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THEME

**Study of Selected Maturity Indices of Compost Derived from
a Mixture of Date Palm Residues and Sewage Sludge**

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Dedication

We dedicate this modest work:

To our dear parents,

For their unconditional love, their sacrifices, and their constant prayers.

Thank you for always believing in us.

To our families, for their moral support and comforting presence during times of doubt.

To our teachers, who shared their knowledge with passion and dedication?

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List of abbreviations

EC: Electrical Conductivity

CEN: European Committee for Standardization (CEN)

EPA: Environmental Protection Agency

FAO: Food and Agriculture Organization

IPCC: The Intergovernmental Panel on Climate Change

OM: Organic Matter

ONA: National Sanitation Office

Org C: Organic Carbon

pH: Hydrogen Potential

PGR: Palm grove residues

SS: Sewage Sludge

T: Treatment

WTP: Wastewater Treatment Plant

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Abstract

Composting is an efficient biological process for recycling organic waste into a stable and environmentally safe product suitable for sustainable agriculture. This study aims to monitor the evolution of physical and physicochemical parameters and to assess certain maturity indices of co-compost prepared in piles from mixtures of palm grove residues (PGR) and sewage sludge (SS). Four formulations were tested: T1 (75% PGR + 25% SS), T2 (65% PGR + 35% SS), T3 (50% PGR + 50% SS), and T4 (75% SS + 25% PGR). Prior to and following the composting process, physical parameters (odor, visual changes, XDR, temperature) and physico-chemical parameters (pH, electrical conductivity, organic matter, organic carbon, total nitrogen, and heavy metals) were monitored and analyzed in all mixtures. After three months of composting, the results revealed differences in the sensory and physicochemical properties of the four mixtures. All final products except T1, exhibited a homogeneous and granular texture, dark brown color, and earthy odor, indicating a degree of stability and maturity typical of finished compost. A significant reduction in organic matter content and pH was observed, especially in mixtures with higher sludge proportions, reflecting substantial biological degradation. Meanwhile, electrical conductivity increased across all treatments, particularly in T4. Based on these findings, it can be concluded that, except for T1, the composts produced meet the criteria of a stable and hygienic product appropriate for sustainable agriculture in hot, arid climates.

Keywords: Composting, Palm Grove Residues, Sewage Sludge, Temperature, XDR, EC, pH, Sustainable Agriculture.

Résumé

Le compostage est un procédé biologique efficace pour recycler les déchets organiques en un produit stable et respectueux de l'environnement, adapté à l'agriculture durable. Cette étude vise à suivre l'évolution des paramètres physiques et physico-chimiques ainsi qu'à évaluer certains indices de maturité d'un co-compost préparé en tas à partir de mélanges de résidus de palmeraie (RP) et de boues d'épuration (BE). Quatre formulations ont été testées : T1 (75 % RP + 25 % BE), T2 (65 % RP + 35 % BE), T3 (50 % RP + 50 % BE) et T4 (75 % BE + 25 % RP). Avant et après le processus de compostage, les paramètres physiques (odeur, changements visuels, température) et physico-chimiques (pH, conductivité électrique, matière organique, carbone organique, azote total et métaux lourds) ont été suivis et analysés dans tous les mélanges. Après trois mois de compostage, les résultats ont révélé des différences dans le comportement sensoriel et physico-chimique des quatre mélanges. Les produits finaux, à l'exception du traitement T1, présentaient une texture homogène et granuleuse, une couleur brun foncé et une odeur terreuse, indiquant un degré avancé de maturité

typique d'un compost mûr. Une réduction significative de la teneur en matière organique et du pH a été observée, notamment dans les mélanges avec des proportions plus élevées de boues, traduisant une dégradation biologique importante. Par ailleurs, la conductivité électrique a augmenté dans tous les traitements, particulièrement dans T4. Sur la base de ces résultats, on peut conclure que, sauf pour T1, les composts produits répondent aux critères d'un produit stable et hygiénique, adapté à une utilisation en agriculture durable dans des conditions chaudes et arides.

Mots-clés : Compostage, Résidus de palmeraie, Boues d'épuration, Température, DRX, CE, pH, Agriculture durable

الملخص

التحلل الحيوي (الكمبوست) هو عملية بيولوجية فعالة لإعادة تدوير النفايات العضوية إلى منتج مستقر وآمن بيئيًا، مناسب للزراعة المستدامة. تهدف هذه الدراسة إلى متابعة تطور المعايير الفيزيائية والفيزيوكيميائية وتقييم بعض مؤشرات النضج للكمبوست المشترك المُعد في أكوام من خليط مخلفات بساتين النخيل (PGR) والحماة الصرف الصحي (SS). تم اختبار أربع تركيبات (T1 : 75% PGR قبل وبعد عملية التحلل، تم مراقبة وتحليل المعايير الفيزيائية (الرائحة، التغيرات المرئية، درجة الحرارة) والمعايير الفيزيوكيميائية (درجة الحموضة، الموصلية الكهربائية، المادة العضوية، الكربون العضوي، النيتروجين الكلي، والمعادن الثقيلة) في جميع الخلطات. بعد 90 يومًا من التحلل، أظهرت النتائج اختلافات في السلوك الحسي والفيزيوكيميائي للخلطات الأربعة. أظهرت المنتجات النهائية، باستثناء المعالجة T1، قوامًا متجانسًا وحببيًا، ولونًا بنيًا داكنًا، ورائحة ترابية، مما يشير إلى درجة متقدمة من النضج النموذجي للكمبوست الناضج. لوحظ انخفاض كبير في محتوى المادة العضوية ودرجة الحموضة، خاصة في الخلطات ذات النسب الأعلى من الحماة، مما يعكس تحللًا بيولوجيًا كبيرًا. في الوقت نفسه، زادت الموصلية الكهربائية في جميع المعالجات، لا سيما في T4 بناءً على هذه النتائج، يمكن الاستنتاج أنه، باستثناء T1، تلبى أنواع الكمبوست المنتجة معايير منتج مستقر وصحي، مناسب للاستخدام في الزراعة المستدامة في الظروف الحارة والجافة.

الكلمات المفتاحية : التحلل الحيوي، مخلفات بساتين النخيل، حماة الصرف الصحي، الحرارة، درجة الحموضة الموصلية الكهربائية، الزراعة المستدامة.

General Introduction

General Introduction

Rapid urbanization, industrialization, and economic development have significantly increased waste generation worldwide. Over time, both the volume and complexity of waste have grown due to expanding human activities and the adoption of unsustainable practices. Inefficient waste management exacerbates various environmental problems, including increased greenhouse gas emissions, pollution of air, soil, and water, and adverse health effects (**Fuchs et al., 2001; Ferronato & Torretta, 2019; Kaur & Kaur, 2024**). For example, when waste is dumped untreated in landfills, it decomposes under uncontrolled anaerobic conditions, producing methane a potent greenhouse gas and potentially degrading soil quality.

Since large portions of these wastes are organic, recycling them through biological processes could help address the humus deficit in overexploited soils (**Gobat et al., 2003**).

Furthermore, soil fertility decline due to intensive or inappropriate agricultural practices is observed in both industrialized and developing countries. This results in a loss of stable organic matter in soils and increased plant susceptibility to diseases (**Larbi, 2006**). This issue is particularly severe in arid regions, where soil organic matter rarely exceeds 1% (**Halitim, 1988**).

On the other hand, arid regions are also prone to desertification, characterized pedologically by a marked decline in soil fertility across physical, chemical, and biological dimensions (**Tejada et al., 2006; Lakhdhar et al., 2008**), mainly due to organic matter depletion (**Albaladejo et al., 2000; Wang et al., 2010; Dlamini et al., 2014**). Farmers and ecologists must therefore develop innovative waste management strategies that preserve the environment by reducing pollution and degradation of natural and agricultural ecosystems.

In this context, composting is currently regarded as an ecologically sustainable component of integrated waste management systems. It offers a durable solution that reduces emissions, improves soil fertility, decreases reliance on chemical fertilizers, and helps combat climate change while valorizing organic waste for agriculture and environmental benefits (**Manzekele, 2008**). Recycling organic waste after appropriate biological treatment can produce valuable organic matter, which is especially beneficial for agriculture in arid regions (**Hassen et al., 1998**). Composting is widely considered an economically viable, hygienic, and ecologically sound waste management system (**Liang et al., 2017; Doña-Grimaldi et al., 2019; Abid et al., 2020**).

Thus, developing composting processes is essential for safely reducing the mass and volume of organic waste and mitigating the negative impacts of using fresh organic waste directly (**Bernai et al., 1998**). Moreover, composting locally reduces transportation and treatment costs while producing a sustainable, local fertilizer, thereby supporting a circular economy. Numerous studies confirm that

composting is an ideal treatment that meets these conditions within accessible financial limits **(Bayard & Gordon, 2007; Lobna, 2014)**.

Applying compost to soil improves its physical, chemical, and biological properties and restores organic matter. Compost contains a high concentration of organic materials and helps replenish soil properties depleted by continuous cultivation. Through gradual mineralization, compost also acts as an organic fertilizer, supplying nitrogen, phosphorus, potassium, and trace elements to plants **(Helene & Geeta, 2015)**.

However, the environmental and soil fertility benefits of composting only materialize if the compost reaches an adequate degree of maturity, which is assessed using various maturity indices. Many organic substrates contain contaminants that prevent their direct application to the environment without proper

In the case of sludge from wastewater treatment systems, they are recognized for their fertilizing power due to their content of organic matter, nitrogen, phosphorus, and trace elements **(Bousselhaj, 2007)**. However, sludge from treatment plants can also contain trace metals (Cr, Zn, Cd, Hg, Pb, etc.) **(Amir et al., 2001, 2005 ; Jouraiphy, 2007)**, organic pollutants (phthalates, PCBs, PAHs, etc.) **(Amir et al., 2005)**, which may cause harmful effects on receiving environments, as well as emerging pollutants such as antibiotics **(Khadra et al., 2012)**, among the 30,000 chemical substances produced in quantities exceeding standards **(Giger, 2003)**. These elements limit the agricultural reuse of sludge, which requires ensuring their safety before any use. Furthermore, sludge from treatment plants is rich in pathogenic germs and parasites, notably protozoa such as amoebae **(Tønner-Klank et al., 2007; Marcinkowski, 2010; Utzinger et al., 2011)**, highlighting the need to optimize sludge treatment and elimination processes during the design of treatment plants.

In Algeria, sludge from treatment plants represents a major environmental challenge for the sanitation sector. It is often disposed of without prior treatment or recovery, leading to increasing risks for the environment and health, especially in southern regions where infrastructure is poorly developed. In the province of Touggourt, sludge is directly dumped in landfills or abandoned on unprotected sites, thus threatening the environment and groundwater resources **(Bensaid et al., 2021)**.

While several developed countries have implemented effective strategies for organic waste recovery, such as incineration, anaerobic digestion, or thermal treatment, Algeria does not yet have a clear policy on this issue, making the search for alternative local solutions an urgent priority **(Bouguerra et al., 2022)**. In this context, the reuse of sludge in agriculture is arousing growing interest because of its richness in organic matter and mineral elements favorable to plant growth, provided that its toxic and pathogenic components are rigorously controlled **(Khelifi et al., 2023)**.

The use of organic waste, particularly sludge from municipal wastewater treatment, has attracted considerable interest, with some of this waste, such as sewage sludge, having demonstrated its ability to maintain soil fertility and improve plant growth (**Gay & Dalvai, 2014**).

For the Touggourt wastewater treatment plant, sludge production is estimated at approximately 4,375 kilograms per day, which represents a significant organic resource that can be recovered in compost production (**Office National de l'Assainissement ONA, n.d**).

Furthermore, the annual maintenance of palm groves in oasis regions generates a significant amount of organic matter. The accumulation of this waste in the oasis environment can cause numerous environmental problems, highlighting the importance of its recycling (**Laouar et al., 2020; Oustani et al., 2022**). Producing compost from local materials, such as plant residues from palm groves, ensures autonomy in the supply of organic matter, reduces production costs, and guarantees the sustainable maintenance of the palm groves (**Chakroune, Bouakka, & Hakkou, 2005; Tirichine et al., 2017; Oustani et al., 2022**).

Integrating activated sludge with palm residues offers an environmentally and economically viable solution, promoting the recycling of organic waste while enhancing the properties of agricultural soils. This study proposes a new low-cost approach based on co-composting sludge with palm grove residues, which are abundantly available in southern Algeria and are often disposed of or incinerated indiscriminately. Using palm fronds, leaves, and fibers as a carbon source combined with nitrogen-rich sludge can form the basis of a local agricultural compost that meets the needs of arid soils while reducing the environmental impact of sludge.

Thus, the primary objective of this study is to characterize and monitor the evolution of certain physical and physicochemical parameters of compost made from oasis residues mixed with activated sludge from wastewater treatment plants in varying proportions, with the aim of obtaining hygienized, stable organic matter with high agronomic value. The study relies on internationally recognized maturity and stability indicators to ensure the compost's suitability for agricultural use.

This work is structured into three parts:

- The first part is devoted to a literature review covering the general principles and benefits of composting;
- The second part describes the materials and methods used to implement the experimental approach;
- Finally, the third part presents the results obtained, accompanied by a detailed discussion and a general conclusion

Chapter I

Literature Review

I.1. Definition

➤ What is compost?

Compost is a stable, aerobic, humus-rich soil material derived from the decomposition of organic waste. It is known as a valuable soil amendment, improving soil structure, water retention, microbial diversity, and nutrient content. Recent definitions proposed by the European Environment Agency (**EEA, 2023**) define compost as "a biologically stabilized, sanitized product of the controlled aerobic degradation of organic materials that may be used as a soil conditioner for agriculture, horticulture and for land reclaiming". When finished, compost is dark brown to black, has a crumbly texture, and smells like a forest floor. Its use has been found to decrease soil erosion, allelopathy, and to increase long-term fertility of the soil

➤ What is composting?

Composting is "a natural biological process under controlled aerobic conditions that converts organic wastes into stable humus-like products using a complex of microorganisms including bacteria, fungi, and actinomycetes," according to the Food and Agriculture Organization (**FAO, 2021**).

I.2. Principle of composting

Composting is essentially a regulated aerobic bioconversion process by which organic materials (e.g., agricultural residues, food wastes, and biosolids) are subjected to microbial decomposition generating relatively stable humus and pre-humus compounds. This degradation is mainly due to successive mesophilic and thermophilic microorganisms degrading readily degradable compounds and then the subsequent maturation of lignin-rich fractions (**Li et al., 2024**). The C/N ratio decreases gradually and heat is generated in microbial respiration during composting, and a humic substance is produced through the mineralization of OM, to improve soil quality. It is similar to the natural process, but is speeded up by optimum conditions of moisture, aeration, and temperature.

According to **Zhang et al. (2023)**, composting represents a sustainable waste valorization route by converting organic residues into environmentally safe and agronomically beneficial material. The final compost product is microbiologically stable, low in phytotoxicity, and rich in humic acids, making it suitable for use as a soil conditioner and nutrient carrier.

I.3. Types of materials used in composting

I.3.1. Plant residues and green waste

Green plant wastes: All plants waste, that originates from the conservation of green areas, parks, glasshouses, sport fields and private gardens. This category includes mostly dead leaves, grass clippings, hedge / shrub cuttings, residues from pruning, and garden maintenance (whether by local authorities, business or householder). These wastes are subject to seasonal variations, particularly due to the vigorous growth of vegetation in spring (increased lawn mowing, pruning, etc.).

From a regulatory standpoint, green waste is classified as biowaste (**Régional des Déchets et de l'Économie Circulaire en Occitanie**).

I.3.2. Sewage Sludge

According to the European Committee for Standardization (CEN) sludge is a mixture of water and solid materials, separated by natural or artificial processes from various types of water that contain it." Wastewater treatment plant sludge is the material generated by a wastewater treatment plant when treating sewage. After all, the water humans drink or use in their homes and works inevitably is wasted. Waste water is channeled through sewers to treatment plants where it is cleansed before returning to its natural environment. The purification in such plants enables to isolate the purified water from a secondary residue, the sludge, that is rich in organic substance, nitrogen, phosphorous, and trace elements. On the one hand, wastewater treatment eliminates the most easily degraded fraction of the organic matter and, on the other the various compounds carried by the water (food debris, fats, textile and cellulosic fibers, soaps, detergents, and cleaning agents) before its reintroduction into the water cycle. (**Jardé, É. (2003)**).

I.3.3 Animal Manure

Animal manure is considered one of the best organic materials used in composting due to its richness in essential nutrients that enhance soil fertility and support plant growth. Manure from cows, sheep, and horses can be used, provided it has undergone adequate decomposition to avoid the spread of pathogens and unpleasant odors. It is also recommended to mix manure with carbon-rich materials like straw or dry leaves to achieve a balanced composting process. (**Keena, 2023**).

I.3.4. Household Waste

Household waste suitable for composting includes food scraps such as fruit and vegetable peels, tea bags, and coffee grounds. These materials are rich in organic matter that benefits the soil. However,

it is important to carefully sort this waste and ensure it is free from plastic, metals, or cleaning agents. Meat, dairy products, and greasy substances should be avoided, as they can lead to rapid spoilage, foul odors, and attract pests, hindering the composting process (EPA, n.d.)

I.4. Composting Phases

According to Nemet et al. (2021), the composting process takes place in two successive stages:

1. A fermentation stage: which is itself divided into three phases, each characterized by a specific temperature range and microbial flora:
 - Mesophilic phase: activity of mesophilic microorganisms, with the temperature rising to around 40°C.
 - Thermophilic phase: thermophilic microorganisms take over, and the temperature increases to between 60°C and 70°C.
 - Cooling phase: the temperature decreases, becoming favorable again for mesophilic microorganisms and fungi.
2. A compost maturation stage: During this phase, the temperature drops below 30°C, and bacteria are largely replaced by fungi, which stabilize the organic matter in the form of humic compounds.

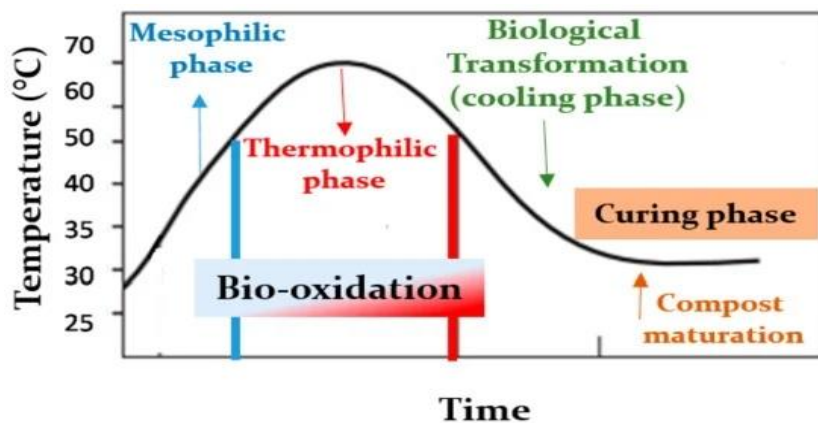


Figure 01: Composting phases (Papale et al., 2021)

I.5. Composting Parameters

The chemical composition of organic substrates used in composting varies widely and plays a critical role in determining the efficiency, duration, and quality of the composting process. Composting is driven by microbial metabolism, in which heterotrophic microorganisms secrete enzymes to degrade complex organic compounds (e.g., lignin, cellulose, proteins) into simpler nutrients such as amino

acids, sugars, and minerals. These nutrients are absorbed and utilized by the microbial community for growth, reproduction, and respiration. Consequently, the availability of nutrients such as carbon, nitrogen, phosphorus, potassium, and sulfur fluctuates throughout the composting phases (mesophilic, thermophilic, maturation), necessitating careful monitoring. (Kong et al., 2024).

I.5.1. Physical parameters

I.5.1.1. Temperature

Two predominant phase temperatures dominate the composting process:

- **Mesophilic** 20°C and 45°C Follows the hydrolytic phase, when a wider range of microorganisms starts to degrade the organic matter.
- **Thermophilic stage:** Occurring at 50°C to 70°C, is dominated by high microbial activity, which speeds up the decomposition and kills many pathogens.

The high temperatures are not only a sign of effective aerobic decomposition but also work to sterilize the compost by killing off pathogens (>55 C) and weed seeds (>62 C). Thus, turning and aeration are key practices for effective temperature management in composting, ensuring efficient decomposition and high-quality compost production. (Azim, 2017).

I.5.1.2. Moisture

All microbial life requires some amount of moisture. The optimal range is 40–65%:

- **Under 40%:** Water is less available and microbial activity slows.
- **Over 65%:** fosters anaerobic environment that can lower the quality of compost.

The initial moisture should be at 50–60% and on maturity, it should be down to ~30% for stabilization and humification. (Azim et al., 2017).

I.5.1.3. Aeration

Aeration provides the oxygen needed for the aerobic bacteria involved in composting. It is necessary for :

- Supporting microbial respiration
- Maintaining optimal decomposition rates
- Preventing the development of anaerobic conditions and odors
- Ensuring proper heat generation during composting
- Making the heat easily transpire, and would remove out the moisture in the water.

An effective aeration is very important, particularly in the thermophilic phase (Azim et al., 2017).

I.5.2. Chemical Parameters

I.5.2.1. pH

According to **Azim et al. (2017)**, the pH level undergoes a characteristic series of changes throughout the composting process.

Initially, the compost mixture typically starts with a near-neutral pH, ranging from 6.5 to 7.0. In the early stages, a period of acidification often occurs, which can lower the pH to between 5.5 and 6.0. This drop is caused by the breakdown of complex organic matter and the subsequent formation of organic acids by microorganisms.

As the process moves into its later phases, a distinct rise in pH is observed, with levels potentially reaching up to 8.0. This increase is primarily attributed to the release of ammonia as nitrogen-rich compounds are decomposed, as well as the consumption of the previously formed organic acids by other microbial communities.

Finally, as the compost reaches maturity, the pH level stabilizes, indicating that the major decomposition processes have slowed and the final product is stable.

I.5.2.2. Nitrogen

Nitrogen in compost primarily exists in organic forms such as (amino acids, proteins, and nucleic acids ...etc.) (**El Fels , 2014**). During composting, nitrogen undergoes:

- **Ammonification:** Conversion of organic N into ammonia ($\text{NH}_3/\text{NH}_4^+$)
- **Nitrification:** Oxidation of ammonia into nitrite (NO_2^-) and then nitrate (NO_3^-) under aerobic conditions.

I.5.2.3. Organic Matter (OM)

Organic matter is the energy and carbon source for microbial communities and is gradually decomposed into CO_2 , H_2O , and humic substances through several microbial stages (**Chen et al., 2024**).

- **Primary Decomposition:** Involves breakdown of simple molecules (sugars, amino acids, lipids).
- **Secondary Decomposition:** specialized microorganisms metabolize resistant biopolymers (cellulose, lignin).
- **Humification:** Results in humic substances that improve soil texture and nutrient retention.

I.5.2.4. C/N Ratio (Carbon-to-Nitrogen Ratio)

The C/N ratio is a critical indicator of compost balance and microbial activity. According **Kong et al. (2024)**, microorganisms use carbon as an energy source and nitrogen for protein synthesis. A high initial C/N slows decomposition, while low ratios result in ammonia loss and odor. Blending materials (e.g., grass with sawdust) helps achieve optimal C/N levels. The initial and final mature compost range of C/N ratio are, respectively 25:1 to 35:1 and 10:1 to 15:1.

I.5.2.5. Electrical Conductivity (EC)

Electrical conductivity (EC) measures the soluble salt content of compost. High EC indicates the presence of mineralized nutrients (e.g., K^+ , Na^+ , Cl^-). Chen and Liang (2025) distinguish two classes of EC for compost:

- Optimal EC for mature compost: 1.5 to 3.5 mS/cm
- High EC (>4 mS/cm) may be phytotoxic for seedlings and salt-sensitive species

I.5.3. Biological Parameters

I.5.3.1. Microorganisms

The biological engine of the composting process is a diverse and dynamic community of microorganisms, primarily of soil origin, including bacteria, fungi, actinomycetes, protozoa, and certain algae.

These organisms are usually native to the organic substrates being composted and initiate decomposition spontaneously, unless the substrate is extremely dry, acidic, or has been sterilized (e.g., post-industrial or post-thermal residues) (**López et al.,2021**).Waste contains the germs of its own decomposition"; in other words, composting rarely requires microbial inoculation (**Kiruba & Saeid, 2022; Glockow et al., 2024**).

Key Microbial Groups Involved in Composting

- **Bacteria**
 - Rapid colonizers in early (mesophilic) stages
 - Degrade simple organic compounds (sugars, amino acids, organic acids)
 - Includes genera like Bacillus, Pseudomonas, Clostridium (**Verma et al., 2023**)
- **Actinomycetes**
 - Thrive in thermophilic and curing phases

- Decompose cellulose, chitin, and lignin
- Produce antibiotics that suppress pathogens (**Satopathy et al., 2024 ; Verma et al., 2023**)
- **Fungi (Mycetes)**
 - Prefer slightly acidic conditions and lower moisture
 - Efficient at degrading complex plant polymers (e.g., lignocellulose)
 - Includes Aspergillus, Penicillium, and Trichoderma (**Kiruba & Saeid, 2022**)
- **Protozoa**
 - Secondary consumers that regulate bacterial populations
 - Contribute to nutrient cycling via grazing (**Satopathy et al., 2024**)
- **Algae**
 - Less common, but present in surface-exposed, moist zones
 - Contribute oxygen and assist in early-stage microbial colonization (**Glockow et al., 2024**)

I.5.3.2. Macroorganisms

Macro-organisms are the visible beings involved in the transformation of organic matter into compost. They are particularly active in the final stages of compost maturation when temperatures decrease but decomposition is not yet complete. (**Chauv et al., 2021**).

I.6. Composting processes

I.6.1. Static pile composting

Pile composting is the simplest and quickest method, ideal for small gardens. In this technique, organic waste is placed directly on the ground to form a pile with a height ranging between 0.5 meters and 1.5 meters. It is essential to choose an appropriate location for this pile to ensure the success of the biological decomposition process. The pile should be:

- In a shaded area, to protect the materials from direct sunlight exposure, which could affect the activity of microorganisms.
- Sheltered from dry winds, which could dry out the pile materials.
- Protected from excess water due to rain, which could cause anaerobic decomposition instead of proper degradation.

It is important to turn the pile regularly to ensure good aeration, which helps activate Autrement. (**2024, 12 juillet**).



Figure 02: Static pile composting (Moon, 2020)

I.6.2. In-Vessel composting

Container composting refers to a set of methods that confine the materials to be composted within a building, a container, or a bin. These methods are based on forced aeration and mechanical turning techniques aimed at accelerating the composting process. Many methods combine the techniques of windrows and aerated piles in order to overcome the weaknesses and exploit the advantages of each method. (Mokrane, E. (s.d.)).



Figure 03: In-Vessel Composting (Goldstein,2023)

I.6.3. Windrow Composting

Composting in windrows involves placing a mixture of raw materials in long, narrow piles called windrows, which are regularly turned or stirred. These windrows are aerated mainly through passive or natural air movement (convection and gas diffusion). The rate of air exchange depends on the porosity of the windrow. Thus, the size of a windrow that can be effectively aerated in this way

is determined by its porosity. A windrow made of leaves can be much larger than a wet windrow containing manure. (Mokrane, (s.d.).



Figure 04: Windrow composting. Viably (n.d.).

I.6.4. Vermicomposting

Vermicomposting is a natural composting process that uses earthworms to break down organic waste. It's a way to convert waste into a valuable soil amendment, known as vermicompost. (Misra, Roy, & Hiraoka, 2003).



Figure 05: Vermicomposting (Nurserylive, n.d)

I.7. Compost Maturity

I.7.1. Definition and importance of compost maturity The safe and effective use of compost in agriculture and forestry relies on achieving a high degree of maturity and stability. These two interrelated parameters ensure that the compost is free of phytotoxic compounds, unstable organic fractions, and pathogenic organisms that may adversely affect plant growth or environmental quality (Peña et al., 2020; Mahapatra et al., 2022).

Compost maturity refers to the degree of biological transformation of organic matter into stable humic substances that are non-toxic to plants and promote seed germination and seedling development (Manea et al., 2024).

Compost stability, in contrast, denotes the extent to which microbial activity has subsided and biodegradable materials have been fully decomposed. Stability is often measured by parameters like oxygen uptake rate (OUR) or CO₂ evolution (Mahapatra et al., 2022). According Peña et al., (2020); Manea et al. (2024), a stable and mature compost is linked to:

- Higher soil biological activity ;
- Improved nutrient availability ;
- Enhanced plant disease suppression ;
- Reduced greenhouse gas emissions . (Peña et al., 2020; Manea et al., 2024)

I.7.2. Classification of maturity indices

I.7.2.1. Physical Indices

These indicators allow a visual and sensory assessment of the compost's condition:

- Temperature: It should stabilize at a value close to that of the surrounding environment, indicating a decrease in intense microbial activity.
- Odor: A pleasant smell of moist earth is expected; the absence of foul odors is a sign of maturity.
- Visual appearance: Mature compost is dark in color, has a homogeneous appearance, and a crumbly texture.
- Particle size: A well-aerated and granular structure is desirable; particles that are too fine can cause the compost to become oxygen-deprived. (El Fels, 2014).

I.7.2.2. Chemical Indices

These indicators are used to quantify the stability of organic matter:

- C/N ratio: Should be between 10 and 15; a value below 12 indicates good maturity.
- pH: A neutral to slightly alkaline pH (between 7 and 9) is a good indicator of stability.
- Electrical conductivity (EC): Reflects the availability of nutrients; moderate EC indicates a balanced compost.
- Mineral nitrogen (NH₄⁺/NO₃⁻ratio): A value below 1 is typical of well-matured compost.
- Humic and fulvic acids: The proportion of humic acids increases with maturation, while fulvic acids decrease; the humification index (HI) can be used as an additional criterion.

- Nutrients (N, P, K): Their concentration increases as decomposition progresses, improving the agronomic value of the compost. (El Fels, 2014).

I.7.2.3. Biological indices

According to Mahapatra et al. (2022), biological indices for evaluating compost maturity include:

- Respiratory activity: Low oxygen consumption or CO₂ production indicates a stable compost.
- Enzymatic activity: Reflects the ongoing microbial dynamics within the compost
- Phytotoxicity tests: Measure the effect of compost extracts on seed germination; a germination index above 50% is generally acceptable.
- Germination Index The germination index is used to measure compost maturity.
- Microbial communities: The qualitative evolution of microbial flora reflects the different stages of composting and can indicate the maturity of the final product (El Fels, 2014).

I.8. Quality of Mature Compost

I.8.1. Agronomic Qualities

- **Improvement of soil structure (aeration, water retention):**
Mature compost enhances soil aggregation, porosity, and water-holding capacity, which improves both aeration and resilience to drought stress (Oued Lhaj et al, 2024).
- **Supply of stable organic matter and nutrients (N, P, K):**
Mature compost acts as a slow-release source of essential macro- and micronutrients, reducing leaching and improving nutrient use efficiency (Paradelo et al., 2023).
- **Enhancement of soil biological activity:**
Compost increases microbial biomass and enzymatic activity, fostering beneficial rhizosphere interactions (Ciavatta et al., 2022).
- **Reduction of phytotoxicity and improved germination rates:**
Properly matured compost reduces phytotoxic compounds (e.g., volatile organic acids) and improves seedling emergence (Karimi, Raza, & Mechri, 2024).

I.8.2. Economic Advantages

- **Reduction in cost of chemical fertilizers:**
Farmers using compost report significant savings due to reduced dependency on synthetic fertilizers (Karimi et al., 2024).

- **Local recovery of organic waste (circular economy):**
Composting promotes localized waste valorization and contributes to bioeconomy models (Paradelo et al., 2023).
- **Compost as a marketable organic soil amendment:**
High-quality compost is increasingly traded as a certified organic input in agroecological systems (Oued Lhaj et al., 2024).
- **Reduced waste management costs:**
Municipalities save significantly on landfill and transport costs through composting infrastructure (Ciavatta et al., 2022).

I.8.3. Practical Aspects

- **Ease of handling and application:**
Mature compost is typically dry, friable, and easy to spread using standard agricultural equipment (Karimi et al., 2024).
- **Homogeneous texture and minimal odor:**
Stable compost is characterized by a uniform, earthy smell and absence of ammonia or sour odors (Paradelo et al., 2023).
- **Stable preservation with no reactivation of microbes:**
Mature compost retains its properties in storage without microbial reactivation or heating, indicating stability (Ciavatta et al., 2022).
- **Hygienization and pathogen removal:**
Composting under thermophilic conditions ensures sanitation and removal of helminth eggs and pathogens (Oued Lhaj et al., 2024).

I.8.4. Environmental Benefits

- **Reduction of organic waste sent to landfills**
Composting diverts food and green waste from landfills, decreasing methane emissions.
- **Decrease in greenhouse gas emissions:**
Substituting compost for synthetic fertilizers reduces N₂O emissions and enhances soil carbon sequestration.
- **Protection of natural resources:**
Compost improves soil water retention and reduces erosion risks on sloped or degraded land.

➤ **Support for sustainable agriculture:**

Compost aligns with agroecological models and regenerative practices, enhancing long-term farm resilience (**Teixeira et al. (2021)**).

I.9. Application of compost in agriculture

The application of compost in agricultural systems represents a climate-smart and ecologically sustainable practice that improves soil health, nutrient cycling, and crop productivity, while also mitigating greenhouse gas emissions.

Compost use significantly enhances soil organic carbon (SOC) stocks, increases microbial biodiversity, and reduces reliance on synthetic fertilizers, thus aligning with global sustainability goals such as those set by the **FAO** and **IPCC (2022)**.

Despite these well-documented benefits, the adoption of composting practices remains suboptimal in many developing countries. Several interlinked constraints contribute to this underutilization:

- Lack of farmer awareness and education on composting benefits, maturity indicators, and best practices remains a key obstacle.
- Insufficient technical infrastructure and limited access to training programs hinder the development of local composting initiatives.
- Economic and logistical limitations such as high labor requirements, transportation costs, and inconsistent compost quality affect both production and market accessibility.

In regions where compost adoption has been successfully promoted, such as parts of Latin America, South Asia, and East Africa, the results include improved crop yields, enhanced soil fertility, and increased climate resilience among smallholder farms. To achieve wider implementation, future strategies should focus on:

- Capacity-building and farmer-to-farmer knowledge transfer
- Decentralized compost production systems
- Public-private partnerships for supply chain development
- Incentives and certification systems for compost quality assurance

Compost application is not only a tool for organic enrichment but a transformative solution for regenerative agriculture, soil carbon restoration, and sustainable rural livelihoods.

I.10. Agronomic Benefits of Mature Compost

I.10.1. Effects of Compost on the Physical and Physicochemical Properties of Soils

Compost incorporation generally improves several key physical and physico-chemical soil properties:

- **Improvement of soil structure**

Compost application promotes soil aggregation, enhances macro-porosity, and reduces bulk density, all of which are essential factors for plant root penetration and aeration.

- **Increase in water retention capacity**

Mature compost enhances water-holding capacity by increasing soil organic carbon and modifying pore size distribution.

- **Stabilization of pH and improved CEC**

Compost buffers soil pH in acidic and alkaline soils and improves cation exchange capacity, enhancing nutrient availability.

- **Long-term fertility via stable organic matter**

Stable humified organic matter in compost sustains fertility and carbon sequestration over time.

I.10.2. Effects of Compost on Biological Properties

Compost application can have several effects on the biological properties of soil:

- **Stimulation of microbial biomass and enzymatic activity**

Compost-amended soils show increased microbial respiration, enzyme activity (e.g., dehydrogenase, phosphatase), and microbial biomass carbon.

- **Improved microbial diversity**

Compost applications foster actinomycetes, beneficial fungi (e.g., *Trichoderma*), and rhizobacteria, enhancing disease suppression and soil health.

- **Suppression of pathogens through competition and antimicrobials**

Compost reduces pathogen loads by encouraging microbial antagonism and generating natural antimicrobial compounds. (Lepesteur, 2022).

I.10.3. Effects on Plants in Forestry

Compost use in forestry supports plant growth by improving soil physical, chemical, and biological properties, enhancing nutrient availability, and promoting sustainable forest ecosystem restoration and productivity.

- **Improved germination and early seedling growth**

Compost-enriched substrates significantly increase the emergence rate and biomass of seedlings such as *Quercus* spp., *Pinus* spp., and *Eucalyptus globulus*.

➤ **Enhanced tolerance to abiotic stress**

Compost-treated seedlings exhibit greater resistance to drought and nutrient-deficient conditions via better root development and soil water dynamics.

➤ **Nutrient enrichment of forest substrates**

Compost provides a balanced supply of macro (NPK) and micro (Fe, Zn, Mn) nutrients, fostering robust root systems and shoot biomass. (Zhang et al. (2023)).

➤ **Increased soil organic matter and carbon sequestration**

Compost adds stable organic matter to forest soils, improving soil fertility and contributing to long-term carbon storage, which benefits both plant growth and climate mitigation (Raihan et al., 2024).

I.11. Effectiveness on Air and Water Quality

The use of mature compost offers several environmental benefits, particularly for air and water quality. By improving soil structure and its capacity to retain water and nutrients, compost reduces runoff and leaching of chemical fertilizers, which decreases pollution of groundwater and surface water.

Additionally, by enriching the soil with organic matter, compost promotes the presence of beneficial organisms. This reduces the need for pesticides and synthetic fertilizers, which are often sources of air and water pollution.

Moreover, compost helps sequester carbon in the soil, limiting emissions of greenhouse gases such as CO₂. This has a positive impact on air quality and contributes to the fight against climate change (EPA (Environmental Protection Agency)).

I.12. Risks Associated with the Use of Immature Compost

The application of immature compost poses several agronomic and ecological risks due to its unstable biochemical composition and high content of undecomposed organic matter. One of the primary concerns is an excessively high carbon-to-nitrogen (C/N) ratio, often resulting from the presence of lignocellulosic residues such as leaves, twigs, and straw.

This condition induces a phenomenon known as “nitrogen immobilization” or nitrogen starvation, wherein soil microbial communities consume available soil nitrogen to decompose carbon-rich substrates, thereby reducing nitrogen availability to plants (Kong et al., 2024; Wei et al., 2021). As

a consequence, affected plants may exhibit chlorosis (leaf yellowing), stunted growth, or even developmental arrest for several weeks.

Additional negative outcomes include the release of phytotoxic intermediates such as volatile organic acids and ammonia, as well as increased risk of pathogen proliferation due to insufficient thermophilic sanitation during composting. To prevent these issues, it is essential to ensure compost maturity before application, which includes:

- Achieving a C/N ratio below 20, preferably around 10–15.
- Maintaining a stable temperature near ambient levels for at least two weeks.
- Using mechanical screening (5–10 mm mesh) to eliminate coarse undecomposed materials.
- Verifying phytotoxicity reduction via germination tests or respiration rate analysis.

If immature compost must be used, it should be amended with nitrogen-rich supplements such as blood meal, poultry manure, fermented nettle extract, or diluted urine, to rebalance the nutrient profile and support microbial mineralization. However, such use is discouraged in high-value or nitrogen-sensitive cropping systems.

Chapter II

Material and Methods

II.1. Objective of the trial

This work contributes to the promotion of sustainable agricultural practices in arid regions particularly in Sahara regions. It aims to study the evolution of physical and physicochemical parameters and to determine certain maturity indices of co-compost prepared from four different mixtures of residual sludge, palm residues, and other palm grove waste. This comparative analysis will provide a better understanding of the individual behavior of each organic mixture, with the goal of making necessary adjustments to optimize the composting process in the future.

II.2. Study Area

The site selected for the implementation of the pile composting experiment was the university's agricultural farm, located approximately 6 km southeast of the city of Ouargla, at the following approximate geographical coordinates: latitude 31.95° N and longitude 5.33° E (Google, 2025) (Figure 06).



Figure 06: Experimental area of study (Google 2025 maps)

II.3. Work methodology

II.3.1. Organic substrates used

The technical conditions of the composting process were properly followed, including regular aeration, a balanced ratio of carbon-rich and nitrogen-rich materials, and the maintenance of appropriate moisture levels.

II.3.1.1. Palm grove residues

Palm grove residues are often abandoned or burned, represent a significant and underutilized biomass. Their recovery through composting offers an ecological solution for producing high-quality organic amendment while contributing to sustainable waste management in oasis regions (Figure 07).

➤ Date palm residues

A wide range of organic materials resulting from maintenance operations, pruning, and the natural growth cycle of palm trees. Among these residues are kornaf (coarse fiber at the base of the fronds), dead leaves, and arjoun (the dry stalk that holds the date clusters). For this study, the date palm residues were collected from the experimental farm of the University of Ouargla Ouargla (Figure 07).

➤ Green waste (grass) and phrgmites

Grass clippings and common reed (**Phragmites communis**) are nitrogen-rich green wastes, which are essential for balancing the carbon-to-nitrogen (C/N) ratio in compost. Incorporating grass and reeds as nitrogen sources in composting ensures a crucial balance that promotes microbial activity and accelerates the decomposition of organic matter. For our trial the green waste were collected from the experimental farm of the University of Ouargla (Figure 07).

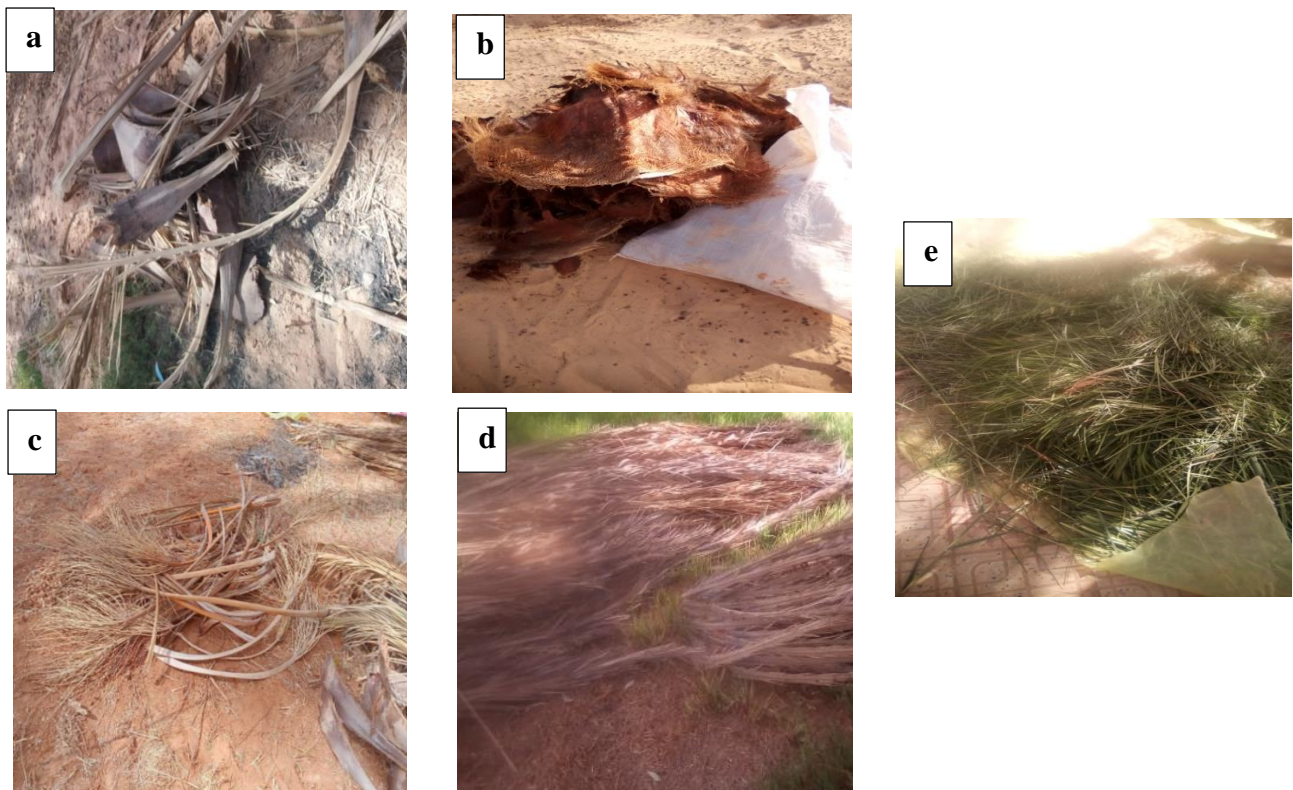


Figure 07: Palm grove residues: a) Petiole , b) Fibrillum, c) Bunch and Pedicels, d) Dried palms , e) Phragmites and grass

II.3.1.4. Sewage Sludge

The term "sewage sludge" refers to the sludge resulting from wastewater treatment. It is a semi-solid residue, often muddy in consistency that comes from the various stages of municipal or industrial wastewater treatment. It is a by-product of wastewater treatment containing organic matter, nutrients (nitrogen, phosphorus), microorganisms, but also sometimes contaminants such as heavy metals or pathogens.

This sludge is mainly composed of suspended organic and mineral matter, which is extracted during settling or clarification stages. The composition of the sludge varies depending on the origin of the wastewater and the treatment techniques used. It can appear in different shades, ranging from gray to dark brown, depending on its organic matter content. Typically, sludge appears as a semi-liquid mixture of fine particles, often compared to clay or siliceous sediment.

In environmental and agronomic terms, the management and recovery of this sludge through composting is a significant ecological issue. It helps limit pollution and turns waste into a valuable resource for agriculture.

For our study, the sludge used for the composting process corresponds to activated sludge supplied by the Touggourt wastewater treatment plant S.T.E.P Administered by the National Sanitation Office (ONA) (Figure 08 and Figure 09). More information about the Touggourt wastewater treatment plant is provided in the appendix.



Figure 08. Sludge drying bed in the Touggourt station (Ghettas,2008)



Figure 09: Sewage Sludge (S.T.E.P Touggourt, 2025)

II.4. Trial management and experimental design

II.4.1. Shredding of palm residues

Grinding palm residues is a crucial step to reduce the size of organic materials and facilitate their breakdown during composting. This process also increases the surface area in contact with the microorganisms responsible for decomposition. Moreover, the fragmentation of the residues improves aeration and the homogeneity of the mixture, which is crucial for effective composting. The reduction in material size also allows for better moisture management, another key factor for microbial degradation.

The grinding machine and the crushed date palm residues obtained are illustrated in the (Figure 10 and Figure 11).



Figure 10: Grinding machine



Figure 11: Ground palm résidus

II.4.2. Soaking of date palm residues in water

Soaking palm residues in water is a technique used to promote the breakdown of tougher materials. Immersing the residues accelerates the fermentation process, which enhances their incorporation into the compost. In our study, we submerged the previously crushed date palm residues in a large water-filled basin for one week (Figure 12).



Figure 12 : Soking palm residues process

II.4.3. Treatments (mixing ratios) and establishment of compost piles

The trial was carried by using compost piles, with each pile representing a different type of sludge mixture supplemented with palm grove plant residues. The organic substrates for the composting process were prepared according to specific mixing ratios, which included the following treatment combinations:

- **T1 :** 75% (PGR)and 25% (SS)
- **T2 :** 65% (PGR) and 35% (SS)
- **T3 :** 50% (PGR) and 50% (SS)
- **T4 :** 75% (SS) and 25% (PGR)

The organic substrates were carefully prepared and mixed according to the specific proportions defined for each treatment. Following this, the compost piles were constructed with precise dimensions: 80 cm in height and 1.5 meters in length. This particular configuration promotes adequate aeration within the piles and helps maintain a stable temperature throughout the decomposition process, which is essential for efficient composting (Figure 13).



Figure 13: Compost pile measurement

II.4.4. Turning and Watering

➤ Turning

Turning the compost pile is a technique used to provide the necessary oxygen for microorganisms to breathe, to homogenize the prepared mixtures, and to release accumulated carbon dioxide and heat (MUSTIN ,1987) . For our case, turning is done once a week. (Figure 14).



Figure 14: Turning the compost

➤ Watering

Watering the compost pile is one of the most important factors that increases the moisture content needed for microbial activity. We watered the pile to reach a moisture level between 50 and 60% (MUSTIN ,1987). This moisture level was controlled by manual estimation through touch. Watering is applied from the top of the pile down to runoff at the base, that is, until percolation is observed. It should be noted that the watering and turning of the mixtures were performed simultaneously (Figure 15).



Figure 15: Watering the compost

II.5. Monitoring of composting parameters

II.5.1. Evaluation of physical parameters

II.5.1.1. Temperature

Thermal monitoring was carried out daily for all treatments during the first week of composting. subsequently, the temperature was measured weekly until the end of the composting operation. The temperature measurement was carried out using a thermometer (Figure 16).



Figure 16 : Mesure la température

II.5.1.2. Odor

Appreciation of changes in the compost smell, transitioning from a strong, unpleasant odor to an earthy smell characteristic of mature compost.

II.5.1.3. Visual appearance

Assessment of the color, texture, and homogeneity of the compost, indicating the degree of organic matter decomposition. The visual parameters of mixtures was carried out before and after the composting process.

II.5.1.4. Particle size

Analysis of compost granulometry, where a reduction in particle size reflects advanced degradation of organic matter. The particle size of mixtures was carried out before and after the composting process.

II.5.2. Monitoring of physico-chemical parameters

The analysis of the physicochemical parameters of the mixtures was carried out before and after the composting process, with a one-month interval. Two representative samples were collected from each mixture one at the beginning and another at the end of the composting period.

The samples were placed in labeled plastic bags, transported to the laboratory, air-dried at room temperature, ground, and stored until the time of analysis. The sampling was conducted as follows :

- **Sample1**=Before-composting
- **Sample2**= After 90 days of composting

II.5.2.1. pH

The measurement of the hydrogen potential (pH) to assess the acidity or alkalinity of the compost. pH was measured using a pH meter, with a solid-to-water ratio of 1:10 (Figure 17).



Figure 17: pH meter

II.5.2.2. Electrical Conductivity (EC)

The measurement of electrical conductivity (EC) helps estimate the concentration of soluble salts present in the compost. Electrical conductivity was measured using a conductometer on an aqueous extract (material/water ratio of 1:10) at a temperature of 25°C. This measurement helps estimate the concentration of soluble salts present in the compost (Figure 18).



Figure 18: Conductivity meter

II.5.2.3. Organic Matter (OM)

The organic matter content was determined by incineration. Three 10 g samples of shredded material were weighed in porcelain crucibles, dried at 105°C for 24 hours, and then incinerated in a muffle furnace at 850°C.

The mass loss by fire represents the approximate amount of organic matter destroyed by combustion, although part of it corresponds to residual water. The actual percentage of organic matter is obtained by correcting this loss with the evaporated water amount.

$$\text{OM}(\%) = 100 \times (\text{Ps} - \text{Pc}) / \text{Ps}$$

Where :

- ✓ Ps = sample weight before incineration
- ✓ Pc = sample weight after incineration

$$\frac{(p1 - p0) - (p2 - p0)}{(p1 - p0)}$$



Figure 19 : Calcination process

II.5.2.4. Organic Carbon

Organic carbon is calculated from the percentage of organic matter using the empirical relation:

$$\mathbf{Corg\ (\%) = OM\ (\%) / 2}$$

II.5.2.5. Total Nitrogen (N)

The total nitrogen content was measured using the Kjeldahl method. Under the action of boiling concentrated sulfuric acid, organic nitrogen is converted into ammoniacal nitrogen. Carbon is released as CO₂, hydrogen as water, and nitrogen is trapped as ammonium sulfate. The reaction is intensified by adding copper sulfate and potassium sulfate as catalysts. After complete digestion, the ammoniacal nitrogen is released by adding sodium hydroxide and then titrated by distillation. Nitrogen content is expressed as:

$$\mathbf{N\ (\%) = N' \times (Ve - Vt) \times 0.14 / P}$$

Where:

- ✓ **N**: total Kjeldahl nitrogen
- ✓ **Ve**: sample titration volume (ml)
- ✓ **Vt**: blank titration volume (ml)
- ✓ **N'**: normality of the sulfuric acid
- ✓ **P**: weight of the test sample (mg)

II.5.2.6. C/N Ratio

The carbon-to-nitrogen ratio is a key indicator for assessing compost stability and maturity.

The C/N ratio is calculated by dividing the total amount of carbon (C) by the total amount of nitrogen (N) in the sample:

$$\text{C/N Ratio} = \frac{\text{Total Carbon (C)}}{\text{Total Nitrogen (N)}}$$

A balanced C/N ratio promotes good microbial activity and effective decomposition.

II.5.2.7. Heavy Metals

Heavy metals are chemical elements that can be toxic to the environment, plants, and humans when present in high concentrations in compost. The commonly monitored heavy metals include: Lead (Pb), Cadmium (Cd), Mercury (Hg), Nickel (Ni), Zinc (Zn), Copper (Cu) and Chromium (Cr).

The compost sample (10g) is first dried, ground, and sieved (usually to a fine particle size, e.g. , 0.2 mm) to homogenize the material. The sample undergoes chemical mineralization, typically using a mixture of strong acids (such as nitric acid HNO₃, perchloric acid HClO₄, and hydrofluoric acid HF) to break down the organic matter and release the heavy metals into a soluble form. The mineralized residue is further treated with acids (e.g., HNO₃ and HCl) to ensure complete dissolution of the metals (Figure 20).

The concentration of heavy metals is then measured using precise analytical techniques, mainly Atomic Absorption Spectrometry (AAS), which quantifies metals like Cd, Cr, Ni, Pb, Zn, Cu by measuring the absorption of light by metal atoms in the sample.

This method ensures compliance with regulatory standards for metal contamination and helps assess the final quality of the compost product.



Figure 20: Atomic Absorption Spectrometry (AAS)

II.5.2.8. XRF (X-ray fluorescence) method

The XRF (X-ray fluorescence) method is an analytical technique commonly used to detect and quantify heavy metals in various matrices, including soils, sludge, organic waste, and compost. This method is non-destructive and offers several advantages for environmental analysis. The organic substrates used for composting are first dried, finely ground, and homogenized to obtain a representative and uniform sample.

The sample is exposed to a primary X-ray beam. These X-rays excite the atoms in the sample, causing them to emit secondary X-rays (fluorescent X-rays) that are characteristic of each element. The emitted fluorescent X-rays are detected and analyzed by a detector. Each heavy metal emits radiation at a specific wavelength, allowing identification and quantification of the elements present in the sample.

The concentration of heavy metals (such as Pb, Cd, Cr, Ni, Zn, Cu, etc.) is determined by comparing the intensity of the fluorescence peaks to those of known standards, usually through prior calibration (Figure 21).



Figure 21: XRF (X-ray fluorescence) method

II.5.2.9. XRD (X-ray Diffraction)

X-ray diffraction (XRD) analysis is a method used to identify the mineralogical composition and crystalline structure of materials. In our study, it allows the detection of mineral phases present in compost, sewage sludge, and date palm grove residues by analyzing the diffraction of X-rays as they pass through the sample before and after composting (Figure 22). Each mineral has a specific diffraction "pattern," which enables precise characterization of the nature of the solid components. The principle of the method is given in Appendix .



Figure 22: XDR X-ray Diffraction.

Chapter III

Results and Discussion

III.1. Physico-chemical characterization of the initial substrates

The physico-chemical characterization of the initial substrates used for composting process is mentioned in table 1.

Table 1. Physicochemical characteristics of the initial organic substrates
(dry weight basis)

Organic substrate	pH	EC (dS/m)	OM (%)	Org C (%)	Total N (%)	C/N
Palm grove residues GR)	6.11	1.3	86.28	43.14	1.1	33.7
Sewage Sludge (SS)	7.4	3.43	56.6	28.3	2.01	14.07

The physicochemical characteristics of palm grove residues (PGR) and sewage sludge (SS) show significant differences regarding their suitability for composting. The palm grove residues exhibit a slightly acidic pH (6.11), while the sewage sludge shows a more alkaline reaction (pH 7.4). Both values fall within the optimal range for composting, as a neutral to slightly alkaline pH is known to favor microbial activity (**Bernal et al., 2009**).

The EC value of PGR is relatively low (1.3 dS/m), indicating a low concentration of soluble salts, which is desirable for reducing salinity in the final compost. In contrast, the sludge has a higher EC value (3.43 dS/m), reflecting a greater salt content. While still acceptable for composting, high salinity levels should be monitored, especially if the compost is intended for salt-sensitive crops (**Lim et al., 2012**). PGR contains a very high level of organic matter (86.28%) compared to the sludge (56.6%). This makes PGR a valuable carbon-rich component, essential for supplying energy to decomposer microbes.

Although the OM content in sludge is lower, it remains within an acceptable range and contributes to the organic content of the composting mixture. The sludge contains a relatively high total N content (2.01 %), while PGR contains only 1.1 %. The sludge therefore serves as an excellent nitrogen source, which is crucial for microbial protein synthesis and overall composting efficiency.

Combining sludge with PGR, which is carbon-rich, can help achieve a more balanced and stable compost (**Zhang & Sun, 2016**). PGR has a higher organic carbon content (43.14%) compared to the sludge (28.3%). This further supports its role as the primary carbon source in the composting process. Maintaining an appropriate C/N ratio ideally between 25 and 30 at the beginning of composting is key to optimizing microbial activity and compost quality (**Haug, 1993**).

III. 2. Physical indicators of maturity

III. 2.1. Temperature

Temperature is a key indicator for monitoring the composting process, as it reflects microbial activity and the breakdown of organic matter. In this experiment, we tracked the temperature of four composting treatments (T1 to T4) over a 90-day period and compared them to ambient air temperature. The goal was to identify the four composting phases: mesophilic, thermophilic, cooling, and maturation. The temperature variations of the four treatments throughout the composting process are shown in figure 23.

The thermal monitoring curve shows that the temperature on the first day signals the start of biological activity of the mesophilic microflora (mesophilic phase), corresponding to the microorganisms' adaptation to their environment. During this phase, temperatures of 29, 32, 34, and 34 °C were recorded for treatments T1, T2, T3, and T4, respectively, due to the multiplication of mesophilic aerobic microorganisms in each treatment.

Between days 2 and 7, a significant temperature increase was observed in all treatments, reaching a maximum of 51 °C in T2. This rise indicates the onset of the thermophilic phase. According to **Mustin (1987)**, the heat generated by predominantly aerobic fermentations causes the temperature increase in composting masses, leading to the destruction of pathogenic organisms. This activity is attributed to thermophilic microorganisms, which enhance the sanitization of the compost (**Vico et al., 2018**). **Devisscher (1997)** explains that the temperature rise during the thermophilic phase results from microorganisms oxidizing the organic matter in the substrates, releasing the energy stored in chemical bonds. While part of this energy is retained by the system, a large portion is lost as heat dissipated into the atmosphere (**Vico et al., 2018**).

Following the first week, a cooling phase occurred (days 7 to 35), during which temperatures dropped to around 27–30 °C across all treatments. Temperatures then gradually declined until the end of the composting trial, averaging about 30 °C. This decrease corresponds to the consumption of easily degradable materials, leading to reduced microbial activity and temperatures approaching ambient levels. During the cooling phase, compost temperatures converged with ambient temperature, reflecting a slowdown in biological activity.

In the maturation phase (days 42 to 90), microbial activity stabilized, humification began, and the compost matured. Temperature increases were observed again between days 72 and 90 (with T3 and

T4 reaching up to 44 °C), likely due to secondary microbial activity, improved aeration during turning, and/or the onset of the summer season.

Thus, after three months of composting, the temperatures of the four piles approached ambient temperature, indicating a significant decline in microbial activity at the end of the process and stabilization of the organic materials used (Majbar et al., 2018; Abid et al., 2020).

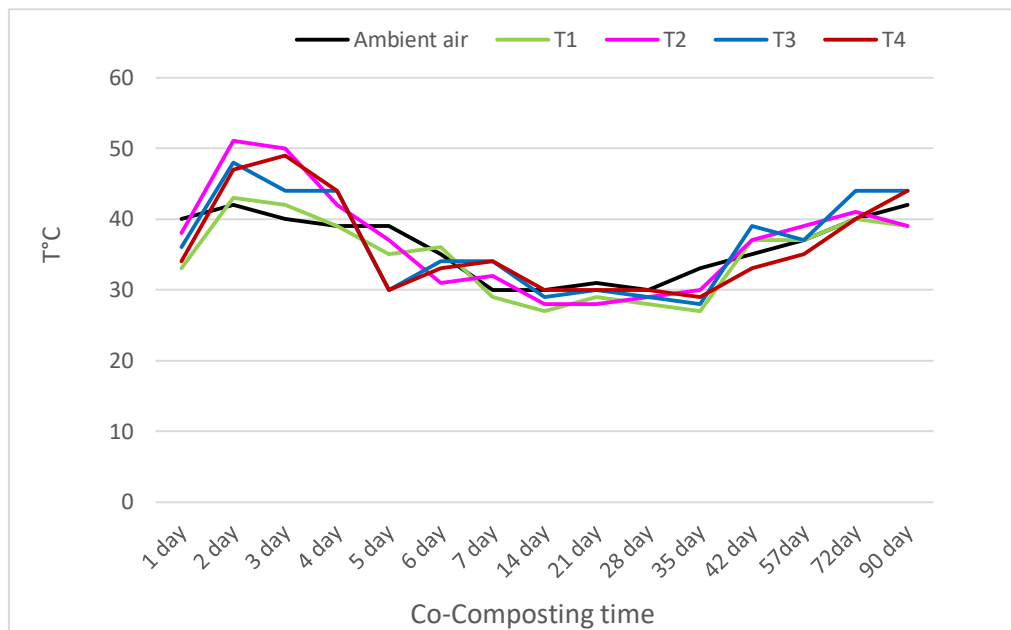


Figure 23: Temperature changes in the four treatments throughout the composting process

The low temperature observed during the composting process, which did not exceed 51°C, can be attributed to the nature of the feedstock, particularly palm residues, which are characterized by a high content of lignin and cellulose. This composition leads to a slow decomposition rate and delays the onset of the thermophilic phase (Volpi et al., 2019).

Despite the addition of nutrient-rich sludge, microbial activity was likely insufficient to generate significant heat. Empirical observations indicate that palm fronds retain their structural integrity for extended periods during composting, highlighting their resistance to microbial degradation. Previous studies have demonstrated that effective composting of palm residues requires controlled aeration and regular turning to attain optimal thermal conditions (Alkoik et al., 2020).

Consequently, it is crucial to consider pre-treatment methods, such as fine shredding or the incorporation of more readily biodegradable substrates, to enhance the thermal performance and efficiency of the composting process (Volpi., Bastos Badan, Santana & Santos (2019).

III.2.2.Odor

Unpleasant odors in the treatments containing a high amount of sludge, particularly T4 and T3, have disappeared, giving way to a slight earthy smell, similar to that of natural soil. This suggests that the organic matter has relatively stabilized compared to the initial state and that aerobic conditions are now dominant in the compost piles.

III.2.3. Visual appearance

After three months of composting with the progression of the biological degradation process of organic matter, several physical signs were observed for all mixtures, indicating an improvement in the condition of the compost and its advancement toward maturity. However, the most significant visual changes are more evident in treatments T2, T3 and T4. Among these indicators:

➤ **Color:** The color of the compost changes during the composting process mainly due to the decomposition and transformation of organic matter by the action of microorganisms.

At the beginning of composting, the organic substrates piled up have green and brown colors, reflecting the origin of the materials used (sludge, palm residues, and green waste).

As composting progresses, the compost darkens, shifting from the lighter tones of the raw materials to a deep brown or even black, especially in mixtures with high sludge (T4 and T3) content (Figure 24). This darkening likely results from :

- The formation of complex organic compounds like humic and fulvic acids, which are key indicators of compost maturity and give the compost its characteristic dark color
- Microorganisms involved in composting produce pigments and alter the chemical structure of the organic matter, further contributing to the dark coloration of the final compost.
- The introduction of oxygen during pile turning promotes oxidation reactions that convert organic matter into more stable, darker substances.
-

➤ **Homogeneity and texture**

Before composting, the mixtures of sludge and palm residues for all blends exhibit a heterogeneous texture, often compact and moist, with recognizable fragments of organic matter (palm fibers, thick sludge). The particle size distribution is variable, with coarser particles originating from the plant residues and sometimes- sticky sludge, which limits air circulation and slows down decomposition. The homogeneity is low, as the components are not yet well integrated.

After three months of composting, all mixtures, except T1 (75% PGR + 25% SS) became more uniform in texture and appearance, with most of the original components unrecognizable. This indicates good interaction and balance among the different materials in the compost pile.

These texture changes are clearly linked to biological activity and the fragmentation of aggregates, which promotes better aeration and creates an environment conducive to fermentation.

Regarding homogeneity, it is significantly improved thanks to regular turning and controlled moistening of the compost piles throughout the composting process, allowing for uniform decomposition of the substrates.

The persistence of recognizable particles in T1 can be explained by the very high percentage of palm residues in this treatment. These residues have a woody biochemical composition that is difficult to biodegrade.

III.2.4. Particle size

With the exception of T1, a noticeable reduction in particle size was observed after composting compared to the initial state, resulting from effective microbial breakdown. In fact, at the beginning, the particles of all mixtures have often larger and recognizable, but as microorganisms break down the organic matter, the particles fragment, decompose, and humify, which reduces their size and alters the granulometric distribution. After three months of composting the compost components have become finer and more friable, improving its physical properties and making it more suitable for agricultural use (Figure 24).

Granulometry evolves through the combined effects of biodegradation, mechanical fragmentation (turning, mixing), and the formation of new, finer, and more stable organic structures, making it a key indicator of compost maturity.

Altogether, these indicators reflect a positive development in the composting process and represent essential criteria for assessing compost maturity prior to conducting more detailed chemical or biological analyses.

The morphological aspects indicating the degree of maturity of the compost for the different treatments (before and after composting) are illustrated in (Figure 24).

Before composting



After composting



T1 :75% (PGR) + 25% (SS)



T2 :65% (PGR) + 35% (SS)



T3 :50% (PGR) + 50%(SS)



T4 :75% (SS) + 25 (PGR)

Figure 24: Visual appearance of the compost mixtures prepared according to the selected proportions.

III.2.5.XRD (X-ray Diffraction)

X-ray diffraction (DRX) analysis revealed that several mineral components underwent a transformation from a well-defined crystalline structure to an amorphous or poorly crystalline form. This transformation indicates significant structural modifications resulting from microbial and biochemical activity throughout the composting process. Such changes are commonly associated with the decomposition of organic matter and are widely recognized as reliable indicators of compost maturity and the progression of the humification process.

Relationship between XRD results and compost maturity :

- Disappearance of Cellulose, Lignin, Hemicellulose: Indicates active microbial degradation of labile organic matter (**Tiquia et al., 2002**).
- Increase in mineral peak intensity : Reflects organic mass loss and mineral concentration in well-composted materials (**Bernal et al., 2009**).
- Persistence of Organic Crystalline Peaks After Composting: Suggests incomplete composting or recalcitrant organic matter (**Zbytniewski & Buszewski, 2005**).

The X-ray diffraction (XRD) results before and after composting of the prepared mixtures are presented in figures 25-26-27-28-29-30 and 31-32. These results show significant structural changes related to the composting process.

- **T1:** Cellulose and lignin peaks were still visible after composting, showing that the compost did not fully mature.
- **T2:** Cellulose is still visible, but lignin is no longer detected. This suggests the compost is beginning to mature, as lignin being more resistant has started to break down.
- **T3:** Still shows cellulose but no visible lignin, indicating the compost is entering the maturation phase.
- **T4:** No data available.

The changes to the treatments are detailed as follows :

T1 :75% PGR + 25% SS)

- Before Composting: Cellulose, Lignin, Quartz, Calcite, Hemicellulose, Hematite , Kaolinite, Illite .
- After Composting: Montmorillonite, Illite, Calcite, Lignin, Cellulose. Very weak or no peaks for lignin and cellulose.

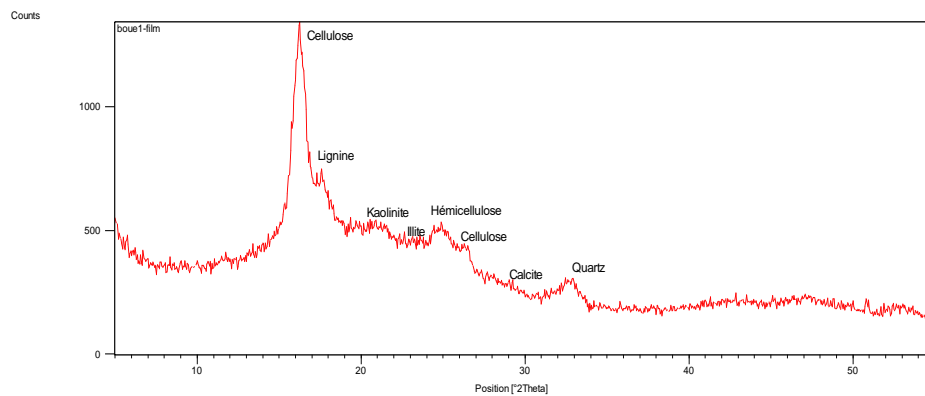


Figure25 : T1. XRD results before composting

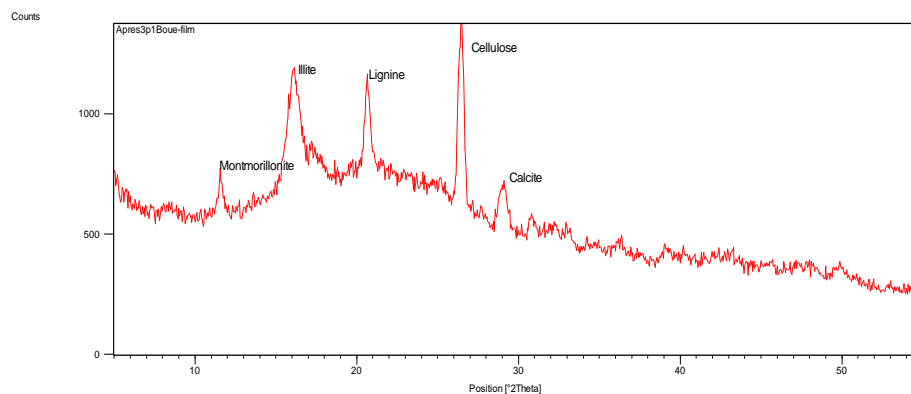


Figure26 : T1. XRD results after composting

T2: 65% PGR + 35% SS)

- Before Composting: Cellulose, Lignin, Hemicellulose, Kaolinite, Quartz, Calcite.
- After Composting: Illite, Kaolinite, Montmorillonite, Calcite, Quartz, Ferrihydrite, Goethite,

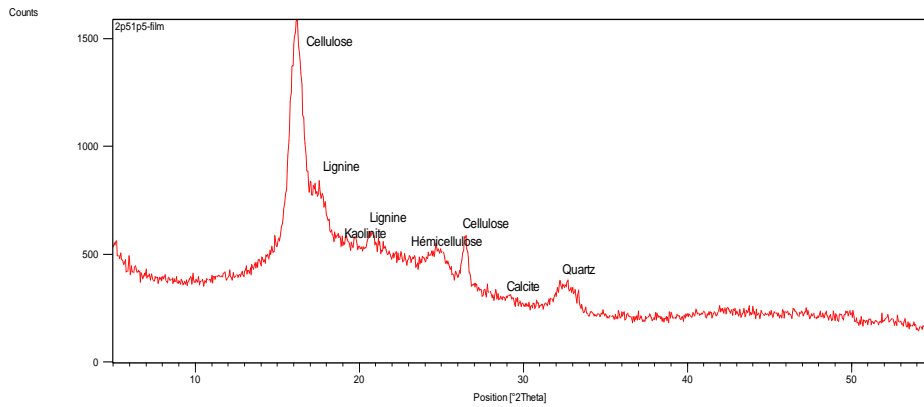


Figure 27 : T2 . XRD results before composting

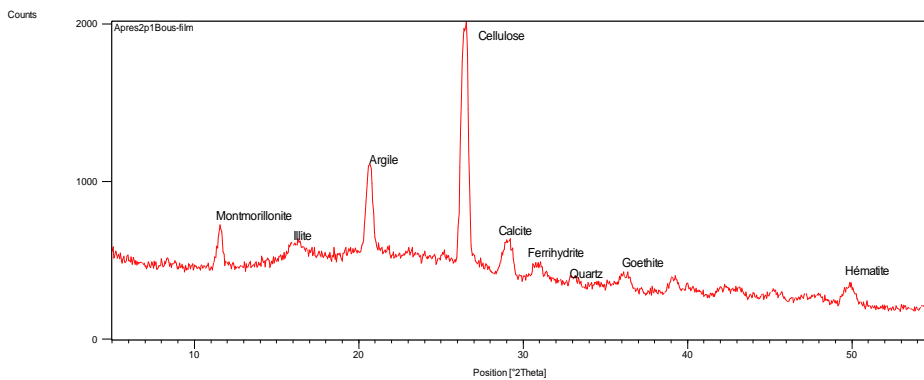


Figure 28 : T2 . XRD results after composting

T3 : 50% PGR + 50% SS)

- Before Composting: Cellulose, Lignin, Quartz, Calcite, Kaolinite.
- After Composting: Kaolinite, Illite, Cellulose.

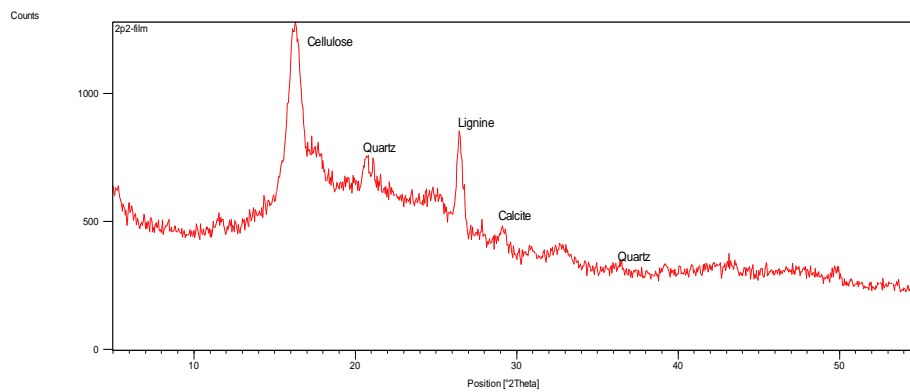


Figure 29 : T3 . XRD results before composting

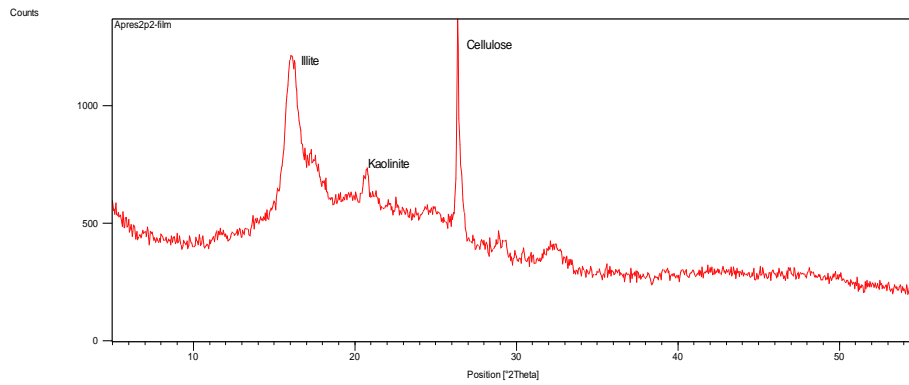


Figure 30 : T3 . XRD results after composting

T4 : 25% PGR +75% SS)

- Before Composting: Kaolinite , Montmorillonite , Cellulose , Lignin , Illite , Hemicellulose , Calcite , Quartz , Iron Oxide , Limonite
- After Composting: "Results from the laboratory analyses are awaited and will be discussed once available."

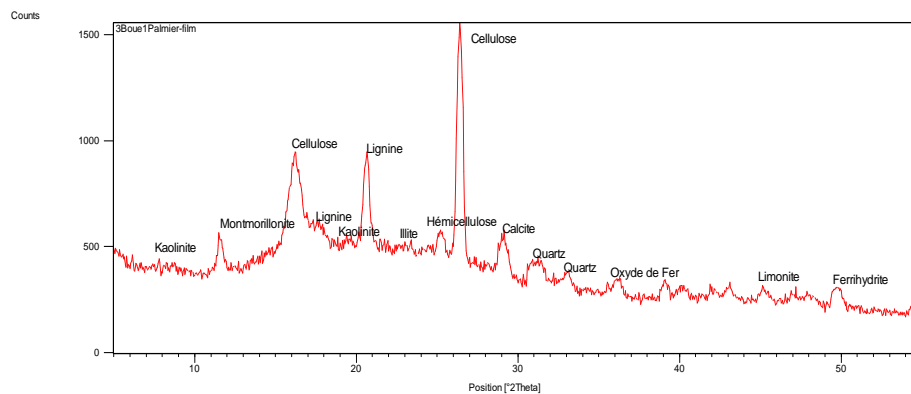


Figure 31 : T4 . XRD results before composting

III. 3. Evolution of physico-chemical parameters during composting

III.3.1. EC and pH

The physicochemical analysis of the four compost mixtures over a 3-month composting period reveals significant trends in both electrical conductivity EC and pH, largely influenced by the relative proportions of palm grove residues (PGR) and sewage sludge (SS).

Overall, EC increased in all treatments, while pH slightly decreased, which aligns with common composting dynamics (figure 33 and 34). These changes are driven by intensive microbial activity, organic matter degradation, and the release of soluble ions such as ammonium (NH_4^+), nitrate (NO_3^-), potassium (K^+), and other minerals (Bernal et al., 2009; Nemet et al., 2021). Mixtures with higher proportions of sewage sludge (T3 and T4) exhibited greater EC increases, reflecting the high salt and nutrient content of sludge. For instance, T4 (75% SS) reached the highest EC value after composting (8.7 mS/cm), indicating rich mineralization, but also signaling potential salinity stress for salt-sensitive crops (Zucconi et al., 1981; Lazcano & Domínguez, 2021).

Conversely, treatments richer in palm residues (T1 and T2) showed more moderate EC increases. This is attributed to the lignocellulosic structure of PGR, which decomposes slowly and contributes less to soluble salt formation (Hachicha et al., 2009). These materials tend to buffer salinity and provide structure, though they may require a longer composting time to fully mature.

Regarding pH, all mixtures initially presented alkaline conditions (>8), typical for sewage sludge-based composts due to high ammonia and base content (Bernal et al., 2009). After composting, a gradual pH reduction was noted across all treatments, especially in T3 (from 8.1 to 7.72). This decrease can be explained by the formation of organic acids, ammonia volatilization, and CO_2 release, which are hallmark processes of active composting phases (Nahar et al., 2021). According to Abid et al., (2020), the intense biodegradation of organic compounds (carbohydrates, lipids and other substances) produces organic acids. These are the cause of the drop in pH values towards the end of the operation importantly, final pH values remained within the optimal range (6.5–8.5) for most agricultural applications, suggesting that the composts were both biologically stable and agronomically safe (Lasaridi & Stentiford, 1998).

According Oustani (2016) ; Abid et al. (2020), the concentration of the compost in mineral salts is very important for the nutrition of the plants, provided that this concentration does not exceed the limit of salinity threshold tolerated by plants (4mS/cm measured by extract paste).

Overall, these results suggest that balanced mixtures, such as T3 (50% PGR + 50% SS), provide the best compromise between nutrient content and stability. In contrast, mixtures with high sludge content (T4) promote rapid mineralization but may require careful management of electrical conductivity (EC) levels to prevent soil salinization. Mixtures rich in organic matter (T1) are safer for sensitive crops but may need extended composting to achieve full maturation and tend to be limited in essential nutrients.

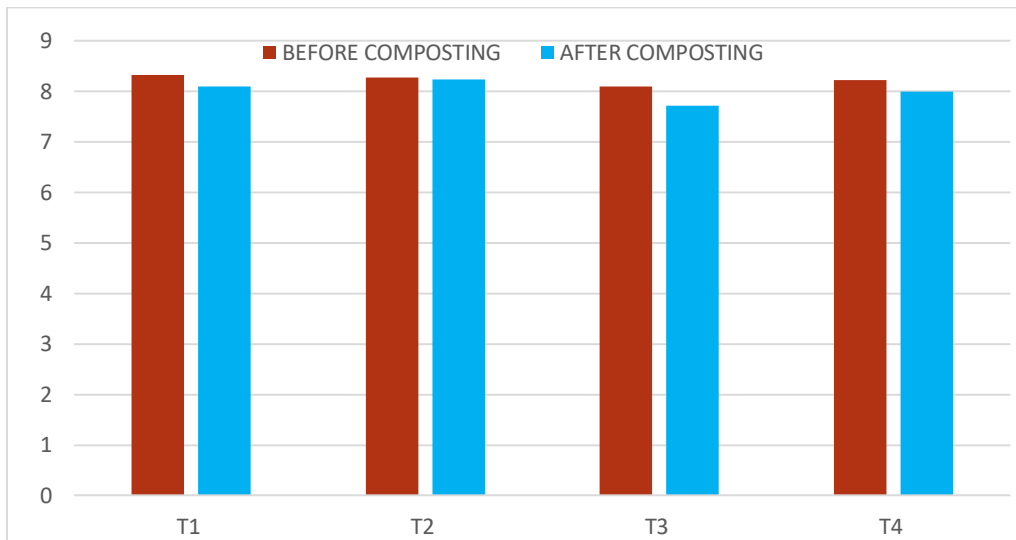


Figure 33 : pH Evolution during the composting process

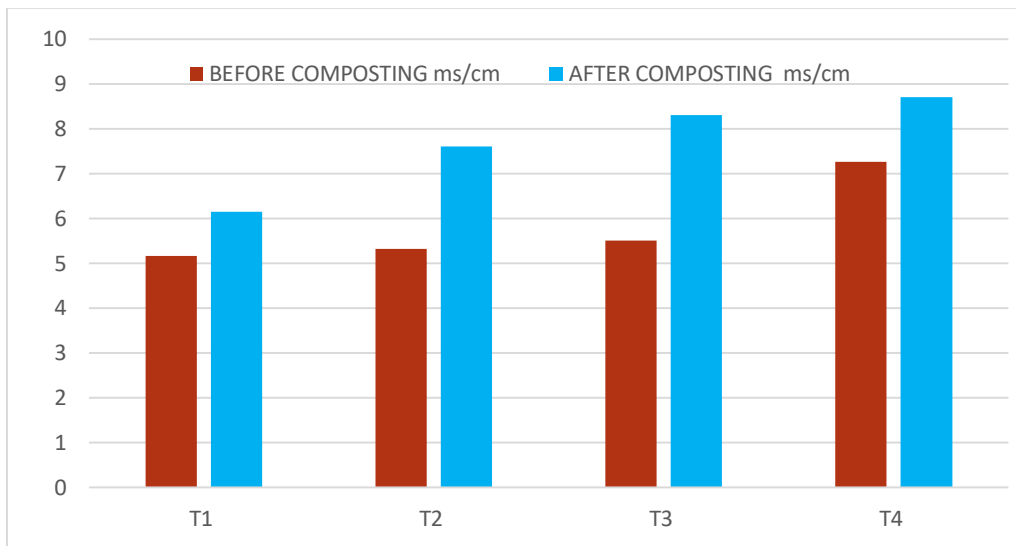


Figure34: Evolution of electrical conductivity during the composting process

III.3.2.Organic matter (MO)

All treatments showed a significant reduction in organic matter content, indicating active microbial degradation and organic substrate breakdown during composting (figure35). This trend is consistent

with the normal composting process where organic matter is converted into more stable humic compounds (Bernal et al., 2009). The MO reduction values across all treatments fall within the expected range of 12.5–47.47%, often cited as a benchmark in composting literature.

The percentages of organic matter reduction compared to the initial state (at the beginning of the composting test) are 47.47%, 21.83%, 21.42%, and 12.5% for treatments T3, T2, T4, and T1, respectively.

According to (Calvet, Chenu, & Houot, 2011), upon decomposition, organic matter is reduced by 20 to 40% as a result of the activity of microorganisms. These latter use the organic substances necessary for their metabolism. .

These results confirm that composting was successful and active, especially in T3, T4 and T2 and support the conclusion that co-composting PGR with sewage sludge is a viable strategy for organic waste stabilization

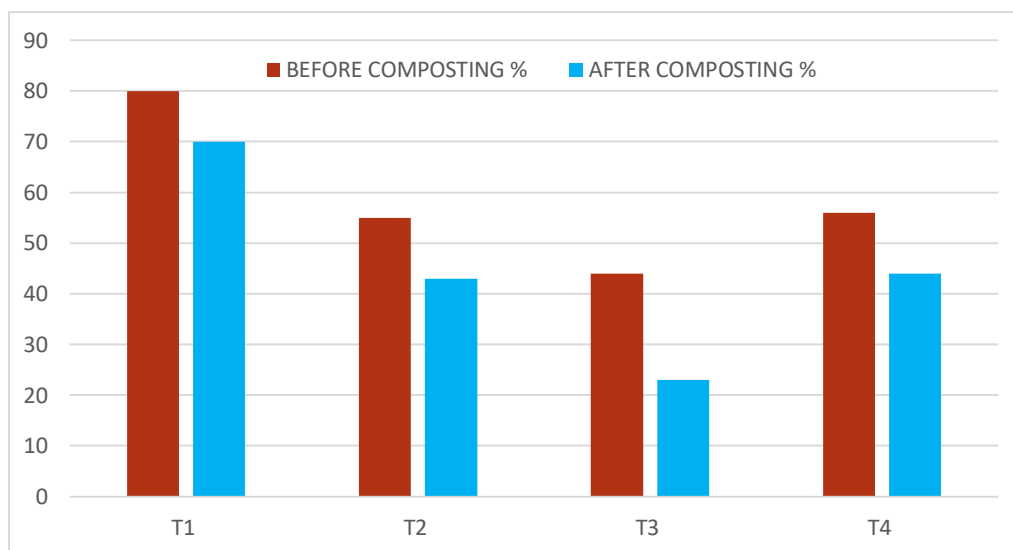


Figure35: Evolution of organic matter during composting

III.3.3.Organic Carbon

Organic carbon follows the same trend as organic matter (Figure36) . All treatments showed a notable reduction in carbon, confirming the mineralization of organic matter by microbial activity. The decrease in carbon is expected as carbon is consumed and partially lost as CO₂ during aerobic composting (Bernal et al., 2009). The results demonstrate that carbon degradation occurred in all treatments, with the greatest reductions observed in T3,T4 and T2.

General Decline in Carbon Content

All treatments showed a notable reduction in carbon, confirming the mineralization of organic matter by microbial activity. The decrease in carbon is expected as carbon is consumed and partially lost as CO₂ during aerobic composting (Bernal et al., 2009).

- T2: Highest Carbon Loss (−50%) : suggesting very active microbial decomposition. This supports the earlier organic matter findings and indicates that this mixture had a favorable C/N ratio, moisture, and aeration for microbial metabolism (Huang et al., 2021).
- T4: Substantial Loss (−43.8%) : also showed a strong carbon decrease, likely due to its initially high organic load (40%) and better nitrogen availability from sludge, which enhances carbon degradation.
- T1: Moderate Carbon Loss (−31.8%) : reflecting effective but less intense degradation than T2 and T4. This is consistent with the MO results, where T1 showed moderate organic matter loss.
- T3: Minimal Carbon Loss (−11.1%) : which may indicate slower decomposition. This might be due to:
 - Suboptimal microbial conditions
 - High C/N ratio
 - Poor aeration or compaction

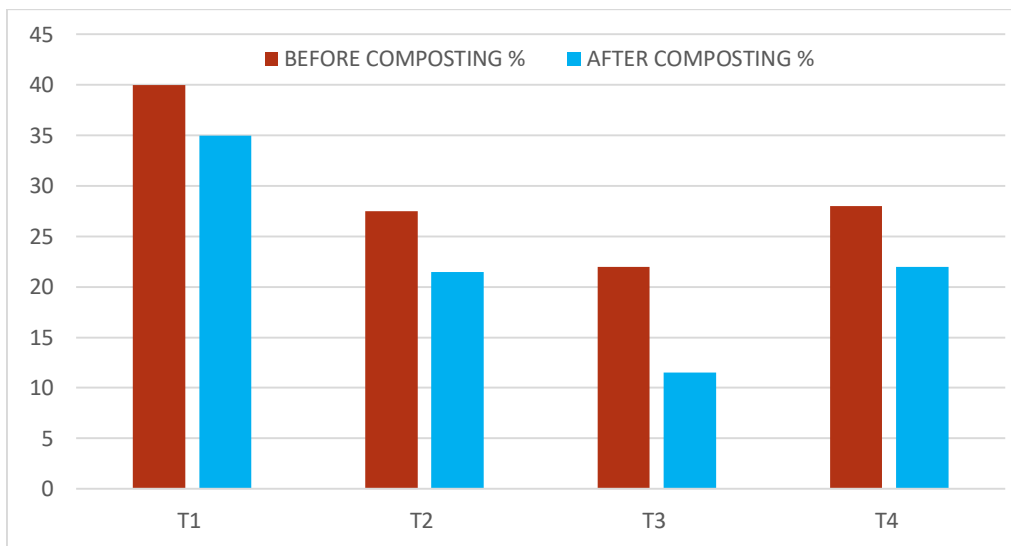


Figure 36 : Evolution of organic carbon during composting

III.3.4. Total nitrogen (TN)

The results of measuring the total nitrogen content in the three treatments during composting are presented in the figure. The data reveal a highly significant difference between the treatments, which can be attributed to the initial composition of each treatment (Znaïdi, 2002). According to these findings, it is observed that the total nitrogen content decreases in all treatments after composting, as detailed below:

- T1 showed a slight decrease in nitrogen (from 1.23% to 1.08%), likely due to low initial nitrogen and slow microbial activity. The compost is less rich in nutrients and not ideal for fertilization without N supplementation.
- T2 maintained most of its nitrogen (2.08% → 1.89%), indicating good stabilization. The final product is mature and suitable for agricultural use.
- T3 experienced a large nitrogen loss (2.18% → 1.01%), possibly due to ammonia volatilization during composting. The compost is mature but poor in nitrogen, reducing its fertilizer value.
- T4 had the highest nitrogen retention (2.26% → 1.90%). It produced a stable, nutrient-rich compost, suitable for crops—though sludge-heavy mixes should be checked for contaminants.

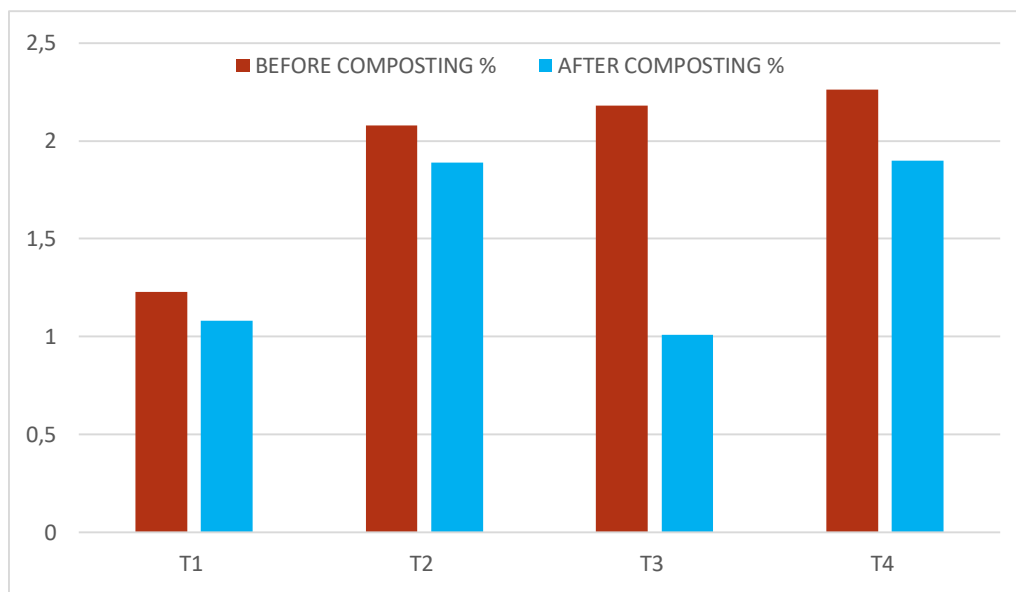


Figure37: Total nitrogen during composting

III.2.5. C/N at end of composting

The results of the C/N ratio measured at the end of composting are presented as follows :

- **T1: 75% Palm Grove Residues + 25% Sewage Sludge)**

- This treatment showed the highest C/N ratio of 32.4, which is well above the recommended range for mature compost.
- A high C/N ratio indicates that the composting process is incomplete and the material is still rich in undecomposed carbon compounds.
- As a result, this compost cannot yet be considered mature and is not suitable for direct application to soil, as it may lead to nitrogen immobilization, affecting plant growth.
- The high carbon content from palm residues likely caused a slow degradation rate due to low microbial activity.

➤ **T2 :65% PGR + 35% SS)**

- The C/N ratio decreased sharply to 11.37, which falls within the ideal maturity range (10–15).
- This low value is a strong indicator that organic matter has been well stabilized and that the compost is mature.
- The balanced mix of PGR and SS provided both structural bulk and nitrogen-rich material, resulting in a stable, nutrient-rich product.
- This compost is well-suited for agricultural application, especially as an organic soil amendment or conditioner, since it will not compete with plants for nitrogen.

➤ **T3 :50% PGR + 50% SS)**

- With a C/N ratio of 11.38, T3 shows very similar results to T2, indicating excellent maturity.
- This result confirms that increasing the sewage sludge content improves compost stability by enhancing microbial activity and speeding up the decomposition process.
- The final product is stable, mature, and suitable for use in farming practices, as it will enhance soil fertility without negative effects.

➤ **T4 :75% SS + 25% PGR)**

- This treatment also yielded a mature compost with a C/N ratio of 11.57.
- The high proportion of sewage sludge contributed a substantial amount of nitrogen, ensuring complete breakdown of organic materials.
- However, while the compost is mature and technically suitable for land application, further attention must be paid to heavy metal content and salinity, which can be higher in sludge-rich mixes.

- If properly monitored, this compost can be effectively used in agriculture, especially for crops with moderate salt tolerance.
- All of T2, T3, and T4 produced mature compost with C/N ratios below 12, making them suitable for use in agriculture.
 - T2 (65% PGR / 35% SS) stands out as the most balanced option:
 - It ensures compost maturity.
 - It uses a moderate amount of sewage sludge, reducing contamination risks.
 - It results in a product that is safe, mature, and beneficial for crop production.
 - T1 requires further composting or nitrogen addition to reach maturity before any land application.

The differences in the C/N ratio among various organic products can be attributed to the variability of their inputs, their level of mineralization, and particularly their nitrogen content. Throughout the composting process, the C/N ratio declines as carbon is released in the form of CO₂ (Mustin, 1987).

Conclusion

The C/N ratio is a key indicator of compost maturity, and the results show that:

- T2, T3, and T4 achieved values within the optimal maturity range and can be safely applied to soils.
- T1 remains immature and is not yet suitable for agricultural use.
- Among the mature composts, T2 offers the best compromise between material use, compost quality, and environmental safety.

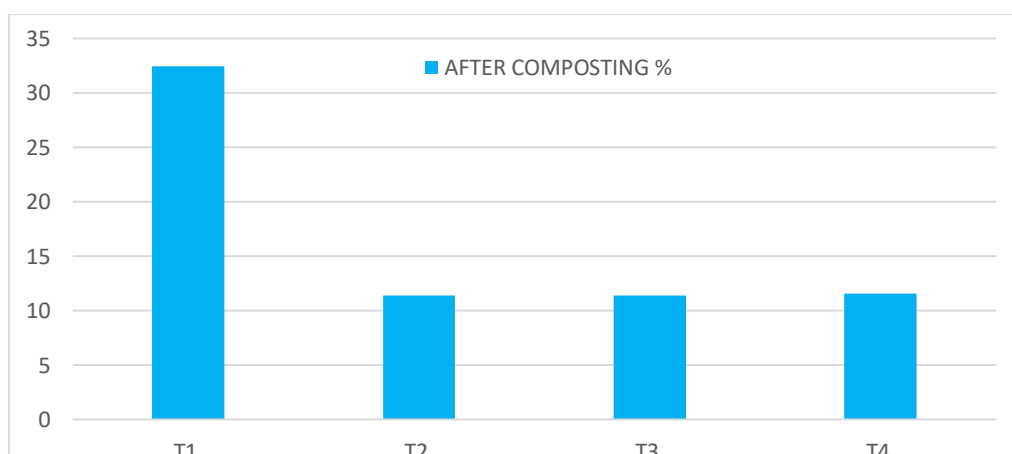


Figure38 : C/N evolution during composting

III.3.6. Heavy Metals

"Results from the laboratory analyses are awaited and will be discussed once available."

III.3.7. XRF (X-ray fluorescence)

"Results from the laboratory analyses are awaited and will be discussed once available."

IV. General conclusion and future perspectives

IV.1. General Conclusion

The present study investigated the composting of Palm Grove Residues (PGR) and Sewage Sludge (SS) in different ratios (T1 to T4), analyzing key physicochemical parameters to assess compost quality and maturity. The results demonstrated clear trends in organic matter degradation, nutrient enrichment, and overall compost stabilization.

- Organic Matter (MO) and carbon content (C Org) decreased significantly across all treatments, especially in T4 and T2, confirming active microbial degradation and successful composting.
- Total Nitrogen (TN) content increased in most treatments, particularly those with higher proportions of sludge, due to concentration effects following mass loss. However, potential nitrogen losses through volatilization were also observed, especially in T4.
- pH remained within acceptable ranges for compost application, showing a slight decrease over time due to organic acid formation.
- Electrical Conductivity (EC) increased moderately to strongly, with the highest values observed in T3 and T4, indicating the release of soluble salts during decomposition.
- The compost temperature curve showed a maximum of 51 °C, confirming that the thermophilic phase was reached an essential condition for pathogen reduction and organic matter transformation.

Overall, the compost mixtures demonstrated good stability and nutrient value, particularly T2 and T3, which showed a favorable balance between organic degradation and nitrogen conservation. However, T4, despite its high nutrient content, may require careful application due to higher salinity levels. The presence of inhibitory substances or low biodegradability in the sludge can impede microbial activity and slow down the composting process. Furthermore, the composition of the sludge can influence the dynamics of the microbial community involved in decomposition.

The limited degradation of organic substrates at T1 is attributed to the high proportion of palm waste, which is rich in complex organic matter to its high content of palm waste rich in organic matter in organic matter but contains a high proportion of lignin and cellulose (petioles, dry fronds, spathes, flower stalks). These are complex and resistant compounds that degrade slowly by microbial activity, which slows down the overall composting process. Also, date palm waste generally has a high C/N ratio. Although sludge is added to provide nitrogen and balance this ratio, but if the proportions or the nitrogen content in the sludge are insufficient or not well balanced, microbial activity may be limited, slowing decomposition, which hinders the maturity of the compost.

The limited progress observed in T4 compared to T2, despite its high nitrogen content, may be attributed to the presence of inhibitory substances or low biodegradability in the sludge. These factors can impede microbial activity and slow down the composting process. Furthermore, the composition of the sludge can influence the dynamics of the microbial community involved in decomposition.

IV.2.Future Perspectives

To further enhance compost quality and optimize the co-composting process, the following directions are recommended:

- **Microbiological Assessment:** Future work should include microbial analyses (e.g., pathogen inactivation, beneficial microbial biomass) to confirm compost sanitization and soil health benefits.
- **Heavy Metal Monitoring:** Since sewage sludge can contain trace metals, it is important to assess heavy metal concentrations to ensure compost safety for agricultural use.
- **Field Trials:** Applying the compost to crops in field conditions will help evaluate its agronomic effectiveness, nutrient release patterns, and potential salt stress on plants.
- **Process Optimization:** Investigating the use of bulking agents (e.g., straw, wood chips) or biochar could improve aeration, reduce ammonia volatilization, and enhance compost quality.

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Appendices

Wastewater treatment plant of Touggourt

This wastewater treatment plant of Touggourt plays a key role in managing the region's wastewater, with infrastructure adapted to the local population and treatment processes aimed at reducing organic pollution and protecting the environment. It is located in the commune of Tebesbest, in the Oued Righ region, which treats the wastewater from the city of Touggourt and its surroundings.

It has a treatment capacity of approximately 62,500 population equivalents, covering nearly 38% of the total population of the four communes of Greater Touggourt (about 164,000 inhabitants) (**Amiri et al.,2017**).

This plant carries out several treatment stages, including mechanical screening, biological treatment, clarification, sludge thickening, and sludge return.

The sanitation network of the city of Touggourt includes about 329 km of pipelines with a high connection rate (over 98%), and the wastewater is collected and discharged into the Oued Righ canal through nine discharge points (**Ghettas, 2008**). The treatment plant mainly processes water from these urban discharges, which have a variable organic load requiring specific treatment to reduce pollution before release into the environment.

Studies show that raw wastewater in Touggourt is rich in organic matter, with parameters indicating variable biodegradability depending on the discharge points. Biological treatment, notably through natural lagooning, is suitable for some less loaded effluents, while others require more advanced treatment.

The operational scheme of an activated sludge treatment process is illustrated in the figure 1.

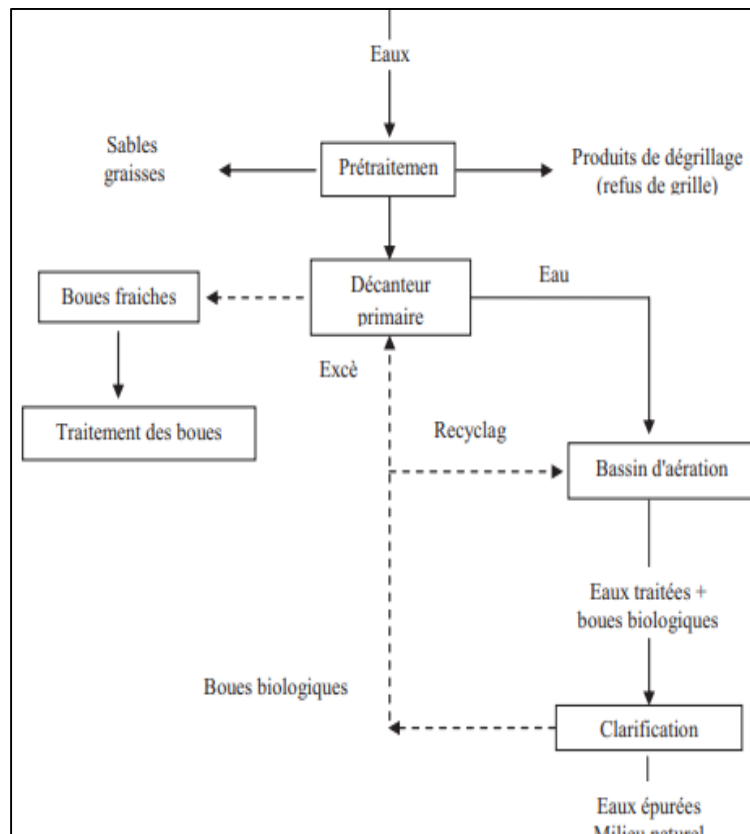


Figure39 : Schéma du fonctionnement d'un traitement par boue activée
(Ladje1, 2006)

X-ray Diffraction (XRD) Analysis Steps

1. Sample Preparation

The sample, often in powder form (palm waste, sludge, dry composts), is finely ground (particle size $< 100 \mu\text{m}$). to ensure random orientation of crystals and placed on the sample holder. The resulting powder is then placed onto a sample holder for analysis.

2. Positioning in the Diffractometer

The sample is mounted in the XRD instrument, which consists of an X-ray source, a sample holder, and a detector.

3. Irradiation with X-rays

A monochromatic X-ray beam irradiates the sample. The X-rays are diffracted by the crystal planes inside the sample according to Bragg's law: $n\lambda = 2d \sin \theta$

4. Data Collection

The detector measures the intensity of diffracted X-rays as a function of the diffraction angle 2θ , typically by rotating the sample and detector to scan through angles.

5. Data Analysis

The resulting diffraction pattern (intensity vs. angle) is analyzed and compared with reference databases to identify and quantify the mineral phases present.

6. Interpretation

From the diffraction peaks, information about the crystalline structure, phase composition, and sometimes crystallite size can be obtained