equation (Nayak et Kalamdhad, 2015 ; Petric *et al.*, 2012):

$$\mathbf{k} = \frac{(\mathbf{OMi} - \mathbf{OMf}) \times \mathbf{100}}{\mathbf{OMf} \times (\mathbf{100} - \mathbf{OMi})} \quad \mathbf{(17)}$$

Where OMi represents the initial organic matter content (%), while OMf indicate the final organic matter content at the end of the process (%).

VI.7. Nutrient Concentration:

The Nutrient Concentration was estimated using cement mode in X-ray Fluorescence Analysis (Ouali *et al.*, 2025) and then calculated as described by Stehouwer et al., (2022).

The sample was ignited at 950 °C for one hour and then homogenized with dilithium tetraborate in a 3:7 mass ratio. This mixture was fused into a glass disk using an electric fusion apparatus for X-ray fluorescence analysis in cement mode. The oxide percentages on an as-received basis (XO) are adjusted for loss on ignition (LOI) using Eq (18).

$$\mathbf{XO = XO\ ignited\ \times \frac{100 - \mathit{LOI}}{100}} \quad \mathbf{(18)}$$

Here, XO represents the percentage of element oxides relative to the ignited sample (%), while LOI indicates the loss on ignition at 950 °C.

VI.8. Germination Index:

The germination index (GI) was assessed according to the methods described by Huang et al. (2016) and Luo et al. (2018), utilizing radish seeds due to their easy availability. An extract was prepared from stored samples and distilled water in a 1:10 (w/v) ratio, agitated at room temperature for 40 minutes at 200 rpm, and then centrifuged at 6000 rpm for 15 minutes. In a 9 mm petri plate containing filter paper, 10 ml of the extract and 10 radish seeds were introduced, while distilled water served as the control to fill the dish in place of the extract. The extract was applied in 25%, 50%, and 75% dilutions. The seed germination index (GI) was quantified through the determination of both the germination rate (RSG) and the relative length of radicles (RRG), as demonstrated in Eq. (19), Eq. (20), and Eq. (21):

$$\mathbf{RSG = \frac{Number\ of\ germinated\ seeds(sample)}{Number\ of\ germinated\ seeds(control)}} \quad \mathbf{(19)}$$

$$\mathbf{RRG = \frac{Total\ radicle\ length\ of\ germinated\ seeds(sample)}{Total\ radicle\ length\ of\ germinated\ seeds(control)}} \quad \mathbf{(20)}$$

$$\mathbf{GI\ (\%) = RSG \times RRG \times 100} \quad \mathbf{(20)}$$

VI.9. Bulk density:

The bulk density of compost measures the mass of substance per unit volume (Jain *et al.*, 2018a) and it recommended to be measured on-site through a procedure that replicates the compaction of compost in its storage environment (Rynk *et al.*, 2022c). Thus, as describe by Singh & Kalamdhad, (2019) and Jain et al., (2018b), a metal container with a volume of 1 L was utilized to measure wet bulk density; it was filled to one-third of its height and tapped on a flat surface to eliminate voids, followed by filling to two-thirds and then to the top. The calculation is performed using the following formula:

$$\mathbf{BDw} = \frac{\mathbf{Mw}}{\mathbf{V}} \qquad \textbf{(21)}$$

Where M_w (g) is the mass of the compost sample in its current state, while V (mL) is the volume of the container.

VI.10. Free Air Space:

Following measuring the bulk density, the container was filled with water, and the appearance and subsequent dissipation of air bubbles on the surface were observed. Water was subsequently added until it completely covered the surface, followed by the application of the Eq 23 (Rynk *et al.*, 2022c):

$$\boldsymbol{FAS}\ (\%) = \frac{\boldsymbol{W_f} - \boldsymbol{W_i}}{\mathbf{V}} \qquad (22)$$

Where W_f (g) is the weight of the container after adding the water, W_i (g) is the weight of the container before adding the water, while V (mL) is the volume of the container.

VI.11. Particle Size:

The determination of particle size involves passing the compost sample through a screen with a specified mesh size, with the results expressed as the percentage of material that passes through the designated mesh size (Agnew et Leonard, 2003 ; Rynk *et al.*, 2022c). In this study, a screen with mesh sizes of 10, 5, 2, and 0,5 mm was utilised.

VII. Statistical Analysis:

The data outlined in this document were acquired from three identical rotary drum bioreactors. The mean, standard deviation, and analysis of variance (ANOVA) test were calculated at a significance level of $P < 0.05$ using MS EXCEL 2021.

Chapter 04: Results and Discussions

Chapter 04: Results and Discussions

I. Temperature:

The temperature is regarded as a critical parameter in the composting process (Rich *et al.*, 2018). It impacts and reflects the microbial activity serving as a valid indicator of the various phases of composting and the associated microbial communities (Hassen *et al.*, 2001 ; Jain *et al.*, 2018b ; Oshins *et al.*, 2022).

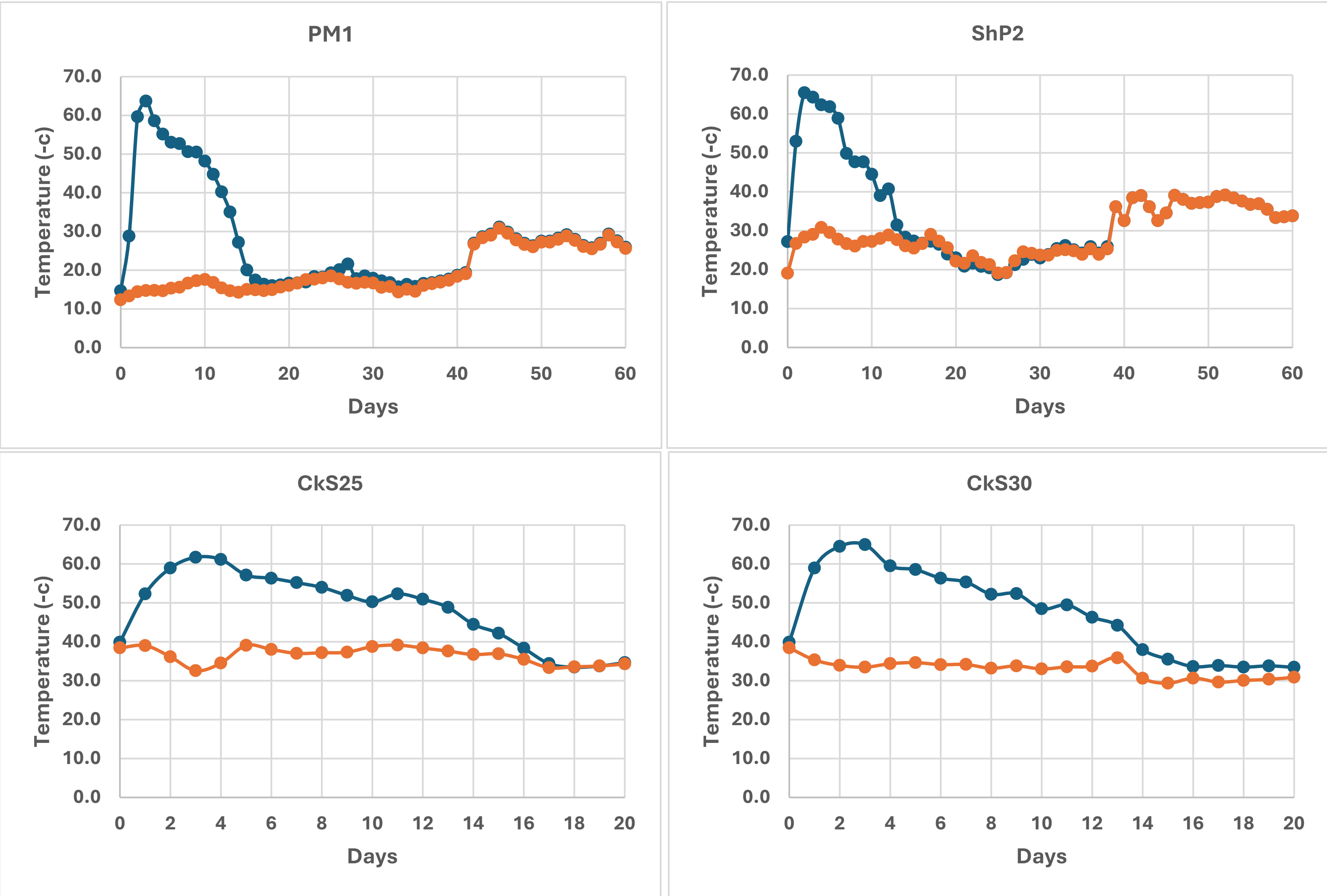


Figure 19: Temperature variation during the composting process in all trials.

Table 6: Bio-oxidation stage summary.

	PM1	ShP2	CkS25	CkS30
Mesophilic				
Ambient (°C)	12.9	19.1	38.4	38.4
Mean (°C)	21.7	27.2	39.9	39.9
Days	2	1	1	1
Thermophilic				
Ambient (°C)	15.7	28	37.3	33.9
Mean (°C)	54.7	56.8	54.7	55.78
Max (°C)	63.7	65.45	61.72	64.95
Days	9	9	13	12
Mesophilic				
Ambient (°C)	15.1	27.2	35.6	31.6
Mean (°C)	28.7	35.2	39.8	37.8
Days	7	6	4	4
Bio oxidative				
Ambient (°C)	14.6	24.8	37.1	34.7
Mean T (°C)	35.1	39.7	44.8	44.4
Days	18	16	18	17
EXI2	16247.3	8392.9	4428.7	6157.4
Ratio BP/TV	18/9	16/9	18/13	17/12
Ratio EXI2/BP	902.63	524.55	246.04	362.2
Mean T/ Days ratios	1.95	2.48	2.49	2.61

Figure 19 illustrates the occurrence of the composting process in all trials, showing a significant difference among them ($P = 0.041$), revealing its typical pattern that could be subdivided into two essential stages. The ambient temperature was about 14.6 in PM1, 24.8 in ShP2, 37.1 in CkS25 and 34.7 in CkS30 during the 20-day composting period (Table 06). The initial stage, i.e. the bio-oxidation or the active stage, takes place from day 0 to day 16-18. This stage comprises a brief Mesophilic Phases (20-45°C) , as in most of rotary drum composting systems (Jain *et al.*, 2018a, 2018b, 2020 ; Kalamdhad et Kazmi, 2008, 2009b ; Kauser et

Khwairakpam, 2022), that lasts only a few hours (ShP2,CkS25, and CkS30) to approximately 2 days in PM1(Table 06 and Figure 19), indicating a rapid onset of microbial activity. Generally, the rising temperature in the bioreactor is contingent upon the initial temperature and the conversion rate of easily accessible substrates, and it is subsequently accompanied by heat release (Kulikowska et Klimiuk, 2011). Immediately after the composting process begins, the mesophilic microorganisms primarily metabolized readily biodegradable organic molecules, such as sugars and amino acids, resulting in heat energy as byproduct, which rapidly raised the mixture's temperature (Jain et Kalamdhad, 2019 ; Li *et al.*, 2021 ; Rich *et al.*, 2018).

As mesophilic microorganisms thrive, their activity intensifies, causing a further rise in temperature, entering the second phase of the bio-oxidation stage, the thermophilic phase (> 45 C). This phase's time frame was 9 days in PM1 and ShP2 trials ,13 and 12 days in CkS25 and CkS30 trials, respectively, as shown in Table 06 and Figure 19. During which, the temperature peak values were estimated at 63.7 ± 1.6 °C, 65.45 ± 0.7 °C, 61.72 ± 1.03 °C, and 64.95 ± 1.4 °C, on the second day in PM1, and on the third days in the other trials.

The high temperatures significantly accelerate the decomposition rate, stimulating the proliferation of thermophilic microorganisms, predominantly fungus and actinomycetes, which are adept at degrading the most resistant organic substances such as lignin and hemicellulose (Bernal *et al.*, 2009 ; Kulikowska et Klimiuk, 2011 ; Muktadirul Bari Chowdhury *et al.*, 2013 ; Sołowiej *et al.*, 2021). Therefore, maintaining high temperatures over several days in succession are crucial for controlling the process's progress and achieving effective composting (Gaspar *et al.*, 2022 ; Vico *et al.*, 2018). Nevertheless, hight temperatures can't reliably indicate organic matter decomposition, as it depends on material characteristics (Kauser *et al.*, 2020). Moreover, this high temperature has a vital role in eradicating potential pathogens, weed seeds, and weed propagules, preventing the hazards to human, animal, and plant health (Jain *et al.*, 2018a ; Rashwan *et al.*, 2021). According to Hassen et al., (2001), temperatures above 55°C seem optimal for sanitation, while temperatures between 45-55°C enhance the biodegradation rate, and between 35-40°C promote microbial diversity. In rotary drum composting, it's crucial to maintain a temperature of 45-65°C for at least three days which is optimal for killing harmful pathogens while preserving the activity of other microorganisms involved in organic matter decomposition during the high-temperature phases (Jain *et al.*, 2020 ; Sudharsan Varma et Kalamdhad, 2014, 2015).

In this study, throughout the thermophilic phases, optimal high-temperature conditions for sanitation and biodegradation rate have been maintained in all four trials, with average temperatures between 54.7 ± 5 °C and 56.78 ± 1.6 °C for at least 9 days and high Ratio BP/TV (Table 06). Subsequently, the cooling phases (Mesophilic Phases II) occurred as a result of the readily available organic material being depleted, leading to a reduction in thermophilic microorganisms' activity (Jain *et al.*, 2018a), coupled with heat loss caused by constant aeration and turning (Ghanney *et al.*, 2021 ; Rich *et al.*, 2018). The cooling phases observed in this research endure around 4 (CkS25 and CkS30) to 6-7 days before eventually stabilizing at ambient temperature.

The peak values, the long-term thermophilic and cooling phases during composting can be attributed to the interaction of various chemical and physical factors. In particular, (1) the bioavailability of the feedstocks, where the lignocellulosic properties of date palm waste, in conjunction with the abundant amount of readily accessible carbon from the additives used in each trial, impact the rate and duration of microbial activity throughout the process (Jain *et al.*, 2018a ; Jain et Kalamdhad, 2019 ; Kalamdhad et Kazmi, 2009b ; Rich *et al.*, 2018 ; Singh et Kalamdhad, 2013 ; Varma *et al.*, 2017), along with (2) the environmental conditions , especially the high ambient temperature in CkS30 and CkS25, where it exceeded 34.7 °C, which may have slowed the heat loss rate , causing longer thermophilic phases (12 to 13 day) and shorter cooling phases (4 day) compared to the other trials, where the temperature was lower (< 24.8°C) (Table 06); (3) the date palm's high insulation capacity, as it has a low thermal conductivity value of 0.496 - 0.083 W/mK, making it one of the most crucial methods of insulation in the field of construction (EL-Mously *et al.*, 2023 ; Ghori *et al.*, 2018); In addition to other factors such as (4) aeration rate and turning frequency (Ghanney *et al.*, 2021 ; Rich *et al.*, 2018), (5) the Mixture volume, etc

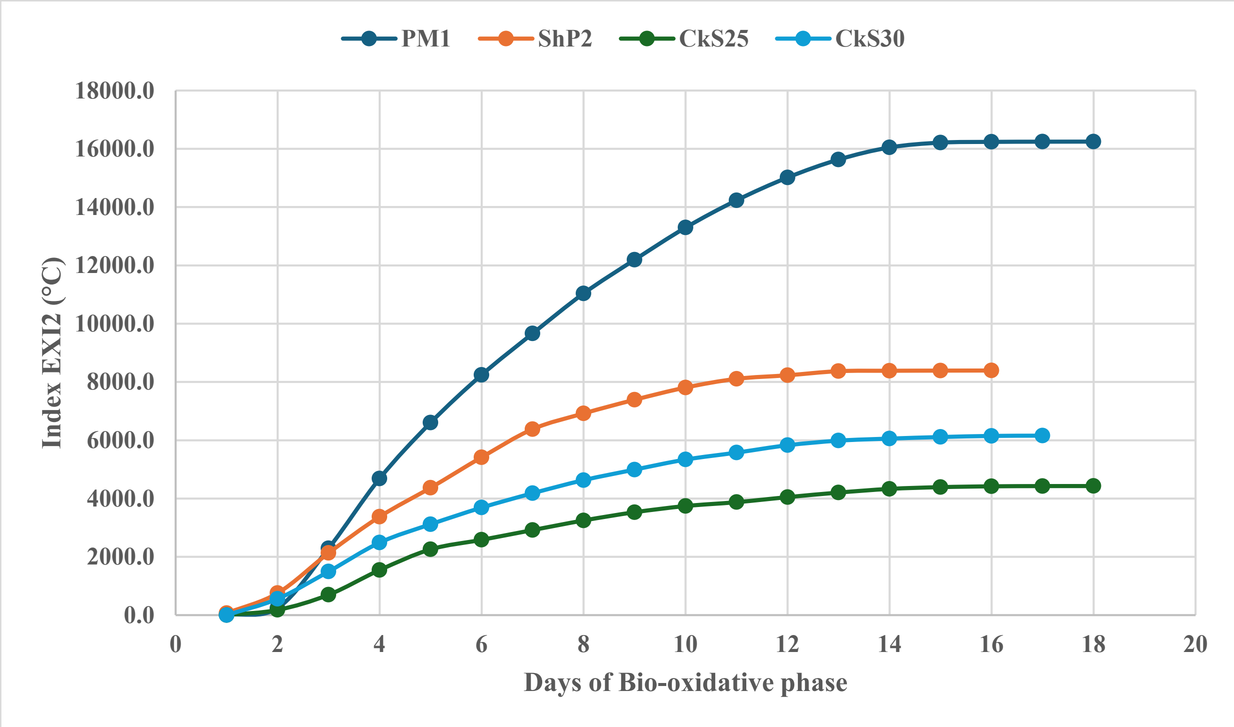


Figure 20: Evolution of the cumulative values of EXI2 during the bio-oxidative phase.

The Figure 20 shows the evolution of the cumulative values of EXI2 during the bio-oxidative phase, which shows the thermal change taking into account the ambient temperature. The figure displays a lag phase at the beginning of the process in PM1, which may have been caused by the psychrophilic conditions (<20) where the ambient temperature at day 0 was approximately 12.9 (Table 06 and Figure 19). However, the index shows an intense, long and fast thermal activity in PM1 twice as much as in ShP2, followed by both CkS30 and CkS25 (Table 01 and Figure 02). This is mainly due to the low temperature ratio in those trials (CkS30 and CkS25), where the ambient temperatures were relatively close to the mixture temperature during the bio-oxidation stage.

The cooling phases symbolize a shift from the bio-oxidation to maturation stage, marked by the colonization of mesophilic flora, which concludes the biodegradation of resistant organic substances (Petric *et al.*, 2012). This stage occurs from day 16-18 to day 60 in trials PM1 and ShP2, and from day 17-18 to day 20 in trials CkS25 and CkS30. While the first stage emphasizes organic materials decomposition, the second stage is dominated by humification processes, resulting in the synthesis of stable humic substances (Zhao *et al.*, 2023), at slow rate (Oshins *et al.*, 2022).

II. Particle Size Distribution (PSD):

The particle size distribution (PSD) in composting significantly impacts the efficiency of the process, influencing aeration, water movement, microbial activity, and the overall quality of the end-product (Zhang et Sun, 2014).

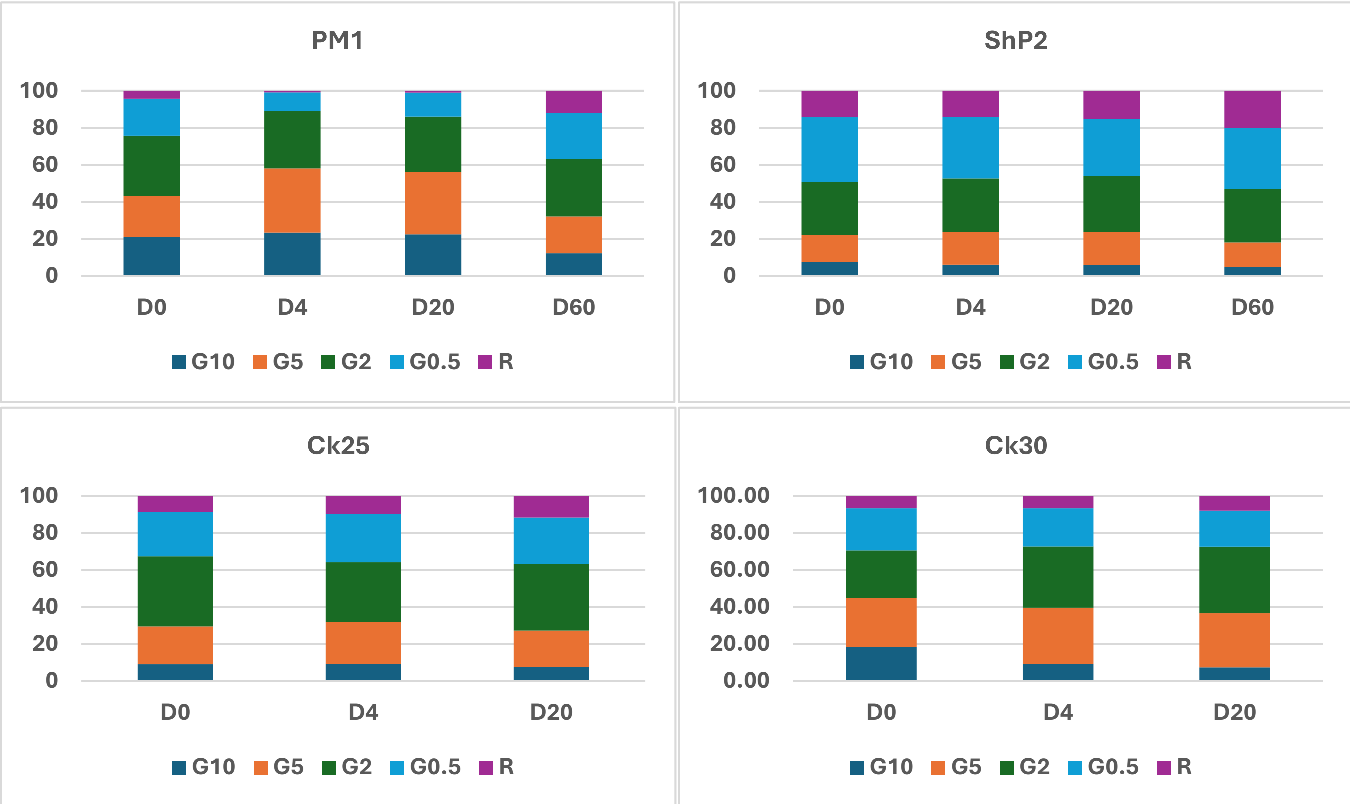


Figure 21: particle size distribution (PSD) in all trials at day 0, 4, 20, and 60 (in PM1 and ShP2).

The Figure 21 illustrates the proportions of particles captured within 10 (G10), 5 (G5), 2 (G2), and 0,5 mm grids (G 0,5), along with the remaining particles (R). The distribution of mass among different particle size fractions varied significantly across all four trials. In all trials, approximately 48.41– 63.74 % of the mass sample was within the 2-0.5 mm fraction, while the <5 mm fraction contributed less to the total mass compared to the 5–10 mm fraction (Figure 21). During the composting process, the majority of decomposition occurs in the 2-0.5 mm fractions (Figure 21) owing to microbe substrate availability, i.e. particle surface area (Wang, 2003), alongside the hight concentration of easily decomposable material and nutrients in that range (<20 mm fraction) (Haynes *et al.*, 2015), especially the C/N ratio, which was observed to be higher in fractions ranging from 3-0.8 mm (Hanc et Dreslova, 2016). Additionally, this explains the low decomposition in the fine fractions <0.5 mm (Figure 21).

In the initial period from days 0 to 4, PM1 experienced a 10.02% loss (in G0.5), followed by ShP2 with a 5.55% loss (in G2), then CkS30 and CkS25 with a 3.17% and 2.03% loss (in G0.5), due to the rapid decomposition of labile carbon in these fractions (Hanc et Dreslova, 2016). As a result, with the decrease in easily decomposable material, the loss rate in the second stage (day 4 to 20) shifted to other ranges and decreased to 1.15% (in G2), 2.4% (in G0.5), 2.73% (in G5), and 1.79% (in G5) in PM1, ShP2, CkS25 and CkS30, respectively.

The final compost should contain a high proportion of particles ranging from 0.25 to 2.00 mm for best outcomes (Zhang et Sun, 2014). By the 20th day, both ShP2, CkS25 and CkS30 showed increase in the proportion of small fractions (< 5 mm) from 78.03 to 76.19%, from 70.48 to 72.65%, and from 55.09 to 63.36%, respectively, while PM1 recorded an decrease in those fractions from 56.82% to 43.84%, likely due to agglomeration of small particles (Tucker *et al.*, 2015). The larger fractions (>5mm) did not undergo significant degradation during the bio-oxidation stage across all trials, attributed to the dominance of lignocellulosic materials in these fractions (Haynes *et al.*, 2015) and their size, which restricts the biodegradation process. Nonetheless, the highest percentage of mass loss was observed during the maturation phase of trial PM1 and ShP2, at 13.81 and 4.71% (in G5 particularly), respectively. This was provoked by the beginning of the decomposition process of the resistant organic compound (Petric *et al.*, 2012 ; Zhao *et al.*, 2023). The final product exhibits a high proportion of small particles across all trials, indicating optimal results for mature compost.

III. Bulk density (BD) and Free Air Space (FAS):

Bulk density (BD) is essential for enhancing the composting process, influencing microbial growth, activity, and organic matter oxidation, along with mechanical properties such as strength, porosity and compressibility (Agnew et Leonard, 2003 ; Jain *et al.*, 2018a, 2019a). Free air space (FAS) is a crucial parameter, as it determines the amount and movement of air throughout the composting matrix structure, thereby influencing heat and mass transport processes and microbial kinetics (Jain *et al.*, 2018a).

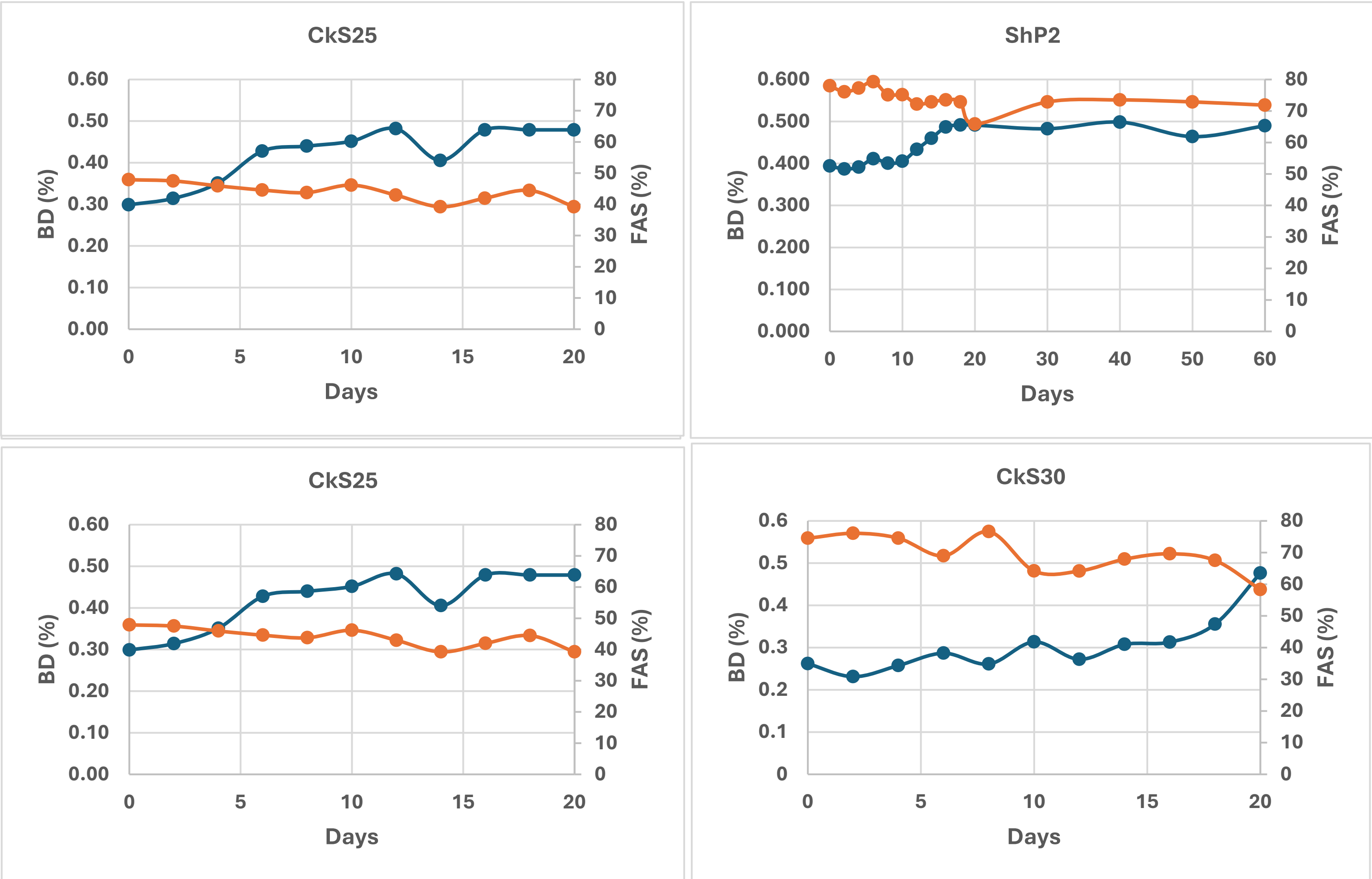


Figure 22: The variation in wet Bulk density (BD) and Free air space (FAS) during the composting process.

Both parameters are closely linked to airflow, creating the necessary aerobic conditions for microbial activity during composting (Jain et Kalamdhad, 2019). Thus, the composting process must be carefully managed to maintain an optimal air-filled porosity (>30%), i.e. FAS (Jain *et al.*, 2019a).

The results of wet BD and FAS values were observed to be highly significant between days and trials ($p < 0.05$), interpreted using ANOVA. The initial wet BD values for PM1, ShP2, CkS30, as well as the CkS25, were 0.43 ± 0.5, 0.39 ± 1.09, 0.3± 0.05, and 0.26 ± 0.8 g/l, respectively, with corresponding initial FAS of 68.07 ± 5.4, 77.98 ± 2.1, 47.89± 3.4, and 74.51± 4.1% (Figure 22), which was within the acceptable range in all trials (>30%). After 20 days composting, the wet BD exhibited an increasing trend throughout the composting process, with initial values changing to 0.47 ± 0.8, 0.49 ± 0.9, 0.48± 1.4, and 0.47 ± 0.7 g/l in PM1, ShP2, CkS25, and CkS30, respectively. Conversely, and due to the inversely proportional relationship between FAS and BD (Jain *et al.*, 2019a ; Jain et Kalamdhad, 2019), the FAS experienced a decrease to 60.66 ± 2.3, 65.84 ± 1.6, 39.23 ± 2.07, and 58.33 ± 1.3 %, respectively, for each of the trials PM1, ShP2, CkS25, and CkS30.

The variations in bulk density (BD) and free air space (FAS) throughout the composting process originate from the decomposition of organic matter (Zhang et Sun, 2014), reducing particle size, and increasing micropores (Azim *et al.*, 2018 ; Jain *et al.*, 2019a). This occurrence results in an increase in wet BD and a decrease in FAS, influenced by the morphology, dimensions, and structure of particles (Azim *et al.*, 2018), moisture content (Huet *et al.*, 2012 ; Jain *et al.*, 2019a), the compaction of the compost matrix from the turning process and/or by overburden (Azim *et al.*, 2018 ; Huet *et al.*, 2012), and the ratios of bulking agents (Jain *et al.*, 2019a ; Jain et Kalamdhad, 2019), particularly in CkS30.

As a result of this phenomenon, the compost volume demonstrates a reduction from 75% to 50% during the initial 20 days of composting in PM1 and ShP2, further decreasing to approximately 40% by the 60th day. whereas CkS25 and CkS30 show a decrease from 50% to 35% (personal observation).

In the final maturation phase in trials PM1 and ShP2, the rate of variations in wet BD and FAS slowed as the remaining organic matter became more resistant to microbial degradation with wet BD stabilized at around 0.47 g/l (PM1), 0.48 g/l (ShP2), and FAS of 63,87 % (PM1), 72.78 % (ShP2) (Figure 22).

IV. Moisture Content:

Moisture is a crucial factor influencing various aspects of composting, from feedstock blending to the final product (Richard *et al.*, 2002). Its role extends beyond dissolving and transporting soluble nutrients required in microbial metabolism but also serves as a medium for chemical and biological interactions and microbial movement (Li *et al.*, 2021, 2022).

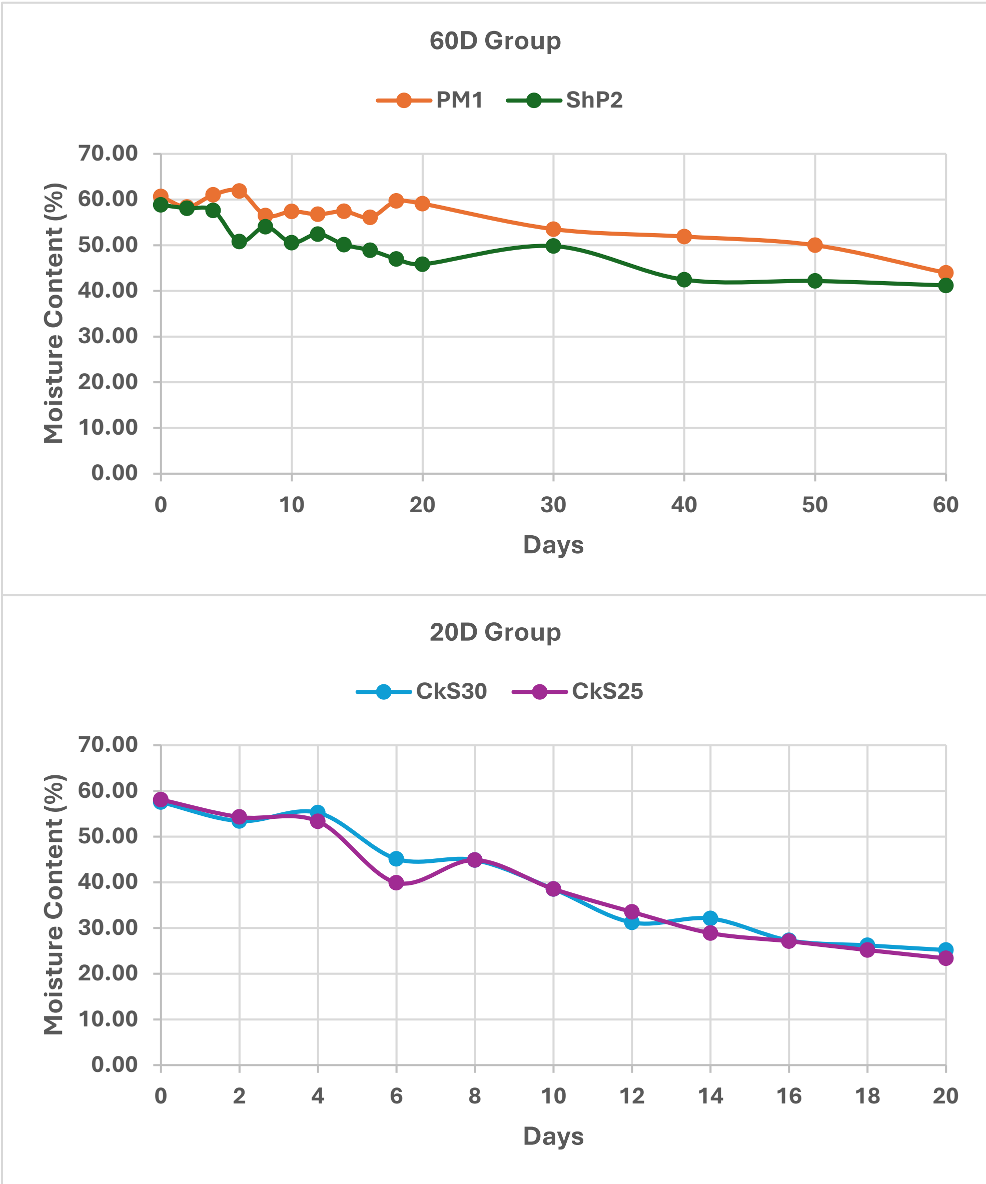


Figure 23: Moisture Content (MC) Variation during the process in all trails.

Table 7: Loss of moisture Content (MC) throughout process phases.

TRIALS	MC LOSS RATE				TOTAL LOSS RATE	
	Mesophilic	**Thermophilic**	**Cooling**	**Maturation**	**D20**	**D60**
PM1	**2.28**	**0.98**	**-2.31**	**0.62**	**2.59%**	**26.56%**
SHP2	**0.75**	**7.52**	**1.66**	**3.06**	**22.09%**	**29.97%**
CKS25	**4.13**	**26.14**	**1.09**	**1.02**	**56.26%**	**-**
CKS30	**3.8**	**25.42**	**1.77**	**3.75**	**59.8%**	**-**

The initial moisture content (MC) is a critical determinant of composting efficiency and product quality (Xie *et al.*, 2023), with most research estimating it around 60% (Alkoaik, 2019). As shown in Figure 23, all trials initially had a MC close to the recommended value, 60.66 ± 1.1 (in PM1), 58.83 ± 0.9 (in ShP2), 57.56 ± 1.04 (in CkS25), and 58.1 ± 0.6 % (in CkS30), indicating the effectiveness of the Recipe preparation techniques both on a dry matter basis (PM1 And ShP2) or by using of compost recipe calculator (CkS group).

During the process, a significant amount of MC will evaporate at a rate that surpasses its production, due to high temperatures caused by the bio-drying process triggered by microbial activity and aeration rates (Ouali et Hiouani, 2024). This loss can be interpreted as an indicator of the decomposition rate (Kalamdhad *et al.*, 2009). Throughout the 20-day composting period, all trials exhibited a downward trend, with a significant variation among them ($P < 0.001$). The reduction in MC loss was observed in the sequence of CkS30 (59.8%)> CkS25(56.26%) > ShP2(22.09%) > PM1(2.59%), which aligns with the inverse order of total average daily temperatures CkS30 (1.95) < CkS25 (2.48) < ShP2(2.49) < PM1(2.61) (Table 07 and Table 06). In most composting trails, the majority of the loss occurred during the thermophilic phase, in which the moisture content decreased by 7.52%, 26.14%, 25.42% in ShP2, CkS25 and CkS30, respectively (Table 07). The exception was trial PM1, where most of the losses occurred in the initial phase (2.28%), with a very small loss rate of 2.49%, even though it experienced intense, prolonged, and rapid thermal activity compared to the others (Table 06), which may be due to low ambient temperature (Epstein, 2011 ; Kalamdhad *et al.*, 2009 ; Ouali et Hiouani, 2024), since it was conducted during the winter, where Kalamdhad et al., (2009) stated that, in winter, high temperatures inside the bioreactor cause water vapor to condense, while improper aeration limits the extraction of the vapors, leading to the generation of high moisture content and/or the formation of leachate. Additionally, the low aeration rates (Rose *et al.*, 2021), rotation frequency (Alkoaik, 2019), and insufficient bulking agent (Jain *et al.*, 2019a ; Varma *et al.*, 2017) plays a significant roles in MC Loss.

The moisture content remained within the acceptable range (40 - 60)(Jain *et al.*, 2018a) throughout the 60 days composting for PM1. However, it fell below the range on the 25th day for ShP2, on the 10th day for trial CkS25 and CkS30, which may have affected the decomposition rate in the early stages of the process. Maintaining an ideal moisture content throughout the entire process is indispensable (Jain *et al.*, 2018a). In this investigation, no water was introduced during the first 20 days of the process in order to assess the MC loss rate. For the remaining duration, mainly in trials PM1 and ShP2, a tactile assessment was used to check the moisture levels prior to laboratory confirmation on sampling days, with water supplied as necessary to sustain appropriate moisture content. Water was injected on the 25th day of the ShP2 trail, which explains the sudden increase in MC observed on the 30th day (Figure 23).

According to Jain et al., (2018a), the final product should ideally have a moisture content of at least 40%. However, CkS25 and CkS30 indicated a MC of 25.18 ± 0.49 and 23.36 ± 0.7 %, respectively, by the 20th day, which is lower than the recommended value. On the other hand, PM1 and ShP2 both showed that the MC were within the acceptable range on both the 20th and 60th days of the process (Figure 23). It's noteworthy to mention that there was no leachate formation during the process in all trials except ShP2 during the initial days.

V. potential of Hydrogen (pH):

The pH plays a critical role in the composting process, influencing microbial activity, nutrient availability, and the overall decomposition rate (Ismail *et al.*, 2013 ; Zhao *et al.*, 2023).

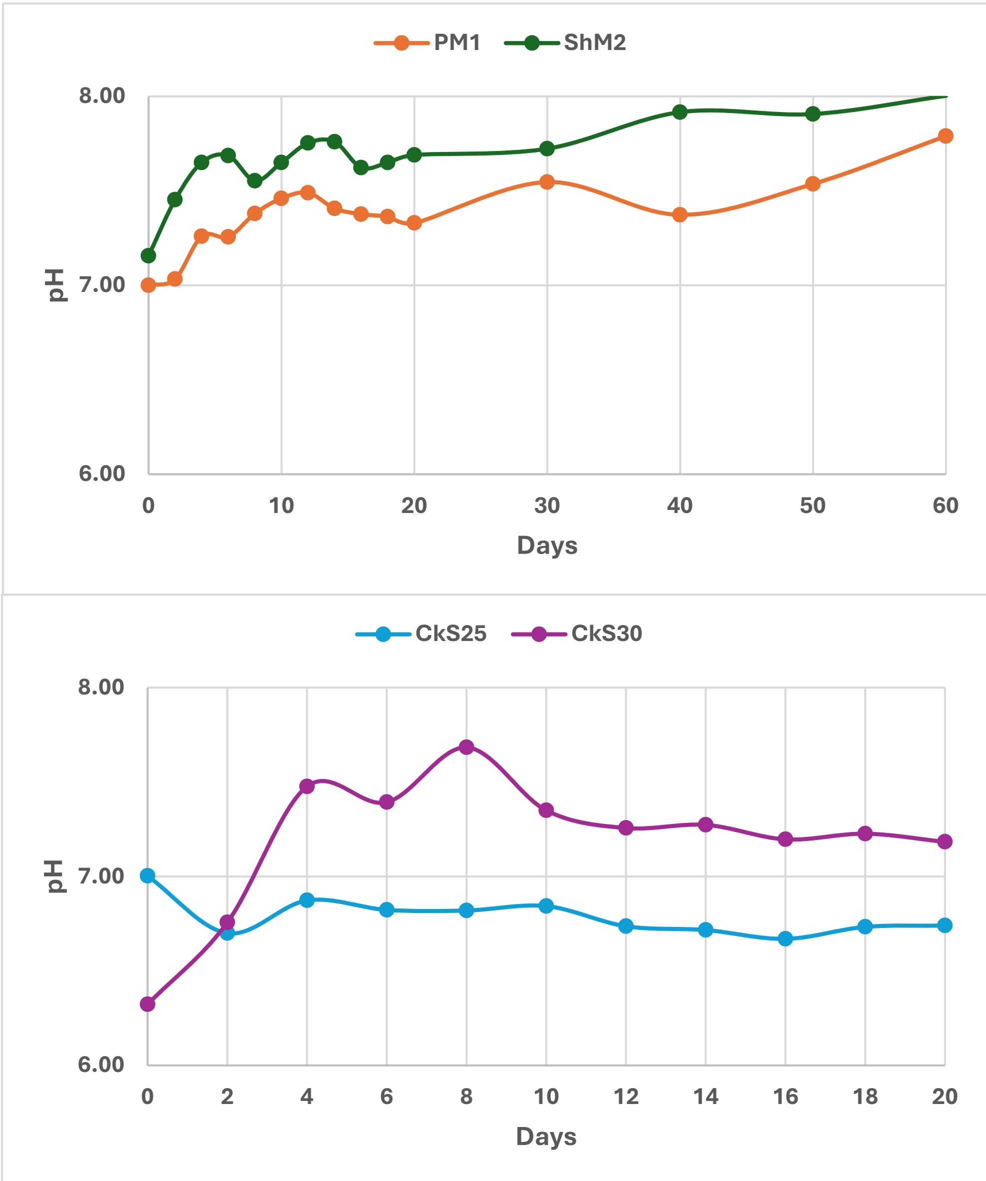


Figure 24: pH Variation during the process in all trails.

The Initial pH levels for all trails fell within the appropriate composting range of 5.5-8 (Varma *et al.*, 2017); where, in trials PM1, ShP2, CkS25, and CkS30, the pH levels were 7 ± 0.3, 7.16 ± 0.03, 7 ± 0.5, and 6.32 ± 0.07, respectively (Figure 24). The decline in the initial pH value observed in CkS30 might be attributed to the utilization of a neutral substance, i.e. chicken litter (7.06 ± 0.07) compared to the poultry manure (8.99 ± 0.02) and sheep manure (8.11 ± 0.03) in trials PM1 and ShP2, respectively, as well as mixing it in a smaller amount with highly acidic DPW (5.46 ± 0.06) compared to CkS25, the results shown in Table 04.

During the mesophilic phases, except for CkS25, the pH value of all other trials increased from their initial values to 7.03 ± 0.05, 7.45 ± 0.04 and 6.76 ± 0.07 in PM1, ShP2, and CkS30 respectively, while CkS25 showed a rapid decrease to 6.7 ± 0.07 (Figure 24). This acidification phenomenon may be primarily caused by the development of anaerobic conditions, which leads to the dissolution of CO2, the formation and accumulation of organic acids, through the breakdown of easy biodegradable compounds such as carbohydrates and lipids by acid-forming bacteria (Diaz et Savage, 2007 ; Habchi *et al.*, 2022 ; Oshins *et al.*, 2022 ; Rich *et al.*, 2018).

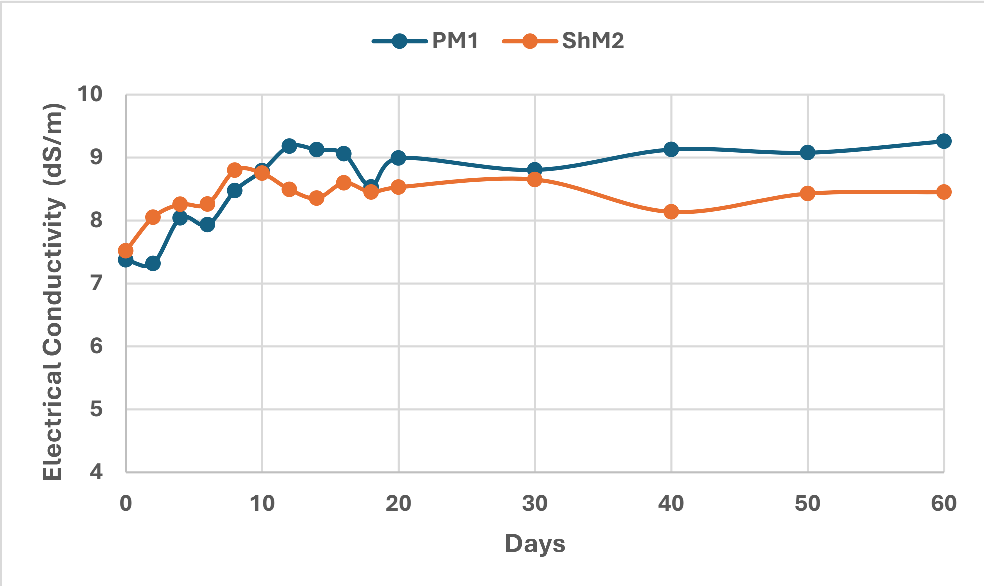
At the outset of the thermophilic phases, all trials displayed an upward trend in pH, probably attributed to the occurrence of ammonification process, alongside the oxidation of the previously produced organic acids owing to the abundance of oxygen through turning and high fungi activity in acid conditions (Cao *et al.*, 2020 ; Ouali et Hiouani, 2024 ; Rich *et al.*, 2018 ; Singh et Kalamdhad, 2013), which may further explain the rapid increase in the trial CkS30. Afterward, the pH fluctuated throughout the phase, recording peak values of 7.49 ± 0.12 in PM1, 7.76 ± 0.06 in ShP2, 6.87 ± 0.08 in CkS25, and 7.68 ± 0.02 in CkS30 on days 12, 14, 4 and 8 respectively.

All trials showed a decrease in pH after reaching their peak values, attributed to the Ammonia volatilization process, where ammonium (NH_4) tends to volatilize at high temperatures and a pH greater than 7.5 (trial ShP2 and CkS30) (Kalamdhad et Kazmi, 2009b ; Oshins *et al.*, 2022). Later, from the 12th day and throughout the cooling phase, the pH exhibited consistency in its fluctuations due to the onset of the cooling phase and/or the formation of buffering agents such as humus (Rich *et al.*, 2018) , reaching values of 7.33 ± 0.03, 7.69 ± 0.04, 6.74 ± 0.02, and 7.18 ± 0.02 in PM1, ShP2, CkS25, and CkS30, respectively, by the 20th day.

In the maturation phase of the procedure, the pH rose swiftly to 7.79 ± 0.02 in PM1 and 8 ± 0.07 in ShP2, owing primarily to the ammonification process, where according to (Oshins *et al.*, 2022), as ammonium remains in the compost, the pH continues to increase until it reaches its pKa range of 9. The pH values of the final products in all trials were within the appropriate range (6.0– 8.5) for agricultural use (Vico *et al.*, 2018).

VI. Electrical Conductivity (EC):

As a measure of the compost's saltiness and its potential plant-growing compatibility, electrical conductivity (EC) is often monitored throughout the composting process (Antil *et al.*, 2014 ; Singh et Kalamdhad, 2013).



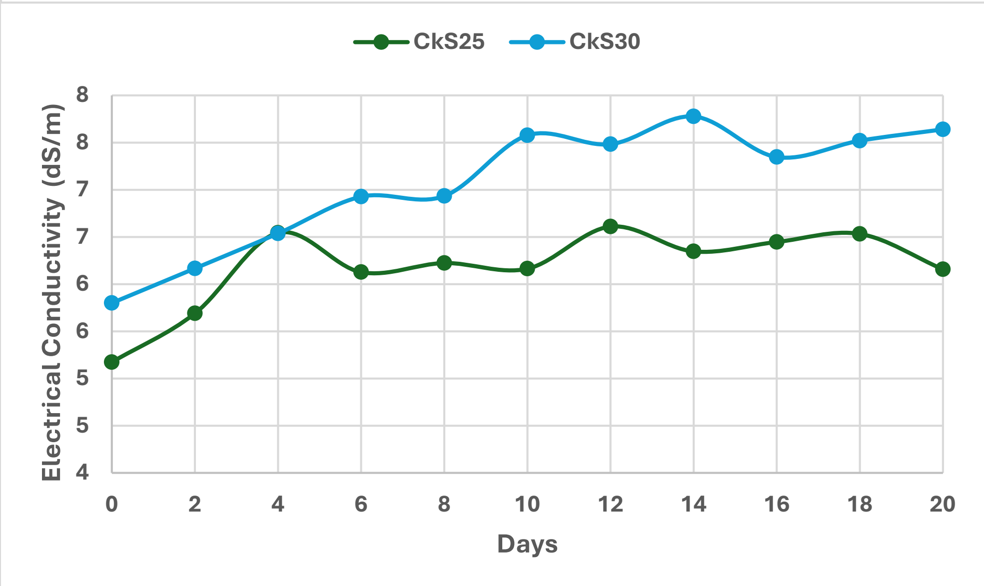


Figure 25: Electrical Conductivity (EC) Variation during the process in all trails.

The initial EC of the trials ranged between 5.17 ± 0.6 and 7.52 ± 0.13 dS/m due to the differences in the composition of the different treatments with PM1 and ShP2 having the highest concentrations of 7.37 ± 0.53 and 7.52 ± 0.13 dS/m, respectively. As shown in Figure 25, all trials showed a significant difference ($P < 0.001$).

During the 20-day composting period, all trials showed a rapid increase in EC from 7.52 ± 0.13 dS/m, 5.17 ± 0.62 dS/m, and 5.8 ± 0.01 dS/m to a peak of 8.8 ± 0.11 dS/m, 6.61 ± 0.07 dS/m, and 7.78 ± 0.06 dS/m on day 8, 12, and 14 in trials ShP2, CkS25, and CkS30, respectively. However, in trial PM1, there was a small decrease from 7.93 ± 0.13 dS/m to 7.32 ± 0.37 dS/m before increasing to a peak of 9.18 ± 0.62 dS/m on day 12. This increase in EC is caused by the rapid degradation of easily biodegradable organic substrates, which leads to an increase in the concentration of soluble salts, such as ammonium and phosphate (Gao *et al.*, 2010 ; Habchi *et al.*, 2022 ; Kalamdhad et Kazmi, 2009b ; Petric et Selimbašić, 2008 ; Sharma et Yadav, 2018). Subsequently, the values decreased progressively until the expiration of the 20-day period, reaching 8.99 ± 0.44 dS/m, 8.53 ± 0.03 dS/m, 6.16 ± 0.06 dS/m, and 7.64 ± 0.02 dS/m in trials PM1, ShP2, CkS25, and CkS30, respectively, mainly due to ammonia volatilisation, which released ammonium ion complied with the reduction of other basic groups, as well as mineral salts precipitation and accumulation (Gao *et al.*, 2010 ; Habchi *et al.*, 2022 ; Kauser *et al.*, 2020 ; Singh et Kalamdhad, 2013).

In the second phase, the EC continued to change, increasing by 0.27 dS/m in PM1 as a result of the release of additional mineral salts that were not bound to stable organic complexes (Sudharsan Varma et Kalamdhad, 2015), and decreasing in ShP2 by 0.08 dS/m, probability due the formation of humic substances that bonded with metal ions, reducing their solubility in water (Singh et Kalamdhad, 2013) and/or due microorganisms metabolising salts (Fu *et al.*, 2021). All trials exhibit higher EC values, surpassing the agricultural use threshold of 4 dS/m (Cao *et al.*, 2020 ; Jain *et al.*, 2018b) from the onset of the process. This is primarily attributed to the high EC in the feedstocks, with sheep manure displaying the highest value at 8.95 ± 0.01 dS/m, followed by date palm waste (7.41 ± 0.31 dS/m), poultry manure (7.02 ± 0.01 dS/m), and then chicken litter (5.43 ± 0.01 dS/m) (Table 04).

Although certain studies indicate that compost with an electrical conductivity (EC) value greater than 4 dS/m may remain suitable for agricultural applications, it is highly recommended to adjust the EC prior to application (Ouali et Hiouani, 2024), which can be achieved by blending high-EC compost or feedstock with low-EC materials (Rynk *et al.*, 2022b), reducing the EC of feedstocks, such as date palm waste, through water soaking for several days (Abid *et al.*, 2020 ; Ouali et Hiouani, 2024), or by applying materials with high capacity to absorb and exchange ions, such as zeolite (Onwosi *et al.*, 2020).

VII. Organic Matter (OM) Decomposition:

During the composting process, the OM and C/N progress are the important key parameters reflecting raw materials biodegradation and transformation as already explained.

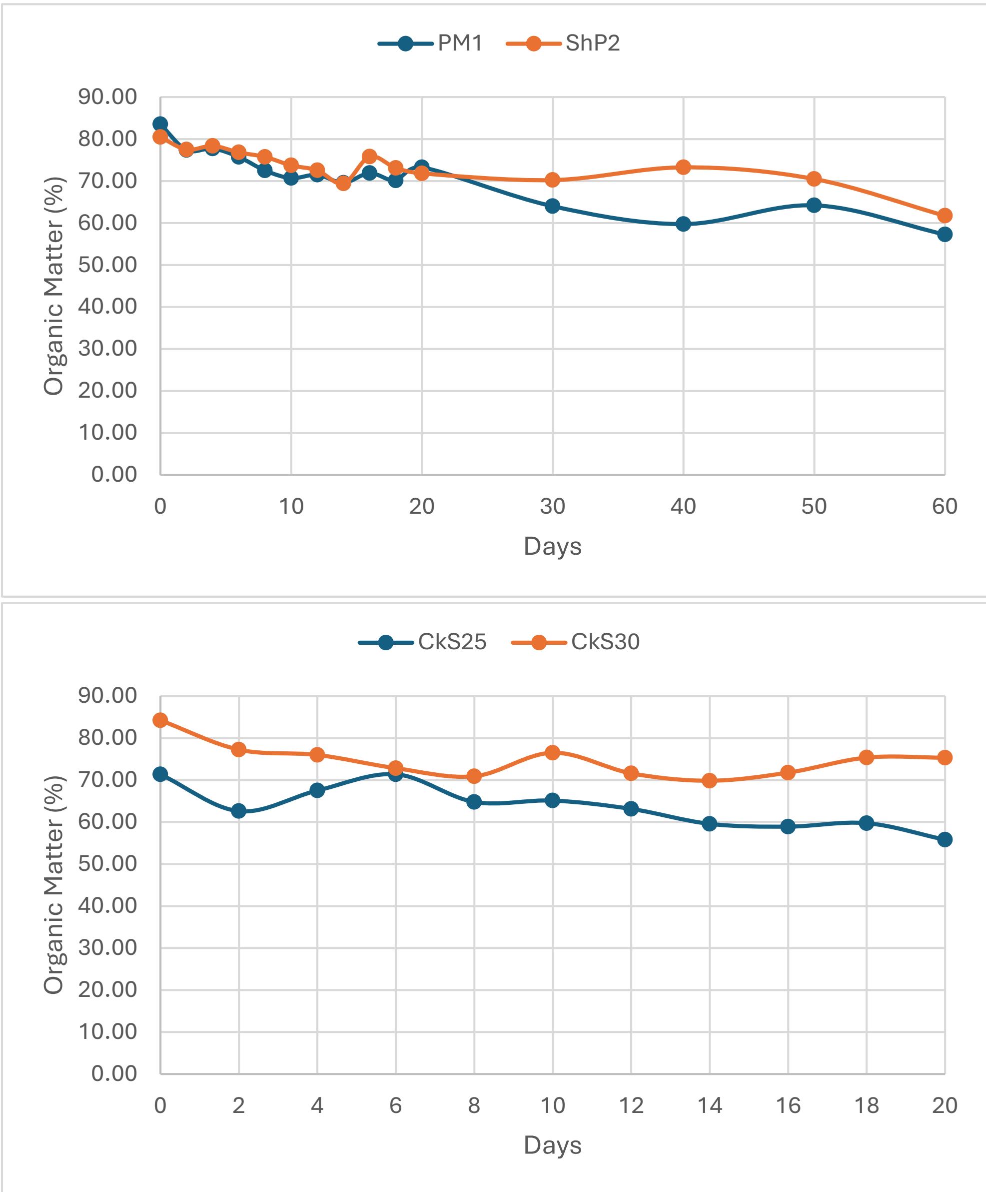


Figure 26: Organic Matter fluctuation during the process in all trails.

Table 8: Organic Matter loss rate throughout process phases and biodegradability at day 20 and 60 (in PM1 and ShP2).

TRIALS	OM Loss rate				Total Loss rate	
	Mesophilic	Thermophilic	Cooling	Maturation	K20	K60
PM1	**7.32**	**8.64**	**0.85**	**18.32**	**0.4595**	**0.7355**
ShP2	**3.67**	**4.88**	**-2.80**	**11.46**	**0.3809**	**0.5544**
CkS25	**12.3**	**-0.8**	**5.4**	**6.61**	**0.4932**	**-**
CkS30	**10.42**	**0.94**	**1.52**	**0.03**	**0.5122**	**-**

Once initiation of the process, an abrupt reduction in organic matter was observed over the mesophilic phase (Figure 26), with values decreasing from 83.51 ± 2.7 to 77.4 ± 4.5, 80.46 ± 0.9 to 77.51 ± 1, 71.34 ± 3.6 to 62.6 ± 3, and 86.22 ± 0.6 to 77.23 ± 3.37 % in PM1, ShP2, CkS25, and CkS30, respectively, which can be arranged according to the loss ratio in the following descending order: CkS25(12.3%), CkS30(10.42%), PM1 (7.32%), and finally ShP2 (3.67%)(Table 08). This is probably owing to the establishment of favourable conditions for microbial activity, including 60% moisture, adequate aeration through turning process (4r/daily), an optimal C/N ratio particularly CkS25 and CkS30 25:1 and 30:1, which enhances the fast onset of the decomposition processes (Calisti *et al.*, 2020). Subsequent fluctuations in organic matter content were observed throughout the process, probably due to dual nature of composting as both a decomposition and synthesis process; with a general tendency to decrease, since it is mainly a biodegradation process (Ouali et Hiouani, 2024).

By the 20th day, the organic matter values for PM1, ShP2, CkS25, and CkS30 were 73.25 ± 4.9, 71.83 ± 1.4, 55.78 ± 2.9, and 75.32 ± 1.31%, respectively. Most of the loss occurred during the initial and thermophilic phase, particularly in PM1 and ShP2, due to the high bacterial activity at the beginning of the process, where during the early phases of composting, easily biodegradable materials decompose quickly, reducing organic matter rapidly, while more resistant components decompose more slowly, thus, as easily biodegradable substances deplete over time, the overall rate of decomposition decreases (Ouali et Hiouani, 2024). However, CkS25 and CkS30 exhibited the lowest loss during the thermophilic phase, possibly due to unfavorable conditions for microbial activity, such as low MC, which developed at mid-process (as explained in MC).

At the end of the 20 days period, CkS30 had the highest biodegradation value at 0.5122, followed by CkS25 at 0.4932, then PM1 at 0.4595 and ShP2 at 0.3809. These results align with Nayak et Kalamdhad, (2015)'s study on rotary drum composting of Sewage sludge in different C:N ratio, where both C:N 30 (Kb = 0.5887) and 25 (Kb = 0.5478) recorded the highest values compared to less ratios. Particle size and the feedstock's resistive nature are two additional important factors that affect the breakdown of organic matter (OM) during composting, along with the C:N ratio, the composting system and conditions (Bernal *et al.*, 2009).

On day 60, the biodegradation values for PM1 and ShP2 further decreased to 57.26 ± 1.3 and 61.72 ± 3.1 %, respectively, indicating a significant difference in the extent of substance decomposition between them (Table 08), most probably attributed to the higher bacterial activity in poultry manure compared to sheep manure (Kalamdhad et Kazmi, 2009b).

VIII. C: N progress:

The C/N ratio serves as a key parameter for assessing organic matter decomposition and evaluating compost quality with respect to carbon and nitrogen content *(Ouali et Hiouani, 2024)*.

Table 9: Variation of Total Organic Carbon (TOC), Total Kjeldahl Nitrogen (TKN), and C:N ratio on days 0, 4, 20, and 60 (in PM1 and ShP2).

Trials	Parameters	Days			
		0	4	20	60
PM1	TOC (%)	46.40	43.19	38.95	31.81
	TKN (%)	1.01 ± 0.01	0.750	1.19 ± 0.02	2.54
	C:N ratio	46.12	57.58	32.73	12.52
ShP2	TOC (%)	44.7	43.54	39.9	34.29
	TKN (%)	0.938	1.204	1.267	1.372
	C:N ratio	47.65	36.16	31.49	24.99
CkS25	TOC (%)	39.63	37.50	30.99	-
	TKN (%)	1.457	1.563	1.799	-
	C:N ratio	27.2	25.63	17.23	-
CkS30	TOC (%)	47.90	42.21	41.84	-
	TKN (%)	1.47	1.53	1.92	-
	C:N ratio	31.83	27.66	21.82	-

The initial C:N ratio in the trials were 46.12 in PM1, 47.65 in ShP2, 27.2 in CkS25, and 31.83 in CkS30, which were higher than the acceptable values in PM1 and ShP2, but approximately within the targeted range of values prepared in CkS25 and CkS30, showing the effectiveness of the second method in recipe preparation.

The C:N ratio decreased in all trials during the composting period, except for PM1, due to a decrease in TOC and an increase in TKN throughout the process (Table 9). As for the initial increase in PM1 between day 0 and 4 it can be due the decrease in nitrogen concentration (Ouali et Hiouani, 2024). During composting, microorganisms mineralize organic matter to extract nutrients such as carbon and nitrogen for their metabolism (Onwosi *et al.*, 2020). Approximately 30-40% of the extracted carbon is subject to catabolism, whereas 60-70% is emitted as CO_2, resulting in a reduction of organic matter and total organic carbon (TOC) (Barrington *et al.*, 2002). On the other hand, whilst nitrogen exhibits a consistent increase throughout the process (Table 9), it gets involved in multiple simultaneous reactions; one of which frequently dominates the others, according to the substrate and environmental conditions, leading to either nitrogen loss or fixation (Meng *et al.*, 2016 ; Ouali et Hiouani, 2024).

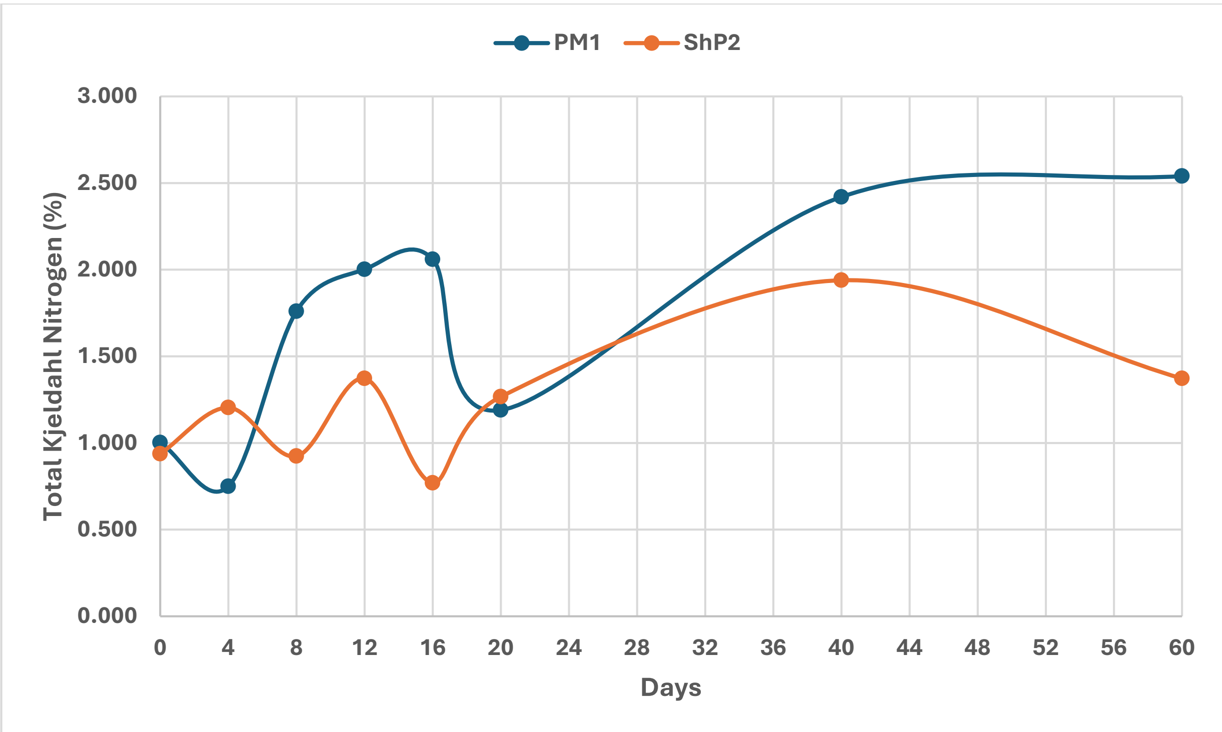


Figure 27: Total Kjeldahl Nitrogen variation during the composting process.

Figure 27 demonstrates the nitrogen fluctuations throughout the composting process in PM1 and ShP2, revealing a significant variation ($P < 0.05$). At the onset of the process, ShP2 exhibited an increase in nitrogen concentration from 0.938 to 1.204, typically attributed to the activity of proteolytic bacteria (Jain et Kalamdhad, 2018 ; Kauser *et al.*, 2020 ; Ouali et Hiouani, 2024 ; Zorpas, 2000), followed by a rapid decline between Days 4 and 8 to 0.924. In contrast, PM1 showed an early decrease at the beginning of the operation (between Days 0 and 4) from 1.002 to 0,75, but had previously experienced a slight increase between day 0 and 2 as shown in (Ouali et Hiouani, 2024)'s study. The reduction observed in both trials results from nitrogen loss to the atmosphere, where high temperature, increased evaporation, and high acidity inhibit the activity and growth of nitrifying bacteria; Consequently, the nitrification reaction diminishes, and volatilisation becomes more pronounced (Bernal *et al.*, 2009 ; Wang *et al.*, 2016a). Afterward, there was an increase in nitrogen concentration from 2 to 7 between days 4 and 16, and from 5 to 10 between days 4 and 12 in PM1 and ShP2, respectively, which is mainly attributable to the loss of biomass as CO_2 alongside the fixation of atmospheric nitrogen by acetobacter bacteria (Kalamdhad et Kazmi, 2009b ; Kauser *et al.*, 2020).

During the later phases of composting, ammoniacal nitrogen (NH_x) can either be converted to nitrate or nitrite nitrogen (NO_x) via the promoted activity of bacterial nitrification (Hou *et al.*, 2017), or immobilised and shifted into organic nitrogen, i.e. humus (Kauser *et al.*, 2020). Thus, the later decrease observed between days 40 and 60 in ShP2, and between days 16 and 20 in PM1 can be explained by the predominance of the nitrification reaction, while the increase between Day 20 and 60 in PM1 and between days 16 and 40 in ShP2 may result from the fixation of ammoniacal Nitrogen as an organic substance, given that the total Kjeldahl nitrogen (TKN) comprises strictly organic nitrogen and NHx (Bridgewater *et al.*, 2017 ; Ouali et Hiouani, 2024 ; Singh et Kalamdhad, 2019).

According to Brinton, (2000) a compost is deemed acceptable only if its C:N ratio is 25 or lower, prior to considering its maturity and stability. In this study, neither PM1 nor ShP2 exhibited signs of maturity and stability until after the initial 20-day period, recording a C:N ratio of 12.52 and 24.99, respectively, by day 60. However, CkS25 and CKS30 both fell within the consideration range, with C:N ratio of 17.23 and 21.82, respectively, which was mainly due to the adjustment of the initial C:N ratio using the compost recipe calculator (Table 9).

IX. Nutrients Content:

Table 10 shows the results of the contents of macronutrient (NPK) and micronutrient in the initial substrate of the compost, at the 4th day, and in the final product after 20-, and 60-days composting in PM1 and ShP2. The difference in the total content of nutrients between trials can be due to the heterogeneity of additives used for composting.

Table 10: Nutrient content on days 0, 4, 20, and 60 (in PM1 and ShP2).

Trials	Days	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	Na_2O	P2O5	TiO_2	Cr_2O_3	Mn_2O_3	ZnO	SrO
PM1	0	5.07	0.21	0.23	10.7	0.9	1.82	0.35	2.74	0.019	0.004	0.041	0.009	0.014
	4	5.58	0.22	0.19	11.38	1.01	2.38	0.43	2.9	0.019	0.004	0.041	0.006	0.015
	20	7.43	0.32	0.32	13.12	1.19	2.46	0.51	3.37	0.027	0.004	0.048	0.024	0.019
	60	8.19	0.36	0.47	15.76	1.36	3.17	0.58	4.05	0.03	0.008	0.06	0.053	0.021
ShP2	0	8.76	1.47	0.54	3.98	1.15	1.96	0.94	1.1	0.08	0.004	0.022	0.005	0.033
	4	9.49	1.7	0.76	4.66	1.19	1.6	0.77	1.24	0.09	0.005	0.024	0.0005	0.037
	20	8	1.4	0.55	3.7	1	1.56	0.75	1.04	0.08	0.005	0.021	0.004	0.031
	60	10.07	1.72	0.76	4.9	1.29	2.02	0.97	1.28	0.098	0.006	0.025	0.007	0.039
CkS25	0	14.76	4.99	1.36	3.12	1.04	1.56	0.29	0.8	0.17	0.01	0.033	0.005	0.009
	4	15.55	5.51	1.39	3.32	1.13	1.77	0.33	0.84	0.18	0.01	0.035	0.003	0.008
	20	16.19	4.1	1.48	3.22	1.06	1.86	0.33	0.65	0.19	0.009	0.032	0.005	0.02
CkS30	0	20.78	4.28	1.63	4.96	1.6	2.05	0.39	1.17	0.19	0.012	0.044	0.006	0.027
	4	11.99	2.65	0.96	2.84	0.91	1.3	0.26	0.69	0.11	0.009	0.027	0.004	0.015
	20	13.32	2.96	1.11	3.25	1.56	1.58	0.13	0.89	0.13	0.008	0.031	0.004	0.019

In CkS30, the initial concentration of nutrients was higher compared to the other experiments. Specifically, the concentrations of (Si), iron (Fe), (Mg), (K), (Ti), (Cr), and (Mn). On the other hand, PM1 shows a high concentration of Al and nitrogen (N), while ShP2 shows a high concentration of Ca and zinc (Zn) (Table 10). During the initial stage (Day 0 and 4), most nutrients' concentrations increase in PM1, ShP2, and CkS25, except for some elements, which initially decrease between Day 0 and 4 before increasing in later stages, such as iron (in PM1), zinc (in all trials), potassium, and sodium (in ShP2). As for CkS30, a decreasing trend in all nutrients was observed from the onset of the process, which is primarily attributed to leachate formation during the initial stages (MC),which is a common phenomenon observed during summer composting (Da Silva *et al.*, 2020).

After day 4, there was a rising trend in CkS30 until day 20 and in PM1 until day 60. However, there was a decrease in most elements in ShP2 and CkS25, although this was later corrected between days 20 and 60 for ShP2. The increase was the result of mass loss corresponding to the mineralisation of organic portions, CO_2 release, and water evaporation

(Gao *et al.*, 2023 ; Kalamdhad et Kazmi, 2009b ; Kauser *et al.*, 2020 ; Sudharsan Varma et Kalamdhad, 2015). Conversely, the observed decrease at various stages may have been attributable to microbes consuming mineralized nutrients (Huang *et al.*, 2004 ; Kalamdhad et Kazmi, 2009a).

Table 11: The K and P concentration on day 0, 20, and 60 (in PM1 and ShP2).

Trials	Concentration (%)	Days		
		0	**20**	**60**
PM1	**K**	**1.516667**	**2.05**	**2.641667**
	P	**1.196507**	**1.471616**	**1.768559**
ShP2	**K**	**1.633333**	**1.3**	**1.683333**
	P	**0.4803493**	**0.4541485**	**0.558952**
CkS25	**K**	**1.3**	**1.55**	**-**
	P	**0.349345**	**0.3668122**	**-**
CkS30	**K**	**1.708333**	**1.316667**	**-**
	P	**0.510917**	**0.3886463**	**-**

In addition to nitrogen, phosphorus and potassium consider as the mains mineral required for plant productivity, i.e. Macronutrients (Kauser *et al.*, 2020) , which serve as significant indicators of the end product quality (Cao *et al.*, 2020). All trials showed a total K content above the minimum values stated by (Stehouwer *et al.*, 2022) (0.2 %) and (Oviedo-Ocaña *et al.*, 2019) (1%) for soil improvers usage from the beginning of the process (Table 11). As for the P concentration in the end product, in all trials except PM1, the total phosphorus content values ranged from 0.3 to 0.5%, while PM1 had the highest amount, exceeding 1%, from day 0. This was attributable to the high total phosphorus values in the feedstocks.

The concentration of macronutrients in compost is generally lower than that in synthetic fertilisers; however, it is frequently applied at higher rates (Sudharsan Varma et Kalamdhad, 2015). Strategies include improving the agronomic quality of the compost through the addition of high-nutrient materials, such as phosphoric rock, in instances with low phosphorus concentration (Oviedo-Ocaña *et al.*, 2019).

X. Sensory Analysis (Colour and Odor):

The Sensory Analysis is a straightforward and effective approach for farmers to evaluate the maturity degree of compost (Alkoaik, 2019). However, Indicators of physical stability, such as homogeneity, heat loss, general appearance, dark coloration, and earthy odors, are more reliable when coupled with additional limitations (Siddiqui *et al.*, 2020).

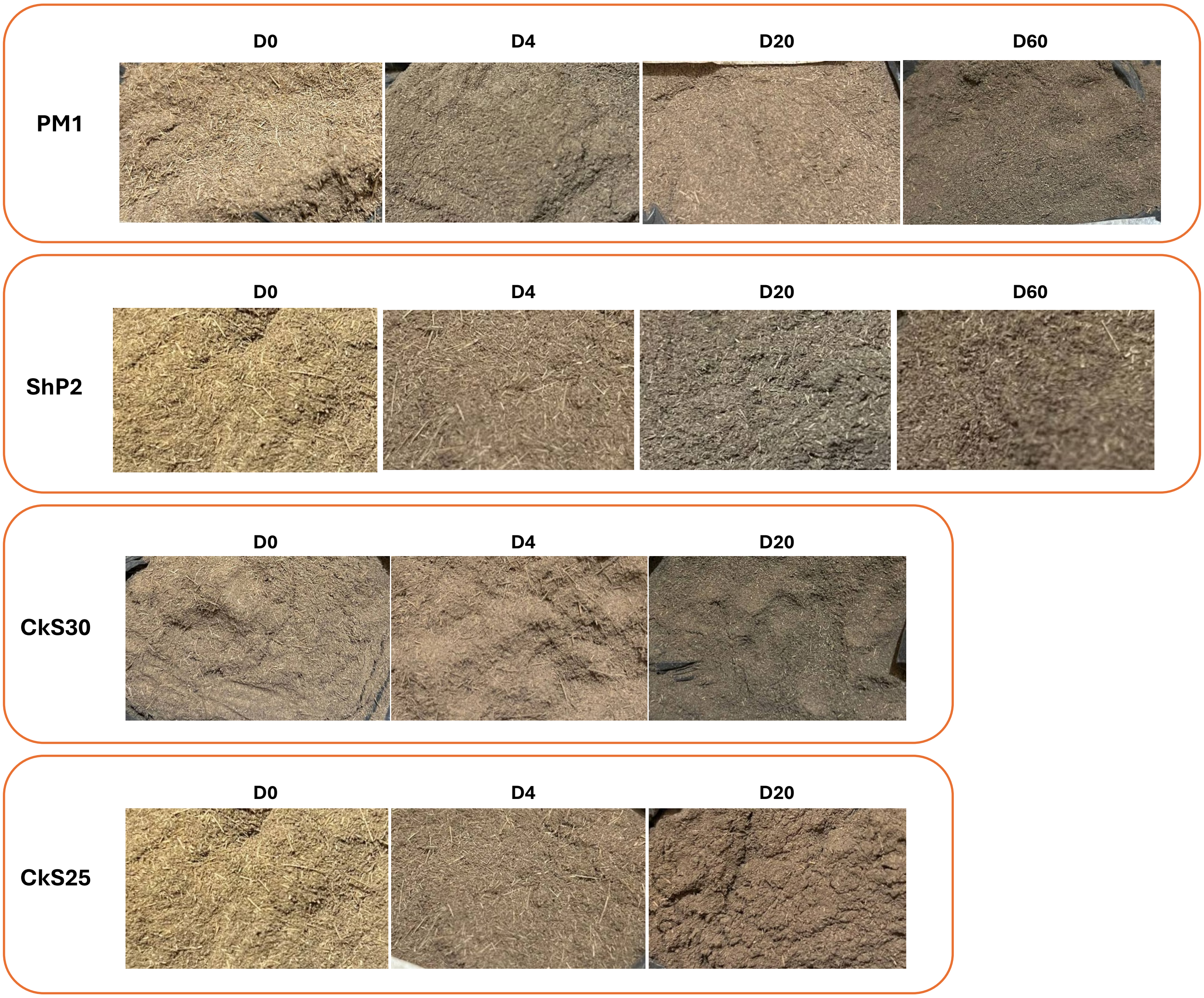


Figure 28: Photos of the mixture at days 0, 4, 20 and 60 (in PM1 and ShP2) show the degree of colour change throughout the process in all trials.

The colour and odour of the composted material might indicate its chemical characteristics (Ouali et Hiouani, 2024); for instance, green hue reflects high nitrogen concentration, while a brown hue indicates the reverse, this can helps farmers estimate the initial mixture ratio (Diaz, 2018 ; Rynk *et al.*, 2022b). According to Figure 28, the feedstock's yellow colour gradually turned blackish brown by the end of the process, as in most of the investigation (Diaz et Savage, 2007). The observed darkening is attributed to the gradual biodegradation of organic matter and the subsequent formation of black-tinted compounds, such as humic substances (Lim *et al.*, 2013 ; Stevenson, 1994). The mature compost must display a greyish-black or brownish-black coloration, contingent upon the amount of brown pigments such as tannins and melanin in the initial feedstocks (Alkoaik *et al.*, 2011).

During the composting process, a range of gases are generated alongside water and carbon dioxide; Most significantly, ammonia (NH3), hydrogen sulphide (H2S), and volatile organic compounds (VOCs) are released, which contribute to the unpleasant odours and can negatively affect the environment, particularly N2O, and CH4 (Bernal *et al.*, 2009 ; Onwosi *et al.*, 2017), indicating issues related to compost immaturity and improper management (Ouali et Hiouani, 2024). According to Nair & Delate, (2016), Compost that has reached full maturity is thoroughly decomposed, stable, and emits a pleasant earthy aroma. After blending the feedstocks and adding water, an unpleasant odour emerged (personal observation),which can be associated with the release of hydrogen sulphide by sulphur-reducing bacteria or faecal coliforms found in the feedstocks (El-Nagerabi *et al.*, 2012).

At the beginning of the thermophilic phase, the magnitude of the odour increased significantly, mainly due to amplified NH4+ volatilisation (Bernal *et al.*, 2009 ; Wang *et al.*, 2016a) , which eventually decreased, approximately five days later, and was ultimately replaced by a more pleasant earthy scent, largely due to 2-methylisoprene and geosmin released by fungi and actinomycetes, which could serve as signs of compost maturity (Epstein, 1997 ; Ouali et Hiouani, 2024).

Based on the earthy aroma and dark brown colour, it can be concluded that the final product by the 20 days of composting in all trials shows signs of maturity. Nonetheless, colour and odour offer only a fundamental insight into the degradation state of the composted material and fail to convey significant information regarding the maturation degree (Bernal *et al.*, 2009).

Figure 29: Insects and white fungi on the compost surface.

Furthermore, with the onset of the thermal phase, a community of worms, insects, as well as fungi emerged on the pile's surface (Figure 29), primarily due to the high temperatures that favoured the proliferation of thermophilic species (Rich *et al.*, 2018), which they began to disappear over time. A similar phenomena occur in other studies (Kadir *et al.*, 2016 ; Rich *et al.*, 2018).

XI. Germination Index (GI):

The germination index (GI) test analyses the interaction between the plant and the substrate (Voběrková *et al.*, 2020). It serves as a sensitive indicator for assessing compost phytotoxicity and harmful component decomposition, making it one of the important tools for determining compost maturity (Cao *et al.*, 2020 ; Muktadirul Bari Chowdhury *et al.*, 2013 ; Zhang *et al.*, 2020 ; Zhao *et al.*, 2023). Moreover, it is a trustworthy measure of compost maturity, equivalent to the CoMMe-101 and Solvita soil test systems (Lee *et al.*, 2020).

Table 12: The germination index (%) of the radish seeds in the final product in all trials at different concentrations.

	Days	Extract Concentration (%)			
		100	75	50	25
PM1	**D20**	**54.3 ± 7.5**	**60.4 ± 9.5**	**70.2 ± 12.6**	**80.5 ± 11.9**
	D60	**87.5 ± 6**	**-**	**-**	**-**
ShP2	**D20**	**53.3 ± 8.5**	**65.4 ± 11.74**	**76.2 ± 9.6**	**79.4 ± 14.01**
	D60	**79.6 ± 5.4**	**-**	**-**	**-**
CkS25	**D20**	**56.91 ± 5.29%**	**67.95 ± 11.5**	**77.3 ± 7**	**89.6 ± 10.5**
CkS30	**D20**	**57.56 ± 9.43%**	**70.09 ± 7.7**	**75.34 ± 13.2**	**92.5 ± 11.3**

GI: Germination Index.

During the composting process, various factors can influence the germination index including electrical conductivity (EC), pH levels, the E4/E6 ratio, ammonium nitrogen (NH4+-N) content, and heavy metal concentrations, in addition to the quality, sensitivity and tolerance of the seeds (Yang *et al.*, 2021). Rashwan et al., (2021) reported that a GI levels above 50% indicate hazardous compost, 50% to 80% indicate highly toxic compost, and over 80% indicate phytotoxic-free compost. The proportion of GI in mature compost should exceed 80% (Sharma et Yadav, 2018).

Table 12 presents the GI values on day 20 for trials PM1, ShP2, CkS25, and CkS30, which were 54.3 ± 7.5, 53.3 ± 8.5, 56.91 ± 5.29, and 57.56 ± 9.43%%, respectively.
These results suggests that the maturation time for CkS trials was reduced in comparison to the other trials. Primarily attributed to the adjusted C:N ratio (Yang *et al.*, 2021) and the low EC (Kazemi *et al.*, 2016), which was 10.43 – 31.52% lower. Nevertheless, according to X. Wang et al., (2019) and Q. Wang et al., (2016), The final outcomes of all trials are deemed to be above

the acceptable range for agricultural application (50%). The extract concentrations result of 75%, 50%, and 25% were 60.4%, 70.2%, and 80.5% in PM1; 65.4 ± 11.74, 76.2 ± 9.6, and 79.4 ± 14.01% in ShP2; 67.95 ± 11.5, 77.3 ± 7, and 89.6 ± 10.5% in CkS25; and 70.09 ± 7.7, 75.34 ± 13.2, and 92.5 ± 11.3% in CkS30, suggesting the potential for utilising the compost in lower doses by combined with a less toxic substance. After 60 days of composting, PM1 and ShP2 reached a GI of 87.5 ± 6 and 79.6 ± 5.4% respectively indicating its full maturation.

Conclusion

Conclusion

The research demonstrated the effectiveness of rotary drum composting in managing the composting process and regulating its various factors, leading to a usable end product in a reduced time frame compared to conventional methods, where all trials indicated a rapid initiation of the process, reaching peak temperatures within three days, with a thermophilic phase lasting a minimum of nine days and an overall active phase extending for at least sixteen days. During this stage, the temperature conditions were adequate to eradicate pathogens and facilitated the decomposition of complex compounds, including lignin. The high temperatures and prolonged thermophilic phase may have resulted from the high thermal conductivity of palm trash and numerous factors; Nonetheless, the reactor's insulation might be enhanced and modified to reduce thermal loss. In terms of the alteration of various factors throughout the process, significant variation was observed among the different factors and the trials. This can be attributed to several reasons, with the main one being the characteristics of the initial mix along with the amount of inter-factor overlap. The factors can be categorized into two groups: the first group, which tends to increase, includes pH, EC, BD, FAS and nutrient concentration (except carbon); the second group, which tends to decrease, encompasses organic matter, particle size, and moisture content. As for nitrogen, although it tends to rise, it depends on the predominant reaction and the surrounding conditions during the process.

The moisture content and nutritional balance, which are critical factors in initiating and sustaining bacterial activity and the overall process, were properly controlled. The arbitrary method utilized in PM1 and ShP2, along with the calculated approach implemented in CkS30 and CkS25, effectively attained optimal moisture levels necessary for the initiation of the process. Moisture content decreased over time in the majority of trials as a result of high temperatures and ongoing aeration, which included the opening of doors all the time, leading to a rapid loss of moisture. This loss probably led to the interruption of bacteria's activity at certain points of the process, especially in CkS30 and CkS25, which were carried out during heated seasons, thereby intensifying the moisture loss. The influence of nutritional balance on the initiation of the process was less significant than anticipated, in contrast to low ambient temperature, which resulted in a lag period in PM1. However, it had a clear impact on both the rate of organic matter decomposition and C:N ratio. CkS30 exhibited the highest decomposition rate, with an initial C:N ratio of 30, achieving a rate of 0.51, then CkS25, with an initial C:N ratio of 25, reached a decomposition rate of 0.49. The adjustments influenced the maturation of the final product, which remained within the acceptable range (C: N < 25) compared to other trials (PM1 and ShP2). This outcome demonstrates the effectiveness of the calculated approach and highlights its significance in optimizing the initial nutritional and moisture values.

In the comparison of poultry (PM1) and sheep manure (ShP2), poultry manure exhibited greater efficiency and bacterial activity, resulting in a higher decomposition rate of organic matter (K20 = 0.4595), comparable to the findings in the CkS group. It also produced more heat and had higher nutritional value than other trials, which suggests that it could be used as an additive in composting. At the same time, it is essential to address its environmental and soil effect.

Although CkS30 and CkS25 indicated initial signs of maturity, fortunately, the 20-day time frame of rotary drum date palm composting proved inadequate for achieving a fully matured and stabilized product. The germination index remained below 60% across all trials, with only PM1 and ShP2 surpassing this threshold following 60 days of composting. This may occur for many different reasons, with the main ones being The lignocellulosic-rich nature of date palm waste, which significantly contributes to its degradation issues, resulting in extended periods for decomposition; Large particle sizes restricted the microbe's accessibility, indicating that employing smaller sizes would enhance the process's effectiveness and/or Incorporating organisms that can degrade lignocellulosic materials at the beginning of the process could serve as an alternative method to enhance the efficiency of the process. The high electrical conductivity (EC) posed a significant obstacle from the outset of the date palm composting process, particularly with the additives employed, exhibited high EC levels that surpassed the permissible limits for soil application (>4 dS/m), hence diminishing the germination index. Immersing the feedstocks in water for several days before usage may be a pragmatic and essential approach to date palm waste composting and agricultural waste generally. The remaining factors exerted minimal influence on the procedure, as they were at acceptable levels from the outset of the process.

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Abstract

The date palm (Phoenix dactylifera L.) is an important crop in the MENA region, particularly in Algeria, where it is widely cultivated in areas like Biskra. This horticulture produces significant waste that needs to be recycled for sustainable development. Composting is a key method to recycle this agricultural waste, reducing reliance on chemical fertilizers and enhancing soil health. However, composting lignocellulosic wastes, like date palm waste (DPW), presents challenges due to its chemical properties that limit biodegradability. The current research utilized a cost-effective rotary drum bioreactor, which offers various advantages, to establish a decentralized system that enables farmers to manage waste effectively on their farms. Two compost preparation techniques were used. The first employed a ratio of 2:2:6 (DPW : Additives : Water) to achieve a moisture content of 60% , for 60 days composting, with poultry (PM1) and sheep manure (ShP2) as additives. The second approach accelerated decomposition by optimizing the initial moisture content and C:N ratio. A calculation technique was used to formulate a mixture with initial C:N ratios of 25 (CkS25) and 30 (CkS30), regarded as optimal for lignocellulosic composting by numerous studies, and included chicken litter as an additive for a 20-day period. To assist farmers with the mixture proportion calculations, an app was developed, taking into account their limited mathematics knowledge. In all trials, the bio-oxidation periods lasted 18 days, while the thermophilic phases lasted a minimum of 9 days. Throughout the trials, organic matter, moisture content, particle size, and wet bulk density showed a decreasing trend compared to their initial values, whereas other parameters exhibited an increasing trend. By day 20, all trial end products had a dark hue, a soil-like odor, and a low temperature. However, the germination index remained below the acceptable threshold for agricultural application (80%), with only the mixtures CkS25 and CkS30 recording a C:N ratios under 25. After 60 days, mixtures PM1 and ShP2 achieved a germination index around 80. In summary, the bioreactor and the mathematical approach proved effective in improving the initial mix; however, a 20-day period was insufficient for producing a fully mature and stable product.

Key Words : Date palm waste, Composting, Rotary Drum Bioreactor, Initial C/N ratio.

Résumé

Le palmier dattier (Phoenix dactylifera L.) est une culture importante dans la région MENA, en particulier en Algérie, où il est largement cultivé dans des régions comme Biskra. Cette horticulture produit des déchets importants qui doivent être recyclés pour un développement durable. Le compostage est une méthode clé pour recycler ces déchets agricoles, réduisant la dépendance aux engrais chimiques et améliorant la santé des sols. Cependant, le compostage des déchets lignocellulosiques, comme les déchets de palmier dattier (DPW), présente des défis en raison de ses propriétés chimiques qui limitent la biodégradabilité. La recherche actuelle a utilisé un bioréacteur à tambour rotatif rentable, qui offre divers avantages, pour établir un système décentralisé qui permet aux agriculteurs de gérer efficacement les déchets dans leurs fermes. Deux techniques de préparation du compost ont été utilisées. Le premier a utilisé un rapport de 2 :2 :6 (DPW : Additifs : Eau) pour atteindre une teneur en humidité de 60%, pendant 60 jours de compostage, avec de la volaille (PM1) et du fumier de mouton (ShP2) comme additifs. La deuxième approche a accéléré la décomposition en optimisant la teneur en humidité initiale et le rapport C : N. Une technique de calcul a été utilisée pour formuler un mélange avec des rapports initiaux C : N de 25 (CkS25) et 30 (CkS30), considéré comme optimal pour le compostage lignocellulosique par de nombreuses études, et a inclus la litière de poulet comme additif pendant une période de 20 jours. Pour aider les agriculteurs à calculer la proportion de mélange, une application a été développée, en tenant compte de leurs connaissances limitées en mathématiques. Dans tous les essais, les périodes de bio-oxydation ont duré 18 jours, tandis que les phases thermophiles ont duré au moins 9 jours. Tout au long des essais, la matière organique, la teneur en humidité, la taille des particules et la densité apparente humide ont montré une tendance à la baisse par rapport à leurs valeurs initiales, tandis que d'autres paramètres ont montré une tendance à la hausse. Au jour 20, tous les produits finaux d'essai avaient une teinte foncée, une odeur de terre et une température basse. Cependant, l'indice de germination est resté inférieur au seuil acceptable pour une application agricole (80%), seuls les mélanges CkS25 et CkS30 enregistrant des rapports C : N inférieurs à 25. Après 60 jours, les mélanges PM1 et ShP2 ont atteint un indice de germination d'environ 80. En résumé, le bioréacteur et l'approche mathématique se sont avérés efficaces pour améliorer le mélange initial ; cependant, une période de 20 jours était insuffisante pour produire un produit complètement mature et stable.

Mots-cles : Déchets de palmier dattier, Compostage, Bioréacteur rotatif à tambour, Rapport C/N initial.

الملخص

يعتبر نخيل التمر (فينيكس داكتيليفيرا إل) محصولا مهما في منطقة الشرق الأوسط وشمال إفريقيا، وخاصة في الجزائر، حيث يزرع على نطاق واسع في مناطق مثل بسكرة .تنتج هذه البستنة نفايات كبيرة تحتاج إلى إعادة تدويرها من أجل التنمية المستدامة .يعتبر التسميد طريقة أساسية لإعادة تدوير هذه النفايات الزراعية، وتقليل الاعتماد على الأسمدة الكيماوية وتعزيز صحة التربة .ومع ذلك، فإن تحويل نفايات الليغنوسيلولوسيكية إلى سماد، مثل نفايات نخيل التمر، يمثل تحديات بسبب خواصه الكيميائية التي تحد من قابلية التحلل البيولوجي .استخدم البحث الحالي مفاعلا حيويا ذو أسطوانة دوارة فعالة من حيث التكلفة، والذي يوفر مزايا مختلفة، لإنشاء نظام لامركزي يمكن المزارعين من إدارة النفايات بفعالية في مزارعهم .تم استخدام تقنيتين لإعداد السماد .استخدم الأول نسبة 2:6 :2(مخلفات نخيل: إضافات: ماء) لتحقيق محتوى رطوبة بنسبة 60 ٪، لمدة 60 يوما سماد، مع الدواجن (PM1) وروث الأغنام (ShP2) كإضافات .النهج الثاني تسارع التحلل عن طريق تحسين محتوى الرطوبة الأولي ونسبة الكربون للأزوت .تم استخدام تقنية حسابية لصياغة خليط مع نسب كربون لأزوت أولية بقيمة 25 (ShP25) و30 (ShP30)، والتي تعتبر الأمثل لتحويل المواد الليغنوسيلولوسيكية الى سماد وفق عدة دراسات، وشملت القمامة الدجاج كمادة مضافة لمدة 20 يوما .لمساعدة المزارعين في حسابات نسبة الخليط، تم تصميم تطبيق حاسوبي، مراعاة لمعرفتهم المحدودة بالرياضيات . في جميع التجارب، استمرت فترات الأكسدة الحيوية 18 يوما على الاكثر، بينما استمرت المراحل المحبة للحرارة لمدة 9 أيام على الأقل .خلال التجارب، أظهرت المواد العضوية ومحتوى الرطوبة وحجم الجسيمات والكثافة الظاهرية الرطبة اتجاها تنازليا مقارنة بقيمها الأولية، في حين أظهرت المعلمات الأخرى اتجاها متزايدا .بحلول اليوم 20، كانت جميع المنتجات النهائية التجريبية ذات لون داكن ورائحة تشبه التربة ودرجة حرارة منخفضة .ومع ذلك، ظل مؤشر الإنبات أقل من العتبة المقبولة للتطبيق الزراعي (80٪)، حيث سجلت الخلائط ShP25 وShP30 فقط نسبا كربون لأزوت أقل من 25 .بعد 60 يوما، حققت الخلائط بي PM1 وShP2 مؤشر إنبات حوالي 80. باختصار، أثبت المفاعل الحيوي والنهج الرياضي فعاليتهما في تحسين المزيج الأولي؛ ومع ذلك، كانت فترة 20 يوما غير كافية لإنتاج منتج ناضج ومستقر تماما.

.الكلمات المفتاحية : مخلفات نخيل التمر، التسميد (كموبستين)، مفاعل تسميد دوار، علاقة نتروجين/كربون الابتدائية