Transforming Date Palm Agro-Waste into Organic Compost: A Review of Sustainable Farming Systems

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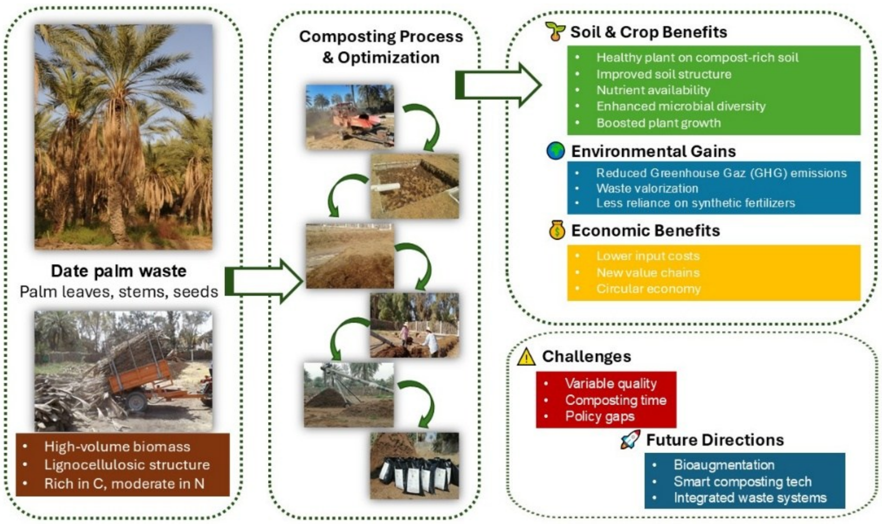
GRAPHICAL ABSTRACT



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Amal Bouzidi,[a] Samir Tlahig ,[b,*] Yassine Yahia,[b] and Walid Elfalleh [c,*]

Sustainable management of agricultural residues is essential to address environmental degradation and promote soil health, particularly in arid and semi-arid regions. Date palm (*Phoenix dactylifera* L.), which is widely cultivated in these areas, generates substantial organic waste, including leaves, stems, seeds, and fibers. Traditional disposal practices such as open burning and landfilling contribute to pollution and the loss of valuable organic matter. Composting offers a promising, environmentally friendly solution by converting date palm biomass into nutrient-rich organic amendments that improve soil structure, enhance fertility, and increase crop yields. This review examines the potential of composting as a sustainable strategy for valorizing date palm agro-waste. It discusses the composting process, nutrient content, and effects on soil properties, microbial communities, and plant growth. The review also highlights challenges such as quality control, scalability, and policy support, while emphasizing the role of composting in reducing chemical fertilizer use, enhancing carbon sequestration, and promoting circular agriculture systems.

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Keywords: Date palm waste; Composting; Sustainable agriculture; Soil health; Organic amendments; Waste management

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INTRODUCTION

Date palm (*Phoenix dactylifera* L.) is among the oldest cultivated fruit crops and serves as a vital component of agriculture and the economy in arid and semi-arid regions, particularly in the Middle East and North Africa (Soomro *et al*. 2023). Despite its nutritional and cultural significance, large-scale cultivation of date palms generates substantial agricultural waste fronds, bunches, petioles, flower clusters, and seeds. When mismanaged, these residues can lead to environmental degradation, including soil and water pollution, nutrient loss, and greenhouse gas (GHG) emissions (El Janati *et al*. 2023). This underscores the need for sustainable waste management solutions that align with environmental and resource efficiency goals (Kavvadias *et al*. 2024). Disposal pathways for date-palm agro-residues vary widely according to policy frameworks, enforcement intensity, and market incentives. Where open-burn prohibitions are actively enforced and landfill diversion targets or tipping fees apply, residues are redirected primarily toward aerobic composting, as well as mulching or anaerobic digestion, through municipal programs or grower cooperatives, leading to improved organic residue recovery and reduced uncontrolled emissions (Abid and Ammar 2022).

By contrast, where regulatory enforcement is weak and collection logistics are underfunded, conditions common in many arid producing regions, open burning and unmanaged dumping persist, particularly during seasonal pruning peaks (Kavvadias *et al.* 2024). Evidence from existing policy and development studies indicates that regulatory measures are most effective when paired with positive economic incentives, such as subsidized shredding or chipping, grants for windrow turners, or public-sector procurement guarantees for compost used in soil-restoration schemes (World Bank 2022).

This review synthesizes literature published between 2010 and 2025, drawing on Scopus, Web of Science, and regional sources, with a focus on processing parameters, compost quality and maturity, and agronomic outcomes related to date-palm residues.

From a composting standpoint, several features make date-palm residues more challenging to handle than "easy" substrates such as animal manures or urban green wastes. The woody trunk and petiole fractions are dense and fibrous, often requiring aggressive shredding or chipping to obtain particle sizes that can be aerated and turned effectively (Benabderrahim *et al*. 2018). When used alone, many date-palm residues exhibit high initial C:N ratios and relatively low nitrogen and phosphorus contents, which slow microbial growth and decomposition unless they are co-composted with manures or other N-rich co-substrates (Khan *et al*. 2025). In arid producing regions, residues are also prone to desiccation, so moisture can fall well below the 50 to 60% range needed for sustained thermophilic activity, whereas poorly structured or compacted piles may develop localized anaerobic pockets, odors, and nitrogen losses where water accumulates (Benabderrahim et *al*. 2018). In some cases, elevated salinity and sodium levels further constrain application levels on sensitive soils (Melebari 2025). These combined constraints help to explain why process design for date-palm composting must pay particular attention to pre-treatments, co-composting strategies and moisture aeration management.

In arid producing regions, residues are also prone to rapid desiccation, with moisture levels frequently falling below the 50 to 60% range required for sustained thermophilic activity, whereas poorly structured or compacted piles may develop localized anaerobic zones, leading to odor formation and nitrogen losses where water accumulates (Benabderrahim *et al*. 2018). In some cases, elevated salinity and sodium levels further constrain application rates on sensitive soils (Zarghami *et al*. 2025). Taken together, these constraints highlight why composting system design for date-palm residues must prioritize appropriate pre-treatments, co-composting strategies, and careful moisture aeration management. All major date producing countries face persistent challenges in managing this biomass. The Middle East and North Africa, as the leading global producers, generate vast quantities of waste annually (Razavizadeh and Niazmand 2022). Traditional disposal methods such as open burning and landfilling contribute significantly to climate change and air pollution through the release of CO_2, CH_4, and particulate matter (Rashid *et al*. 2023). These practices also harm soil quality, disrupt microbial ecosystems, and intensify methane emissions due to anaerobic decomposition (Mishra 2025).

Saudi Arabia produces approximately ~2 million tons of dates annually and hosts an estimated ~30 to 40 million date palms, underscoring the scale of biomass management challenges associated with this production system. Estimates of annual pruning residues vary depending on pruning intensity, tree age, and accounting approaches, but they generally fall within the hundreds of thousands of tons rather than the hundreds of millions previously reported. For example, per-tree residue estimates of ~15-40 kg translates into comparable national-scale ranges, reinforcing the need for recovery pathways beyond open burning or unmanaged dumping, including aerobic composting as a mitigation and valorization option (FAOSTAT 2023).

Co-composting with nitrogen-rich inputs (*e.g.*, manures) is an effective strategy when the initial C:N ratio exceeds ~30-35:1, but it is not the sole determinant of successful composting performance. Comparable improvements in stabilization and compost quality can be achieved through other well-documented operational controls, including particle-size reduction through shredding (increased reactive surface area), structural bulking to enhance porosity and air-filled space, maintenance of moisture around ~50 to 60% to limit anaerobic conditions and nutrient leaching, and forced aeration or regular turning to sustain thermophilic phases. In some systems, additional conditioning approaches such as biochar addition or mild alkaline pretreatments further improve aeration and buffering capacity. Composting configurations that combine several of these levers consistently report faster stabilization, improved physicochemical quality (pH and EC within agronomic ranges, lower NH_4^+/NO_3^- ratios), and enhanced plant performance in application trials (Aydi *et al*. 2023).

Unregulated waste disposal results in environmental hazards including soil salinity, biodiversity loss, and methane emissions. Composting presents a sustainable alternative by converting biomass into biofertilizers that support long-term agricultural productivity (Thadiyan *et al*. 2024). Its successful integration into farming systems, however, depends on targeted research, infrastructure development, and supportive policy frameworks (Abid and Ammar 2022). When widely adopted, composting can reduce chemical inputs, prevent soil degradation, and promote circular agricultural practices (Ait-El-Mokhtar *et al*. 2022).

Environmental benefits of composting extend beyond farms. By avoiding anaerobic decomposition in landfills, composting significantly reduces methane emissions and contributes to climate change mitigation. This is especially relevant for countries like Saudi Arabia, where Vision 2030 prioritizes sustainable environmental practices

Evidence from life-cycle assessment (LCA) and techno-economic analysis (TEA) indicates that aerobic composting of date-palm residues, and analogous pruning biomass, can lower net greenhouse-gas emissions relative to open burning or landfilling when system boundaries account for avoided disposal and nutrient-substitution credits. Cost competitiveness is primarily driven by collection and transport, size reduction, and aeration or turning requirements, but these costs may be partially offset by N–P–K credits, soil water-holding benefits, and, where applicable, public procurement or incentive schemes. Although compost generally has a higher cost per unit nitrogen than mineral fertilizers due to its lower nutrient density, its multifunctionality that includes improved soil structure, enhanced water-holding capacity, increased soil organic carbon, and salinity management can make it economically favorable at farm and municipal scales (Khadim et *al*. 2024).

Socially, community-based composting initiatives enhance public awareness, promote local participation, and create economic opportunities. Engaging farmers, youth, and rural stakeholders in decentralized composting projects builds capacity, encourages environmentally responsible behaviors, and offers educational and financial benefits. Economically, composting allows farmers to reduce reliance on expensive chemical fertilizers, increasing resilience to market fluctuations (Ansar *et al*. 2025). Excess compost can also be marketed locally, supporting circular economies and green job creation (Khoshnodifar *et al*. 2023).

Many agricultural residues are considered recalcitrant due to their high lignocellulosic content and resistance to microbial degradation. Date palm residues fall within this category of recalcitrant biomass, sharing structural characteristics with other perennial crop wastes such as oil palm residues, cereal straw, and sugarcane bagasse. Recognizing this recalcitrance is essential for understanding the specific composting strategies required for their effective stabilization and valorization.

In arid regions such as Saudi Arabia, where water scarcity and environmental pressures intersect, composting offers a strategic approach that links ecological restoration with economic sustainability. This review explores the potential of composting date palm waste to enhance soil properties, biodiversity, and crop yields while addressing challenges such as compost variability, adoption barriers, and infrastructure gaps. It highlights innovative practices including co-composting, pre-treatment technologies, and community engagement to propose actionable strategies for sustainable agriculture. By unlocking the value of date palm residues, composting can help build climate resilience, ensure food security, and advance eco-friendly farming systems in arid regions worldwide.

COMPOSITION OF DATE PALM WASTE

Chemical and Physical Properties of Date Palm Waste Components

Date palm (*Phoenix dactylifera* L.) waste is predominantly composed of lignocellulosic biomass, a complex material made up of cellulose, hemicellulose, lignin, and a variety of essential minerals (Fig. 1).

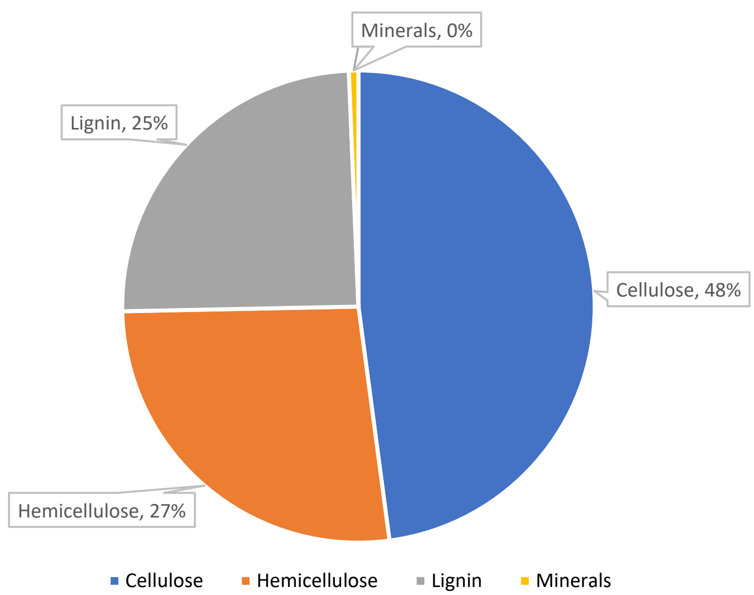

Fig. 1. The average weight percentage of chemical components of the date palm

These components not only define the physicochemical characteristics of the waste but also play a critical role in its decomposition behavior and composting potential (Abid *et al*. 2020). Cellulose, the most abundant polysaccharide in date palm residues, constitutes approximately 47.9% of the biomass. It is composed of β-(1→4) -linked D-glucose units that form a crystalline structure, providing mechanical strength and enzyme resistance, with thermal decomposition typically occurring at around 260 °C (Beyler and Hirschler 2002). This rigidity makes cellulose an important target for bio-based materials and bioethanol production, while also presenting a challenge in composting without adequate pre-treatment. In practice, low-cost mechanical pretreatments such as chipping or shredding are often sufficient to improve aeration and accelerate composting of date-palm residues and can be implemented at farm or cooperative scale. More energy- or chemical-intensive pretreatments may further enhance biodegradability but are generally only economically justified in centralized or high-input systems.

Hemicellulose is an amorphous carbohydrate polymer composed of a heterogeneous mixture of sugars, including xylose, arabinose, mannose, and galactose. In date palm waste, hemicellulose represents approximately 26.8% of the dry biomass and is characterized by a shorter degree of polymerization, higher solubility, and weaker structural organization compared with cellulose and lignin. Consequently, it decomposes more readily, with thermal degradation occurring at relatively moderate temperatures ranging from 200 to 250 °C, reflecting its lower structural resistance (Ali *et al.* 2024). These physicochemical properties make hemicellulose more favorable for microbial breakdown during composting, allowing it to serve as an early and readily available carbon source that supports microbial metabolism and accelerates organic matter transformation, particularly during the initial composting stages (Ait-El-Mokhtar *et al.* 2022). Additional processing steps, such as dewatering, can further improve composting efficiency by enhancing sugar availability or concentration and optimizing moisture conditions for microbial activity.

In contrast, lignin, which accounts for approximately 24.7% of date palm waste, is a highly branched aromatic polymer responsible for the hydrophobic and structurally rigid nature of this biomass. Lignin exhibits strong resistance to microbial degradation and undergoes thermal decomposition only at elevated temperatures ranging from 280 to 500 °C, during which phenolic compounds may be released that can inhibit microbial growth and activity (Chen *et al.* 2014). This resistance restricts microbial access to hemicellulose and cellulose fractions and constitutes the primary factor underlying the recalcitrant behavior of date palm residues during composting.

Therefore, pre-treatment strategies play a critical role in maximizing the composting efficiency of date palm waste, particularly given its high lignin content. Approaches such as mechanical shredding, chemical pre-treatment, and targeted microbial inoculation are widely reported as effective means of disrupting the rigid and hydrophobic lignin matrix, thereby improving microbial accessibility and accelerating the biodegradation of hemicellulose and other organic components (Chen *et al.* 2014; Ait-El-Mokhtar *et al.* 2022). By mitigating lignin-driven recalcitrance, these interventions enhance composting kinetics, reduce the inhibitory effects of phenolic by-products, and promote efficient organic matter stabilization, ultimately improving compost quality and process reliability (Ali *et al.* 2024).

Beyond the organic matrix, date palm waste is also rich in essential mineral elements. The inorganic fraction contains key macronutrients such as potassium (K), calcium (Ca), magnesium (Mg), and phosphorus (P), along with micronutrients including iron (Fe), zinc (Zn), manganese (Mn), silicon (Si), and sodium (Na) (Kavvadias *et al.* 2024). These nutrients not only enhance the fertility and nutrient profile of the resulting compost, but they also support plant growth when the compost is applied as a natural soil amendment. Thus, by coupling effective pre-treatment methods with the mineral richness of date palm waste, composting can be transformed into a highly efficient and sustainable process.

Effective dewatering processes are crucial in the pre-treatment of date palm waste, as they help regulate moisture content and reduce excess sugars through the addition of dry matter or juice concentration techniques. This step enhances microbial accessibility and prevents imbalances in the composting matrix. In particular, hemicellulose, which constitutes approximately 26.8% of the fibrous content, is an amorphous polysaccharide with a low degree of polymerization and relatively high solubility, making it easily degradable at moderate temperatures ranging between 200 and 250 °C (Alkalbani *et al*. 2022). These properties allow for a rapid breakdown during composting, providing an accessible carbon source for microbial metabolism.

However, lignin, comprising about 24.7% of date palm waste, poses a greater challenge due to its complex aromatic structure, which renders it both hydrophobic and structurally rigid. It resists degradation and requires high decomposition temperatures between 280 and 500 °C, during which phenolic compounds are released substances known to inhibit microbial growth (Chen *et al*. 2014). Therefore, targeted pre-treatment strategies, such as mechanical disruption, microbial inoculation, or chemical oxidation, are essential to break down lignin and enhance overall composting efficiency.

In addition to its organic components, date palm waste includes a valuable inorganic fraction that is rich in essential macronutrients (*e.g.*, K, Ca, Mg, and P) and micronutrients (*e.g.*, Fe, Zn, Mn, Si, and Na), which significantly improve the fertility and nutrient balance of the resulting compost. However, excessive concentrations of certain minerals can disturb pH levels and destabilize compost maturation; thus, careful monitoring and control may be required throughout the process (Abid and Ammar 2022). These physicochemical characteristics (Table 1), when combined with appropriate pre-treatment methods, underscore the considerable potential of date palm waste as a renewable biomass resource. This resource plays a pivotal role in advancing sustainable composting practices and contributing to the bioeconomy, particularly in arid regions where circular waste management solutions are increasingly vital. The nutrient profile, coupled with the carbon-to-nitrogen (C:N) ratio, is fundamental in optimizing the composting process. The interplay of these factors directly governs microbial activity and enhances the efficiency of organic matter decomposition, thus improving compost quality. For aerobic composting, an initial C:N ratio of approximately 25:1 to 35:1, combined with moisture contents around 50 to 60%, is widely reported to support rapid microbial growth and sustained thermophilic activity. Common pretreatments including particle-size reduction through shredding (increased surface area), structural bulking to maintain porosity and oxygen diffusion, and co-composting with nitrogen-rich materials when the initial C:N is high modify both the effective C:N ratio and substrate accessibility. In some systems, biochar addition or mild alkaline conditioning further contributes by improving pH buffering and nitrogen retention during active decomposition.

By contrast, anaerobic digestion (AD), which is not genuine composting and lies outside the main scope of this review, typically operates at a lower target C:N range (≈20-30:1). Deviations from this range may result in ammonia inhibition at low C:N or reduced biogas yields at high C:N. AD is mentioned here only to clarify that optimal C:N requirements are process-specific and should not be directly compared with aerobic composting.

Accordingly, Table 1 summarizes physicochemical properties of finished aerobic composts derived from date-palm residues, reflecting the combined effects of feedstock composition and pretreatment strategies.

Table 1A. Date-palm Residue Feedstocks and Process Configuration Reported in the Reviewed Studies

Reference	Residue type	Residue processing / pre-treatment	Composting conditions / maturity	Experimental use
Ghouili 2023	Palm leaves + cow manure	Not reported	Not reported	Not reported
Abid *et al*. 2020	Leaflets (fronds) + goat manure	Crushed (size as reported); soaked (≈5 days)	Aerated windrow composting (watered/managed during process)	Not reported
Aydi *et al.* 2023	Date-palm residues + animal manure (70:30)	Not specified	Compost used as finished material; process details not specified	Used as soilless substrate
Toubali *et al.* 2020	Green waste (quack grass)	Not specified	Composted to maturity (details referenced to Meddich 2016)	Mixed at 5% (w/w) with sterilized soil
Sadik *et al.* 2012	Date-palm mulch + fresh cow manure (1:1, 2:1, or 3:1)	Mechanically ground to ~2 inches; microbial activator added; moisture ~60%	Turned windrow; turning every 5–7 days	Not reported
Raja *et al*. 2021	Finely ground date-palm residues (0.5 cm)	Ground to ~0.5 cm	Composting duration treatments: 0 (uncomposted), 15 weeks, 30 weeks (mature)	Compared DP-0 vs DP-15 vs DP-30
Benabderrahim *et al.* 2018	Date-palm wastes (pruned fronds/residues)	Ground; soaked 7–10 days; dried; mixed with cow manure (3:1)	Windrow composted; turning every 2 weeks; matured ~6 months	Not reported
Abid 2018	Date-palm waste fibers + goat manure	Fibers crushed/shredded (structuring agent)	Co-composted to maturity (stable; C/N ≈ 17 as reported)	Added at 5% to substrates
Mbarek *et al.* 2019	Date-palm wastes (34%) + sheep manure (66%)	Air-dried & crushed for lab analyses (sample prep)	Windrow composting up to ~6 months (immature vs mature compost described)	Not reported

Notes (Table 1A): Residue processing / pre-treatment" covers only steps applied before composting (chopping/shredding/grinding/soaking/drying). NR = not reported.

Table 1B. Physicochemical Properties of Finished Composts Produced from Date-palm Residues (and comparator compost where applicable)

Reference	pH	EC (dS/m)	Total C (%)	Total N (%)	C/N Ratio
Ghouili 2023	7.80	8.69	18.58	1.21	15.36
Abid *et al.* 2020	6.10 ± 0.18	1.42 ± 0.22	48.50 ± 1.20	0.81 ± 0.04	60.0 ± 2.10
Aydi *et al.* 2023	7.88 ± 0.11	8.32 ± 0.18	–	–	–
Toubali *et al.* 2020	7.74 ± 0.01	5.46 ± 0.00020	5.72 ± 0.45	1.32 ± 0.01	–
Sadik *et al.* 2012	6.66	–	44.45	0.58	76.63
Raja *et al.* 2021	7.80	2.10	53.82	0.80	58.50
Benabderrahim *et al.* 2018	7.6 ± 0.3	3.2 ± 0.4	32.5 ± 32	1.2 ± 2	27.08
Abid 2018	7.00 ± 0.16	7.86 ± 0.08	–	–	–
Mbarek *et al.* 2019	8.33 ± 0.01	7.30 ± 0.21	–	–	29.12

Notes (Table 1B): "–" = not reported in the original study. C/N is shown as reported by the authors (or can be recalculated as %C/%N only when units are consistent and clearly stated).

Suitability for Composting: Nutrient Profile and Carbon-to-Nitrogen (C: N) Ratio

The potential of the date palm waste to undergo composting depends on two key parameters, namely the carbon-to-nitrogen (C: N) ratio and nutrient composition of the waste. Such parameters play an important role in affecting microbial activities and degradation of organic matter as well (Zhao *et al*. 2025). The waste promotes high microbial activity and thus quality of compost due to abundant carbon (C), nitrogen (N), phosphorus (P), potassium (K), and other essential organic components found within them (Abdelaal *et al*. 2025). Naturally, the waste has low nitrogen, which may limit the speed of decomposition. Thus, to compensate for nutrient availability, the addition of nitrogen-rich materials is required such as animal dung or leguminous wastes (Ayaz *et al*. 2025). The C:N ratio showed a high variation for date palm waste, which was between 50:1 and 80:1 depending on the plant part (leaves, fronds, or fibers) it contains (Ali *et al*. 2025). Hence, because of a lack of nitrogen, higher ratios would slow the decomposition rate; supplementation with nitrogen-rich sources such as food waste or green plant residues is suggested to maximize microbial activity (Khan *et al*. 2025). The optimum C:N ratio for composting is between 25:1 and 35:1. Pre-treatment methods such as shredding or hydrolysis will improve biodegradability (Hřebečková *et al*. 2025). Addition of date palm waste with nitrogen-rich materials such as poultry manure or legume residues enhances microbial degradation, and the right measurement of moisture and aeration are essential for microbial metabolism and anaerobic conditions during composting. The high lignocellulosic content of date palm waste makes it particularly appropriate for long-term composting, contributing to the development of stable humic compounds that improve soil structure and water retention (Kavvadias *et al*. 2024). Future studies should focus on enzymatic and microbiological treatments to boost nitrogen availability and accelerate the decomposition process, thus enhancing composting efficiency and sustainability (Chen *et al*. 2014).

Composting Process and Optimization

Composting is a microbially-driven aerobic or anaerobic process that transforms organic waste into a stable, nutrient-rich soil amendment. It plays a pivotal role in sustainable agriculture, soil health, and organic waste management. However, composting date palm (*Phoenix dactylifera* L.) waste presents specific challenges due to its high lignocellulosic content, elevated carbon-to-nitrogen (C: N) ratio, and low biodegradability (Kavvadias *et al*. 2024). Overcoming these challenges requires understanding the core composting mechanisms, identifying influential parameters, and implementing appropriate optimization strategies.

Organic-residue treatment includes two distinct biological routes: aerobic composting, an oxygenated, thermophilic biostabilization process yielding mature compost; and anaerobic digestion (AD), an oxygen-free process producing biogas and a digestate that may be post-composted. Aerobic composting is particularly effective for date-palm residues due to its efficiency in degrading complex lignocellulosic matrices (Nakhshiniev *et al*. 2012). Thermophilic and mesophilic microorganisms dominate this process, driving the internal temperature to the range 50 to 70 °C, which accelerates organic matter decomposition and enhances pathogen and weed seed suppression. Despite its rapid stabilization, aerobic composting necessitates controlled aeration either through mechanical turning or forced air systems (Fig. 2). Studies have demonstrated that co-composting with nitrogen-rich amendments, such as poultry manure, significantly enhances microbial activity and accelerates the decomposition of date palm biomass (EL-Mously *et al*. 2023).

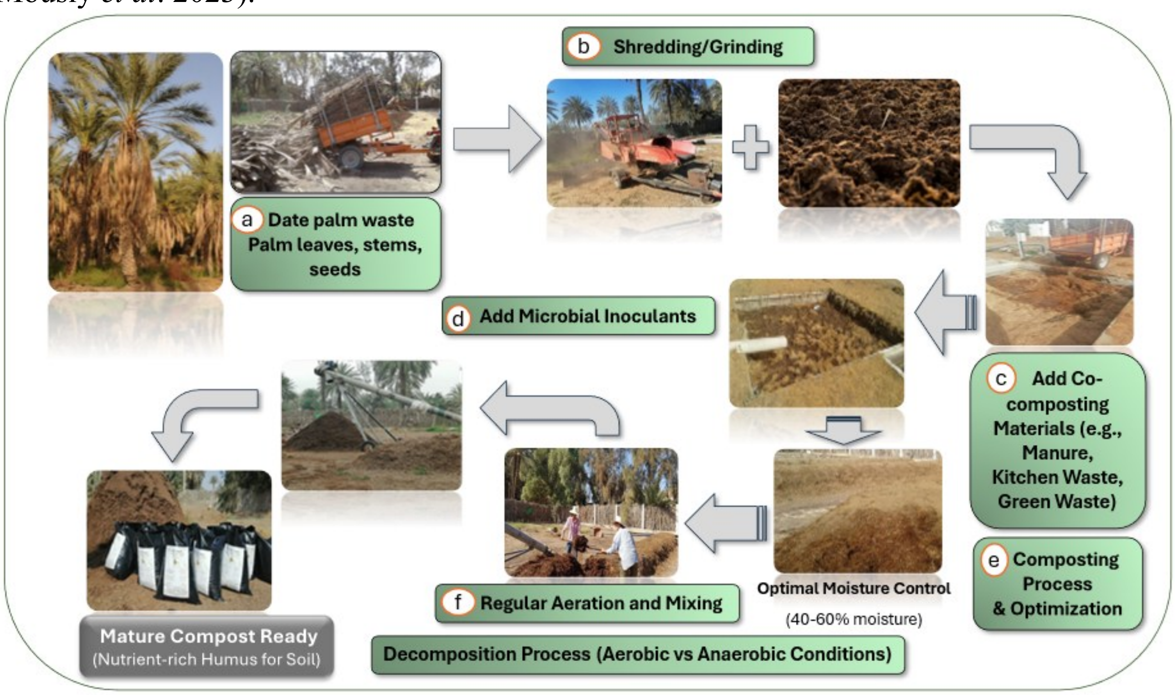

Fig. 2. Date palm waste composting process

Conversely, anaerobic digestion operates under limited oxygen conditions, relying on fermentative and methanogenic microorganisms to convert organic matter into stabilized digestate and biogas primarily methane and carbon dioxide (Mckenzie *et al*. 2022). Although the process is slower and more sensitive to inhibitory compounds, it offers advantages such as lower operational energy inputs and biogas recovery for renewable energy generation. Anaerobic digestion of date palm waste is less common; however, when integrated with anaerobic digestion systems, it presents an attractive solution for simultaneous waste valorization and energy production. Challenges such as the production of volatile organic compounds (VOCs) and associated odors must be managed effectively to ensure environmental compliance (Remmani 2024).

A range of physicochemical factors critically influence the efficiency and quality of compost produced from date palm residues. These include particle size, moisture content, inoculation strategies, and selection of co-composting substrates. Reducing particle size improves the surface area available for microbial colonization and enzymatic action. However, excessive size reduction may result in compaction, reduced oxygen diffusion, and anaerobic pockets, negatively impacting microbial respiration. Optimal moisture content (50% to 60%) is essential to maintain microbial activity; insufficient moisture limits metabolic processes, while excess water can lead to anaerobic conditions and nutrient leaching (Ali *et al*. 2025).

Compost maturity for date-palm residues

In this review, *maturity* denotes the end of active biodegradation when the product is stable, non-phytotoxic, and agronomically safe. Practical indicators include the return of pile temperature to near-ambient after a sustained thermophilic phase; low biological activity (*e.g*., OUR/AT4); germination index (GI) ≥ 80–90% in sensitive test species; NH_4^+/NO_3^- < 0.16 to 0.5; and stable pH (~7 to 8) with EC within crop-appropriate thresholds. Maturity is especially important for date-palm residues because their lignocellulosic/waxy tissues and potential salinity can otherwise cause ammonia/organic-acid phytotoxicity, temporary nitrogen immobilization, and salt stress at application. Where reported, maturity metrics are summarized in Table 1B.

For date-palm residues, moderate mechanical size reduction represents the most cost-effective pretreatment in most reported systems. To further enhance biodegradation rates, microbial inoculants including lignocellulolytic fungi (*e.g.*, *Trichoderma* spp., *Phanerochaete chrysosporium*), nitrogen-fixing bacteria (*e.g.*, *Azotobacter* spp.), and Actinomycetes are often introduced. These functional microbes facilitate the breakdown of recalcitrant lignin and cellulose compounds, reduce composting time by up to 40%, and enrich the compost with plant-available nutrients (Ninkuu *et al*. 2025).

A critical parameter in composting optimization is achieving a balanced C:N ratio. Chicken, cow, and sheep manure, as well as vegetable and fruit kitchen waste, and even green plant byproducts such as legumes and grass clippings, are all nitrogen-rich materials that can assist the vertically high carbon date palm waste (Kavvadias *et al*. 2024). Research indicates that incorporating goat manure with date palm waste increases the C:N ratio from 60 to 20 at the end of composting which enhances organic matter stabilization (Khan *et al*. 2025). In addition, combining 30% manure and 10% green plant residues with date palm waste results in an ideal C:N ratio of 25:1 which improves the rate of decomposition and nutrient retention (Kavvadias et *al*. 2024). Thus, the effect of C:N ratio on decomposition rate and nutrient conservation is tightly linked to moisture management, and balanced C:N values only express their full benefit when moisture is maintained within the 50 to 60 % range described above, which supports optimal microbial activity and oxygen diffusion.

Examples of successful large-scale composting initiatives further highlight the potential of date palm waste management in arid regions. Notably, a recent pilot-scale program in Saudi Arabia utilized a combination of date palm waste, poultry manure, and biochar to enhance compost quality (Alkoaik *et al*. 2019). This integrated approach not only optimized the C:N ratio but also significantly accelerated the composting process, achieving a 50% reduction in composting time compared to traditional methods. These findings demonstrate the viability of innovative composting strategies for promoting sustainable waste management in water-scarce environments. More specifically, composting was conducted within 60 to 90 days, producing good-quality compost with an increased level of nutrients (Arroussi *et al*. 2022).

Moreover, this approach also enhanced humus content, which resulted in better soil fertility, and greatly improved microbial diversity, which promoted decomposition rates (Ghouili *et al*. 2023). These findings underscore the importance of adopting well-optimized composting strategies to maximize the benefits and minimize the limitations of composting date palm waste. In summary, optimizing this process requires an integrated approach involving the careful selection of co-composting materials, control of moisture and aeration, use of effective microbial inoculants, and precise adjustment of the C:N ratio. These strategies are essential for transforming date palm residues into a high-quality organic fertilizer, supporting sustainable agriculture, circular waste valorization, and the development of the bioeconomy, particularly in arid and semi-arid ecosystems. The high quality and nutrient richness of compost derived from date palm waste open the door to numerous agronomic and environmental applications.

Compost maturity is a critical factor governing the agronomic safety and effectiveness of compost derived from date palm residues. Mature compost is characterized by the stabilization of organic matter, the reduction of phytotoxic compounds, and the establishment of a balanced microbial community. In studies of date palm waste compost produced with forced aeration, maturity was shown to be associated with a high germination index (83.8%) and was negatively correlated with salinity, C/N ratio, and total soluble phenols, indicating depletion of phytotoxic substances as compost stabilized (Mohamed et *al.* 2020). The seed germination index (GI) is widely accepted in compost science as a biological maturity indicator, where values ≥70% typically reflect mature and safe compost (compost maturity assessment literature). The carbon-to-nitrogen (C:N) ratio commonly decreases during composting as organic matter is decomposed, and C:N values <20 are often considered indicative of mature compost products in practical assessments. Immature compost from lignocellulosic date palm residues may contain organic acids, ammonia, or soluble phenolics that inhibit seed germination and root development, highlighting the importance of ensuring maturity before agricultural use. Properly matured date palm residue compost provides more stable nutrient release, enhanced soil biological activity, and reduced risk of phytotoxicity, making compost maturity a fundamental prerequisite for its safe and effective use in agricultural systems.

Applications of Date Palm Residue Compost

Date palm residue compost has gained recognition for its diverse and valuable applications in agriculture, environmental management, and urban gardening (Table 2).

Table 2. Applications of Date Palm Residue Compost

Application *Area*	Benefits	Example Uses	References
Soil Health Improvement	Improved structure, aeration, water retention	Agricultural fields, degraded soils	Kavvadias *et al*. (2024)
Crop Productivity	Increased yield, reduced synthetic inputs	Cereal crops, vegetables, orchards	Merad *et al*. (2025)
Pest and Disease Management	Suppression of pathogens, enhanced resilience	Integrated pest management programs	Hessane *et al.* (2025)
Urban and Home Gardening	Nutrient-rich potting media, space-efficient	Rooftop gardens, container plants	Kalukuta *et al*. (2025)
Biochar and Active Carbon	Fertility boost, pollutant absorption	Soil amendment, gas absorbers, water filtration	Mansour *et al*. (2025)
Water Pollution Management	Heavy metal and toxin removal	Filters for heavy metals, dyes, phenolics, pesticides	Kavvadias et al. (2024)
Sustainability and Circular Economy	Environmental benefits, reduced waste	Green building materials, insulating boards	Al-Moftah *et al*. (2025)

Recent experimental and field studies provide quantitative support for these applications. Application levels of date palm waste compost in the range of 10 to 20 t ha^{-1} have been reported to increase soil organic matter by approximately 15 to 30%, improve water-holding capacity by up to 25%, and reduce soil bulk density by about 10 to 20% compared to unamended soils (Khadim et *al*. 2024).

Date Palm Waste Compost plays a crucial role in enhancing soil health, improving crop productivity, managing pests and diseases, and supporting urban horticulture. By significantly improving soil structure, aeration, and water retention, compost helps to reduce compaction and promotes root penetration. Furthermore, it enriches the soil with organic matter, thereby stimulating microbial activity that facilitates nutrient cycling and ensures long-term fertility (Kavvadias *et al*. 2024). Compost produced from water-soaked mixed date palm waste and goat manure showed a reduction in organic matter content of about 36% during composting and a decrease in the carbon-to-nitrogen ratio from 60 to 20, indicating effective decomposition and maturation of the compost product (Abid et *al.* 2020). The introduction of compost into the soil enhances aggregate stability, reduces erosion, and improves the soil's moisture retention capacity, which is particularly critical in arid and semi-arid regions where water conservation is a priority. Additionally, compost improves the cation exchange capacity of the soil, which enhances nutrient retention and availability for plants, ultimately promoting healthier plant growth and ecosystem stability (Khadim *et al*. 2024). The decomposition of organic materials within compost releases essential macronutrients and micronutrients, fostering sustainable soil management practices.

The use of compost has a direct positive impact on crop productivity (Ait-El-Mokhtar *et al*. 2022). It enhances plant growth, yield, and quality by improving biomass accumulation, fruit size, and nutritional content, while also increasing photosynthetic efficiency and root development (Aydi *et al*. 2023). For example, in a controlled growth experiment, the addition of compost to soil significantly increased pepper plant root and shoot biomass compared to manure and unamended controls; the fresh aerial biomass with compost was 332.2 g compared to 86.01 g with manure and just 3.63 g in the control (Kalukuta et *al*. 2025). This organic amendment releases macronutrients such as N, P, and K elements slowly, making them available to plants over time and minimizing nutrient leaching and runoff. Moreover, compost promotes the diversity of soil microbes that play vital roles in building symbiotic relationships for nutrient uptake and disease prevention. The organic matter in compost improves soil tilth, enhancing root development and water absorption. It also boosts enzymatic activities in the soil, aiding the metabolic processes crucial for plant development, which ultimately results in increased plant yield and quality. One of its most remarkable benefits is its ability to suppress weeds by creating a healthier, more competitive soil environment, thereby reducing reliance on chemical herbicides. Additionally, compost serves as an excellent nutrient source, decreasing the need for synthetic fertilizers, reducing production costs, and minimizing environmental pollution (Zangoueinejad and Alebrahim 2024).

Beyond its positive impact on plant growth, composting mitigates the harmful effects of chemical fertilizers on soil health, such as nutrient imbalances and the destruction of beneficial microorganisms. By recycling agricultural waste into compost, the accumulation of waste is minimized. This contributes to the advancement of circular agriculture. In terms of pest and disease management, compost supports the population of beneficial microbes that compete with plant pathogens and pests in the soil, producing bioactive substances that inhibit their activities and reduce disease incidence (Haggag 2020). Compost has been shown to promote microbial diversity and enhance soil suppressiveness, which helps prevent the establishment and growth of harmful pathogens. Beneficial fungi such as *Trichoderma* spp. and *Bacillus* spp. play a key role in antagonizing plant pathogens through antibiotic production and resource competition (Hashem *et al*. 2016)

Compost also contributes to increased organic content in the soil and activates resistance pathways in plants, offering another layer of defense against pest attacks. Additionally, microorganisms that specialize in chitin degradation assist in integrated pest control by breaking down the exoskeletons of pests. Another important function of compost is the adsorption of unwanted chemicals, such as pesticide residues and heavy metals, followed by their biodegradation, which prevents their accumulation in the soil (Laishram *et al*. 2025).

The use of compost alters nutrient proportions in a beneficial manner and alleviates crop salt stress by providing a source of positive ions (Melebari 2025). Date palm waste compost, being of relatively low density and rich in nutrients, is particularly suitable for urban farming, rooftop gardening, potted media, and home gardens. It serves as a renewable growing medium in urban farming programs, allowing plants to thrive in confined spaces with minimal dependence on chemical fertilizers (Akensous *et al*. 2025). Incorporating compost into potted plants and self-contained gardening systems improves soil fertility, increases water retention, and enhances aeration, promoting healthy plant growth (Johnson Jeyaraj and Sankararajan 2025).

Composting embodies the core principles of sustainability, particularly in waste management and agricultural practices (Smith 2025). It transforms organic waste into stable, nutrient-rich materials that enhance soil structure, fertility, and biological activity, thus supporting sustainable food production systems. Life cycle assessment studies have provided quantitative indicators of waste diversion efficiency and greenhouse gas mitigation associated with composting systems, confirming their contribution to sustainable waste management (Al-Moftah et *al*. 2025). Recent advances in composting technologies, such as the use of specific microbial inoculants and biochar amendments, have been shown to accelerate composting processes, enhance nutrient stabilization, and improve compost maturity (Burezq 2024). These improvements increase the agronomic value of compost, offering long-term environmental and economic advantages for future generations. Figure 3 illustrates the three major applications of date palm waste compost, namely sustainable agriculture, urban horticulture, and environmental conservation.

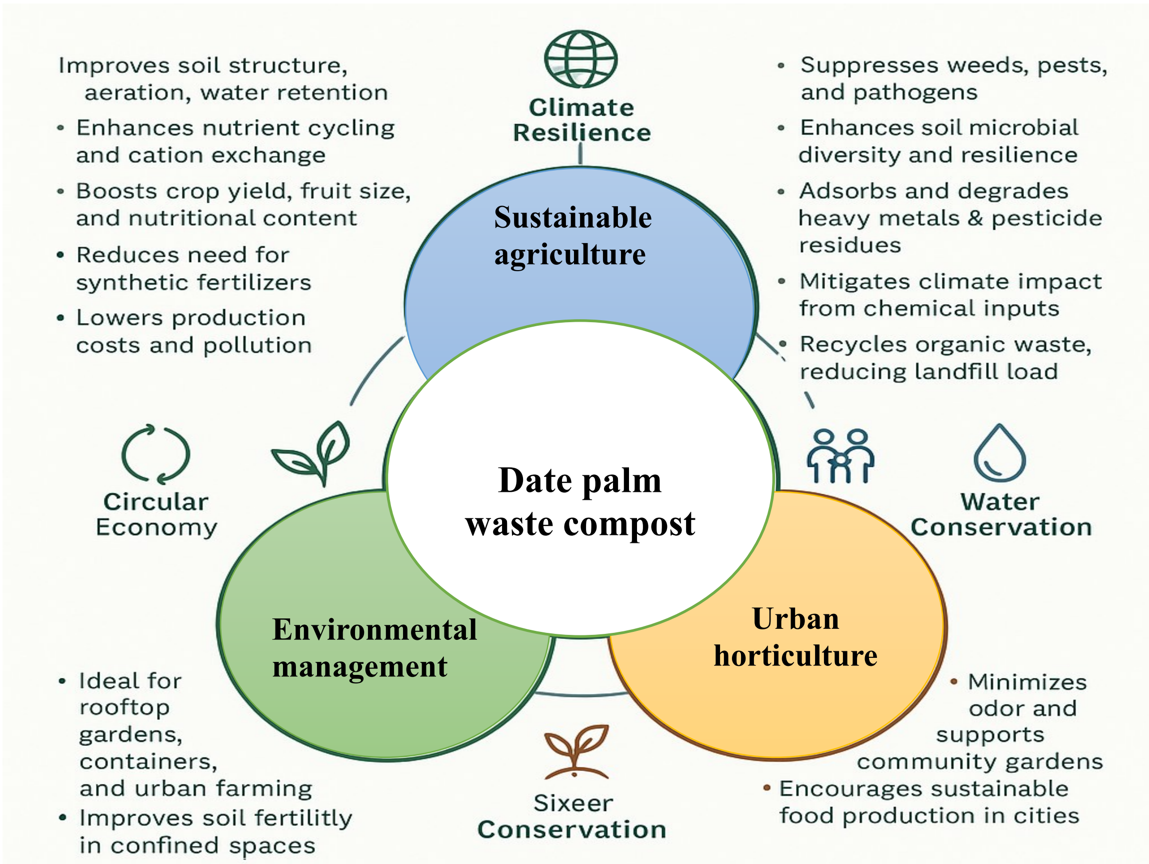

Fig. 3. Environmental and economic benefits Date palm waste compost

In agriculture, compost application improves soil organic matter content, enhances nutrient availability, and promotes crop productivity while reducing dependency on chemical fertilizers (Ou-Zine *et al*. 2021). In urban horticulture, compost use in green roofs and urban gardens contributes to heat island mitigation, improves biodiversity, and supports the development of circular urban economies (Mishra 2024). Additionally, composting diverts organic waste from landfills, reducing methane emissions and contributing to environmental protection (Al-Moftah *et al*. 2025).

Promoting composting practices in both large-scale farming and small-scale urban gardening provides a viable solution to organic waste management challenges while fostering ecosystem resilience. Continued innovations in composting methods and microbial technologies are expected to amplify the environmental and economic benefits of composting, ensuring a lasting positive impact for future generations (Musa and Elnour 2024).

Environmental and Economic Benefits

Composting date palm waste is one of the most effective solutions for environmental and economic sustainability in agriculture, thus contributing to the shift towards a circular economy. This process involves converting agricultural waste into productive resources, promoting environmental conservation, soil improvement, and reducing dependence on synthetic fertilizers (Ben Mahmoud *et al*. 2022). Integrating compost into agricultural practices ensures optimal resource management and waste reduction, thereby closing the nutrient loop for long-term agricultural productivity (El Janati 2022).

The incorporation of date palm waste into the composting process is a key element in circular economy systems, as composting transforms organic waste previously considered useless into an agricultural input that simultaneously reduces environmental burdens and improves resource efficiency (Abid and Ammar 2022). Composting also preserves soil organic matter, which stimulates microbial activity, improves soil structure, aeration, and water retention, thus making water more available to crops (Shah and Wu 2019). These improvements are essential for increasing crop productivity and ensuring long-term sustainability, as they consume fewer natural resources while reducing production costs (Khan *et al*. 2025). Moreover, composting reduces dependence on chemical fertilizers, which are not only expensive but also pollute the environment and degrade the soil over time (Khare *et al*. 2025).

The most significant impact of composting date palm waste is its ability to mitigate greenhouse gas emissions. Open burning and waste disposal significantly contribute to methane and carbon dioxide emissions, which are responsible for global warming (Al-Moftah *et al*. 2025). Unlike these methods, composting provides aerobic decomposition, which significantly reduces methane emissions while promoting carbon sequestration in the soil (Wang *et al*. 2025). This process helps offset carbon emissions and mitigate the effects of climate change (Al-Moftah *et al*. 2025). Composting and enhanced carbon storage will be a crucial intervention for mitigating agriculture's carbon footprint while strengthening climate-resilient farming practices.

The economic argument for composting date palm waste is that such activities reduce the farmers’ costs in buying synthetic fertilizers while maximizing their production yields (Mahina *et al*. 2025). The analysis of the costs and benefits of compost production favors its viability, especially in areas where date palm waste is generated in abundance. While organic soil amendments are ever on demand from conventional and organic agriculture, other compost marketing and distribution avenues would open. These investments in composting enterprises will provide better returns and offer a mitigative approach to environmental impacts. Composting maintains soil health in the long term, eliminating the need for costly future rejuvenation methods, thus ensuring land sustainability. In general, the principles of circular economy applied to modern agriculture allow for the efficient valuation of organic waste, such as date palm residues, instead of disposal. This approach not only conserves land but also natural resources and enhances soil productivity. Ultimately, nutrients are recycled, and compost improves soil structure while maintaining and further increasing microbial diversity, making ecosystems more resilient for sustainable agricultural practices (Ben Zineb *et al*. 2024).

Research and investment directed toward technologies enabling compost production should, therefore, be accorded priority on account of the major environmental and economic advantages. In refining secondary processes of production (Rehali *et al*. 2025), filling in knowledge gaps about the potential revenue of large-scale composting would further strengthen the economic case for this practice (Liu *et al*. 2022). As farmers begin to see the benefits of composting as a technique for enhancing the sustainability of agriculture and reducing degradation of the environment, the practice would benefit from adoption by farmer communities through an enabling environment of policy incentives, technical assistance, and market development efforts.

Challenges and Limitations

The composting of date palm waste presents several challenges and limitations that affect both the efficiency of the process and the quality of the final compost product. A primary constraint is the high lignin content in date palm residues (Najahi *et al*. 2023). Lignin, a complex and recalcitrant organic polymer that strengthens plant cell walls, is notably resistant to microbial degradation. Consequently, the decomposition of highly lignified date palm biomass is markedly slower than that of other organic materials, often taking up to a year for complete breakdown (Gałązka *et al*. 2025). This prolonged degradation process results in delayed compost maturation and reduced product quality (Wang *et al*. 2025). To address this, interventions such as microbial inoculants, enzymatic hydrolysis, or mechanical pre-treatments such as shredding are often required to accelerate lignin breakdown and enhance composting efficiency (Yang *et al*. 2021).

Another challenge lies in the variability of waste composition, which fluctuates by region, farming practices, and harvest timing (Souli *et al*. 2022). These variations affect the moisture content, nutrient profile, and fiber structure of the date palm residues, making it difficult to standardize composting protocols (El Janati 2023). As a result, the inconsistency in raw materials can lead to a final compost product of uneven quality and agronomic effectiveness (De Corato 2020). Seasonal fluctuations in biomass availability further complicate the logistics of continuous composting operations, requiring improved waste storage and inventory management strategies to ensure year-round supply.

Technical and logistical constraints also pose significant barriers to the large-scale adoption of date palm waste composting. The bulky and fibrous nature of the residues necessitates specialized equipment for effective shredding, mixing, and aeration. Furthermore, maintaining optimal conditions for microbial activity such as temperature, oxygen levels, and moisture content is challenging at industrial scales, often demanding advanced infrastructure and continuous monitoring systems (Waqas *et al*. 2023). In addition, the need for skilled labor and substantial capital investment limits the feasibility of composting operations in some regions.

To overcome these barriers, there is a need for the development and adoption of innovative composting technologies, efficient waste management frameworks, and policy support that promotes sustainable agricultural waste valorization. Research and extension services should focus on scalable solutions that are locally adaptable and economically viable to maximize the environmental and agronomic benefits of composting date palm waste (Abid and Ammar 2022).

Innovations and Future Directions

Innovative strategies are emerging to address the inherent challenges of composting lignin-rich date palm residues, particularly their resistance to microbial degradation. One of the most promising developments lies in the application of microbial biotechnology and genetic engineering. Recent research has identified a variety of ligninolytic microorganisms, especially specific strains of fungi and bacteria, that are capable of breaking down lignin with greater efficiency (Zhou *et al*. 2025). The incorporation of these naturally occurring or genetically engineered microbes into composting systems has shown significant potential to accelerate decomposition, improve compost quality, and shorten processing time (Barooah and Chetri 2025).

Genetically modified microbial strains that express high levels of lignin-degrading enzymes represent a breakthrough in optimizing the composting of highly recalcitrant organic matter such as date palm waste (Liu *et al*. 2022). As with other recalcitrant lignocellulosic biomasses, this resistance to degradation necessitates adapted composting conditions, pretreatments, or microbial interventions to ensure efficient decomposition. These engineered microbes can rapidly convert complex polymers into simpler, bioavailable compounds, thereby enhancing the nutrient content and agronomic value of the final compost product (Khan *et al*. 2025). However, the large-scale deployment of genetically engineered or highly specialized microbial strains is often constrained by regulatory requirements, biosafety considerations, and high implementation costs, limiting their use mainly to laboratory or pilot-scale systems in many date-palm-producing regions.

Beyond technological advancements, the successful scaling of composting initiatives requires robust policy support and stakeholder engagement. Government institutions and agricultural organizations have a crucial role in promoting sustainable composting practices through financial incentives, regulatory frameworks, and subsidies aimed at encouraging farmers and agro-industries to adopt composting as a viable waste management strategy. Composting strategies therefore need to align with local regulatory frameworks and prioritize low-cost, policy-compliant technologies to ensure practical adoption.

Moreover, the development of standardized composting protocols including quality benchmarks, application guidelines, and monitoring tools can foster consistency, safety, and market trust. Raising awareness through training programs, workshops, and community-based outreach can further engage farmers, agronomists, and environmental organizations in recognizing the environmental, economic, and social benefits of converting date palm waste into valuable compost.

From an application perspective, cost remains a major limiting factor, as capital investment, energy demand, labor, and regulatory compliance can substantially increase the overall cost of advanced composting technologies. Future research should thus emphasize economically viable, region-specific composting solutions that balance efficiency with affordability.

Taken together, these innovations and collaborative strategies can help build a circular bioeconomy, reduce dependence on chemical fertilizers, and advance climate-smart agriculture, particularly in arid and semi-arid regions where date palm cultivation is economically and culturally significant (Khan *et al*. 2025).

CONCLUSION AND FUTURE PERSPECTIVES

Composting date palm waste offers an eco-friendly and efficient solution for managing agricultural waste, particularly in arid and semi-arid regions such as Saudi Arabia. By converting agricultural residues into nutrient-rich compost, this practice not only helps reduce pollution but also enhances soil fertility and supports the principles of a circular economy.

While challenges such as high lignin content, waste variability, and logistical constraints still exist, recent technological advancements including enzymatic treatments, biochar integration, and microbial biotechnology show great promise in optimizing the composting process. These innovations can speed up the degradation of date palm residues, improve compost quality, and make the management of these agricultural by products more feasible and cost-effective.

However, to fully realize the potential of composting, it is essential to implement strong policy support, develop the necessary infrastructure, and raise awareness through education and outreach. These efforts will help encourage wider adoption of composting practices by farmers and industries. Additionally, creating standardized guidelines for compost production and use will ensure consistency and foster greater trust in composting as a reliable agricultural practice.

In the context of Saudi Arabia's Vision 2030, integrating composting into national sustainability strategies offers a significant opportunity. Not only will it help address the growing issue of agricultural waste, particularly from date palm cultivation, but it will also improve soil health, reduce pollution, and contribute to climate-resilient agriculture. By improving soil fertility, water retention, microbial diversity, and reducing greenhouse gas emissions, composting plays a key role in enhancing both environmental and agricultural sustainability.

This review has highlighted both the potential benefits and the challenges of date palm waste composting, while also suggesting innovative solutions, such as nitrogen-rich additives, pre-treatment techniques, and collaboration among stakeholders. Overcoming these challenges will help scale up composting efforts, making a meaningful contribution to sustainable development goals, including soil restoration, climate action, and food security both in Saudi Arabia and in other regions facing similar challenges.

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Conflicts of interest

The authors declare no conflicts of interest.

Declaration of Competing Interest

The authors confirm the absence of any conflicts of interest and disclose no significant financial support that may have biased the study findings.

Data availability

Data will be made available on request

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