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ORIGINAL ARTICLE

Composting date palm residues promotes circular agriculture in oases

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Abstract

Dry leaves of date palms (DPs) are by-products of date cultivation that are often mismanaged in oasis agroecosystems. Ideally, they should be upcycled in a circular agriculture model before producing and exporting high-value products. Compost inputs enhance soil organic matter and conserve soil. This study investigated composting of four mixtures based on farming system requirements and the availability of organic resources. The DPs were used alone or combined with sheep manure and rock phosphate. We experimented with farm-scale windrow composting to improve understanding and support decision-making. The results showed that temperature increased rapidly to 70 °C at the beginning of composting in the mixtures with manure. Organic matter content decreased by 40% in all windrows during composting, which indicated organic matter mineralisation and loss of volatile solids. Composting DP with or without sheep manure for 136 days with two turnings conserved nitrogen and increased the nitrogen content of compost. Mixing DP with sheep manure and rock phosphate increased the final total phosphorus content of compost to 0.52% (dry matter basis). Our results highlight that composting DP is a feasible alternative to improve circularity in oasis agroecosystems, by increasing organic matter content and fertiliser value, thus paving the way for sustainable production of high-value products from DP.

Keywords Composting · Dry palms · Rock phosphate · Nitrogen · Phosphorus losses · Circular agriculture

1 Introduction

Date palm (*Phoenix dactylifera* L.) is the main crop in oasis agroecosystems in Saharan and sub-Saharan regions [1]. Unlike the oil palm, it is cultivated in arid regions. In Morocco, the date palm covers 59,613 ha [2] and provides 40–60% of the annual agricultural income of farmers [3]. The Plan Maroc Vert (2009–2020) and Green Generation strategy (2020–2030) paid special attention to the date palm sector given its vital socio-economic impact on the population of oasis areas [4]. The national date palm planting program aims to plant 5 million palm trees in the Green Generation strategy, including 4 million in the Draa-Tafilalet region, with 2.4 million trees for the intensification of traditional oases and 1.6 million trees for extensions (i.e. monocropped date palm) [4].

One of the largest organic waste products (OWPs) in oases is dry date palm (DP) leaves, which remain attached to the tree until they are pruned. Every year, 1.6 million t of DPs are produced worldwide: Agoudjil et al. [5] estimated 105 million date palm trees in the world, each of which produces approximately 15 dry leaves of ca. 1 kg each [6, 7]. In recent years, they have been abandoned in fields, which can cause insect and disease infestation, or burnt, which can cause other environmental issues, especially accidental fires (Fig. 1).

Processing agricultural waste after producing high-value products generates large amounts of OWPs. One way to upcycle them in agriculture is to transform them into a stable organic amendment such as compost to provide stable

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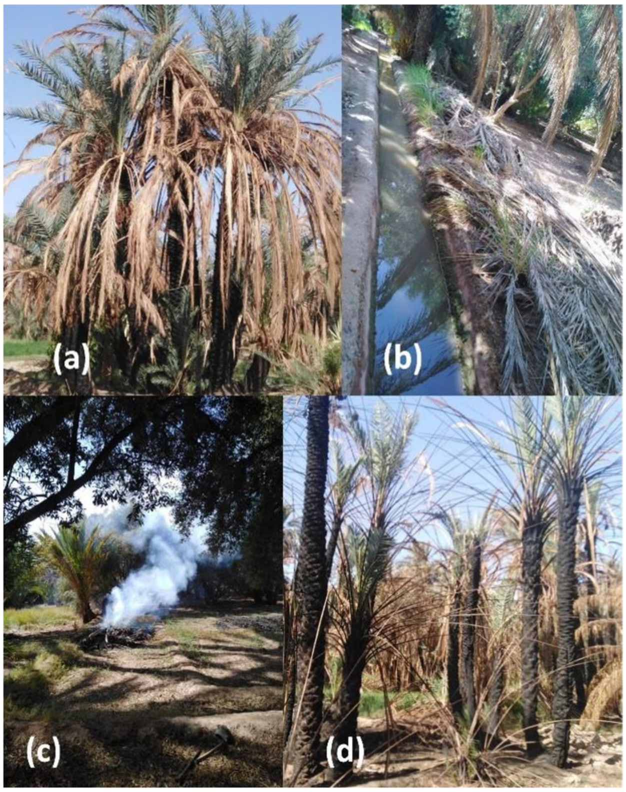

Fig. 1 Current management of dry palm leaves in the Draa-Tafilalet region of Morocco: **a** dry leaves on a palm tree, **b** pruned leaves left beside an irrigation canal, **c** burning leaves, and **d** palm trees after a fire

carbon (C) compounds and fertilising nutrients. Compost produced on farms has replaced commercial compost in recent years [8]. Composting is recognised as an attractive agricultural practice and an economical and sustainable approach to OWP management because it is simple to perform and can be adapted to a wide range of farming systems [9, 10]. However, nutrient losses during composting are a key environmental issue as they reduce the fertiliser value of the final compost [11]. Only a few studies have considered DP in arid areas [12, 13]. Factors such as C availability, the bulk density of dry matter, water content, and aeration influence nutrient losses from compost, particularly nitrogen (N) volatilisation, which differs from immobilisation of N in organic compounds [14–16]. Additives are used during the composting of low-nutrient feedstock to increase the final nutrient content of the compost produced [17]. Composting also helps recycle a variety of OWPs in agriculture, thus increasing nutrient efficiency and reuse. For example, Khiyami et al. [18] mixed 70% DP with 30% shrimp and crab waste to produce a final compost with high nutrient content.

For crop production, phosphorus (P) is generally considered the second limiting nutrient after N in most soils. Composts prepared from OWPs need to be enriched in P in some way [19], while those prepared from animal manure have a higher P:N ratio than most crop requirements [20]. In dry areas, Evans et al. [21] reported that one way to increase P availability to plants is to produce compost from OWPs enriched with either animal manure or rock phosphate (RP). Insufficient P content can limit microbial degradation during composting [22]. Adding RP during composting increases P availability, which increases microbial activity and reproduction and thus increases degradation of OWPs, which results in a stable and mature final compost [23, 24]. Moreover, because adding RP can increase N conservation [25–27], it is an interesting alternative to increase the final nutrient content of compost. Many studies have investigated effects of adding RP on the composting of a variety of feedstock, but none has investigated DP.

Adding organic matter (OM) to soil is the most common practice for maintaining or restoring soil fertility, particularly for soils with degraded structure and low OM content [19, 28]. Other factors interact with compost application, such as climatic conditions, soil properties, and agricultural practices, particularly irrigation and tillage [29, 30]. High irrigation or rainfall amounts can cause nutrients from compost to move deeper into the soil, which increases the potential for them to leach into groundwater. Incorporating compost decreases bulk density and increases water-holding capacity [31], nutrient contents, and biological activity [32–34]. In European experiments, Bruni et al. [35] observed that incorporating 1.93 t C ha^{-1} $year^{-1}$ into the soil increased soil C by more than 4‰ $year^{-1}$. El Janati et al. [6] reported that 1 ha of monocropped date palm produces 2.4 t of DP per year, which could provide ca. half of the amount of C required to increase soil C. They also reported that agricultural soils in oasis regions have poor structure and low OM content (i.e. $< 1.5\%$). Thus, recycling DP through composting in a circular agriculture model is of great interest to promote oasis sustainability.

We hypothesised that composting DP could promote the harvest and reuse of DP, thus avoiding abandoning or burning it in oases and paving the way for further production, biotransformation, and economic development in the regions of date palm production. The originality of our study, compared to previous studies of DP co-composting, was to design and analyse composting processes based on the current farming system of oases in the Draa-Tafilalet region (Morocco). Thus, this study provides a new scientific basis for a “ready-to-use” process for reusing DP, while responding to a range of farmer priorities, such as management of soil OM or fertility.

2 Materials and methods

2.1 Conceptual framework for choosing composting processes

We used a general approach with three steps (Fig. 2): (1) surveys, to analyse the sources of and needs for organic products to define mixture options; (2) a composting experiment, to test contrasting composting processes adapted to a variety of farmer contexts; and (3) compost-use experiments, to characterise the composts to promote suitable uses for managing either soil OM or fertility. The first and third steps have been discussed by El Janati et al. [6] and El Janati et al. [28] respectively.

The main sources of OWPs available in oases were livestock manure (i.e. sheep, goat, and cattle) and DP, whose characteristics and amounts varied among three types of farming systems (see Table S1 for the amounts of organic C, N, and P produced by the three types). The amount of DP produced was estimated at (i) 1 t ha^{-1} year^{-1} on traditional farms with 53 date palm trees ha^{-1} and (ii) 2.5 t ha^{-1} year^{-1} on modern farms with 160 date palm trees ha^{-1}. DP had a high OM content (90.9%) and low N and P contents, thus providing mainly a source of organic C in farming systems. On traditional farms, the amount of livestock manure produced was estimated at 19.4 t farm^{-1} year^{-1} [6]. Manure was a source of N, P, and several other nutrients that increased soil fertility for crop production. It was applied directly on soils. Farmers considered it as a scarce resource for fertilisation. Sheep was one of the main livestock species that contributed to farmers' incomes. Because genetic conservation of the local sheep breed D'man is a current issue of farm sustainability [36], sheep manure (SM) was chosen as the manure feedstock for our experiment.

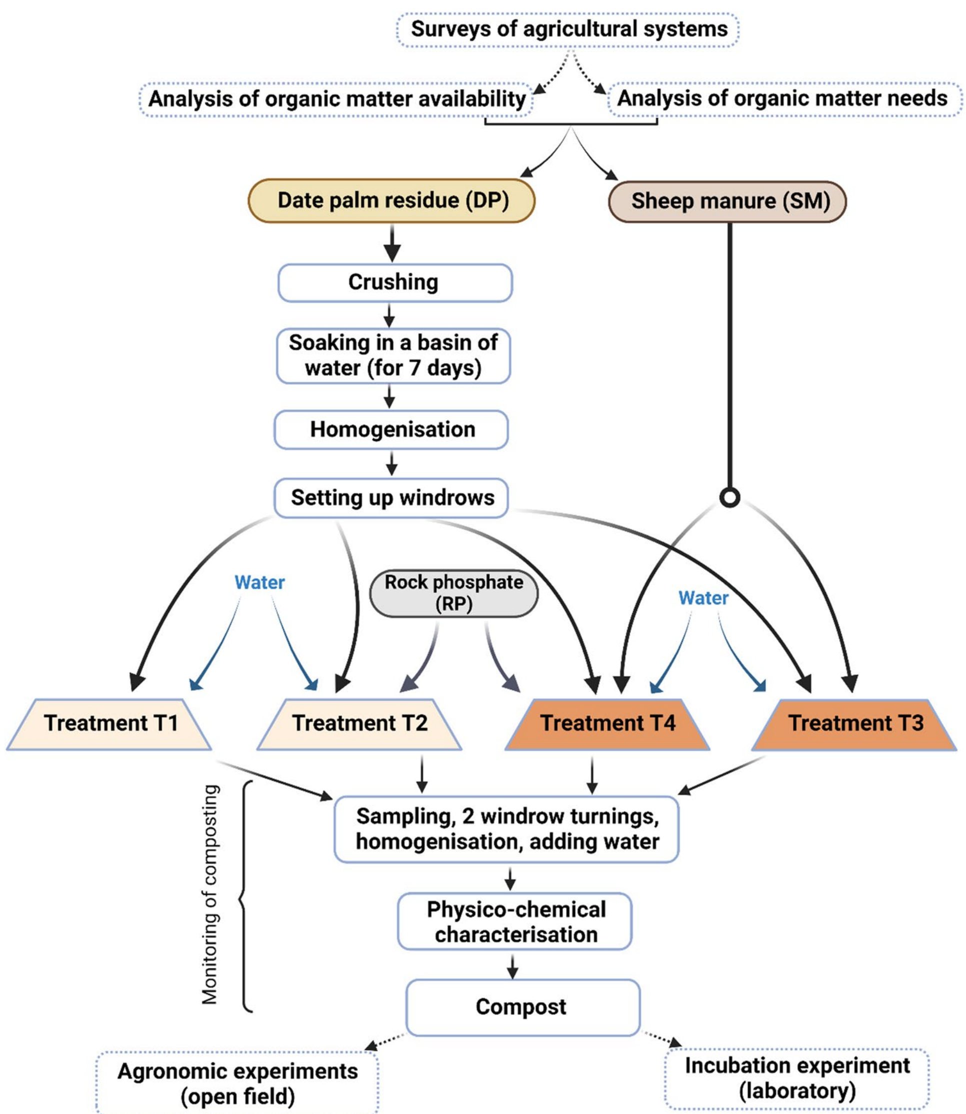

Fig. 2 Design of on-farm composting of date palm residues in a circular agriculture model. Step 1: surveys (see details in El Janati et al. [6]); step 2: composting (see details in El Janati et al. [42]); and step 3: compost characterisation (see details in El Janati et al. [28])

Nutrients were exported from farms mainly after harvest (see Table S2 for the organic N and P exported by crops and dates on the three types of farms). Crop residues consumed by livestock represented ca. one-third of total nutrient exports by crops. Modern farms that produced only date palms had no livestock manure; thus, a composting treatment using only DP was one of the mixtures tested.

Manure is a source of nutrients and microflora that increases microbial activity during composting. We decided to use a mixture with SM to provide farmers with an option to increase the area on which compost could be applied. We considered that mixtures needed to contain at least 30% manure to significantly influence the final nutrient content (i.e. impact on crop production) and the biotransformation caused by the initial microbial population (i.e. impact on the composting process), as observed by Abid et al. [12] and Sadik et al. [37]. A 70:30 ratio of DP:SM (v:v) was used for practical reasons.

RP is added to composting mixtures to (i) improve composting by removing the P limitation of microbial activity and (ii) increase the compost's final P content. The P added, which is considered to be a non-volatile element, should be conserved throughout composting. Moreover, the effects of adding RP to such feedstock have not been studied. Thus, we hypothesised that adding RP would increase the temperature of the windrow and increase N conservation by removing the P limitation to microbial growth. Moreover, adding RP was expected to increase the P content of the compost produced, which would increase crop productivity.

We applied the same operations to all composting mixtures. Crushed DP was pre-processed by soaking it in a basin of water before setting up windrows, to stimulate microbial colonisation of DP particles (i.e. "attached microflora") and increase the biodegradability of crushed DP during composting [12]. We turned the windrows to ensure that temperature and humidity changed in order to promote succession of microorganisms on feedstock aggregates and ensure homogenisation of the final products. We limited the number of turnings to limit the need for labour and to create a more acceptable process for farmers. We also hypothesised that limiting windrow turning would decrease water and N and C losses during composting. Thus, we decided to turn the windrows twice, after 5 weeks (day 39) and 11 weeks (day 81). We decided to use a relatively long composting period (> 4 months, 136 d) to degrade the DP.

2.2 Experimental design

The experiment was conducted at the experimental station of the National Institute for Agricultural Research of Morocco in Errachidia (31°55′13.0″ N, 4°26′59.0″ W). This station is dedicated to research on oasis agroecosystems. The study site has a dry and continental arid climate, with hot summers (maximum 43 °C), cold winters (minimum – 3 °C), and mean annual rainfall of 116 mm. The soil is a loam [28]. The experiment was performed in autumn and winter, with air temperature ranging from 15 to 35 °C, and total rainfall of 14 mm during the 136 days of composting. The composting feedstock used was DP and SM, which were collected from the experimental station (Table 1). DPs were crushed to a length of ca. 4 cm and then soaked in a basin of water for 7 days. The amounts of each feedstock varied among mixtures (Table 2). The mixture was sampled after mixing the feedstock and before adding water to reach 70% water content (wet mass basis). Because water percolated out of the mixtures before this percentage was reached, however, the initial water content, considered to reflect the water-holding capacity, was determined from the volume of water added to each mixture.

Table 2 Initial volume and raw material composition of the mixtures (in m^3 or kg wet weight $windrow^{-1}$). T1-dry palm leaves; T2-dry palm leaves and rock phosphate; T3-dry palm leaves and sheep manure; T4-dry palm leaves, sheep manure, and rock phosphate. *FAS* free air space

Treatment	T1	T2	T3	T4
Total volume (m^3)	5.15	5.15	5.15	5.15
Total weight (kg)	1510	1522	1766	1778
Dry palm leaves (kg)	1310	1310	850	850
Sheep manure (kg)	0	0	516	516
Rock phosphate (kg)	0	12	0	12
Water (kg)	200	200	400	400
FAS (% total volume)	74	74	71	71

Table 1 Initial composition of feedstock used in composting mixtures: date palm leaves before (dry) and after (wet) soaking, sheep manure, and rock phosphate (calculated from mixture analysis, not directly observed). Values are expressed as a percentage of wet weight (dry matter) or dry matter (the others)

Initial feedstock	Dry matter	Organic matter	Total N	Total P	Total K	Total Mg	Total Ca	Total Na
Dry palm leaves	93 ± 0	88 ± 0	0.44 ± 0.01	0.03 ± 0.00	0.49 ± 0.03	0.26 ± 0.01	1.01 ± 0.09	0.05 ± 0.01
Wet palm leaves	38 ± 2	90 ± 1	0.59 ± 0.03	0.03 ± 0.01	0.12 ± 0.02	0.14 ± 0.01	0.61 ± 0.03	0.05 ± 0.00
Sheep manure	88 ± 2	74 ± 1	1.93 ± 0.05	0.82 ± 0.04	2.34 ± 0.05	0.61 ± 0.01	2.72 ± 0.56	0.64 ± 0.03
Rock phosphate	100 ± 0	0.00	0.00	6.04 ± 0.03	0.00	0.00	16.12 ± 0.20	0.00 ± 0.00

The initial water content was 67 ± 2% in treatments T1 and T2 and 56 ± 2% in treatments T3 and T4. During mixing, 12.1 kg of RP was added to one treatment with DP and one treatment with SM. This small amount was determined based on the small P export of intensive date cultivation in monocropped areas (Table S2).

The experimental design was a randomised complete block of mixtures of DP, SM, and RP, with three replicates each (Table 2). The four treatments (12 windrows in total) were 100% crushed DP (T1), 100% crushed DP and RP (T2), 70% crushed DP and 30% SM (T3), and 70% crushed DP and 30% SM and RP (T4). All windrows were set up with the same dimensions (length × width × height) at the beginning and after each turning. The initial dimensions were 3.6 × 2.0 × 1.4 m. On day 39 (first turning), they were 3.5 × 1.9 × 1.3 m. On day 81 (second turning), they were 3.2 × 1.8 × 1.2 m. The final heights (day 136) were 0.98 m for T1 and T2 and 0.93 m for T3 and T4 (see Table S3 for additional information on initial physical and chemical properties of the mixtures).

At each turning, all windrows were weighed and sampled, and their dimensions were recorded. The wet weight was measured using a digital scale. Then, the three windrows of each treatment were mixed together to increase the repeatability within each treatment. The total mass of each treatment was then divided into three identical windrows. Water was added to these replicates to maintain a water content of 55–65%. The volume of water added was the same for the three replicates of each treatment but differed among treatments.

2.3 Sampling

Three representative samples (ca. 400 g each) were taken from each windrow on the first and last days and the two turning days. Samples were prepared by mixing six subsamples taken from six sites of each windrow until they were homogenised.

2.4 Measurements

The temperatures of each windrow were measured using a metal thermometer (K-type Thermometer probe HI766TR2) each morning (9:00–11:30 am) until day 123. The temperatures were measured at three locations: the top (30 cm from the surface), middle (centre), and bottom (30 cm from the base) layers. The air temperature was also recorded.

After setting up each windrow, but before weighing it, its total volume (V_{tot} in m^3) was calculated from the mean height (h_{avg} in m), width (w_{avg} in m), and length (L_{avg} in m) measured at three positions along the windrow:

$$V_{tot} = \frac{h_{avg} \times w_{avg} \times L_{avg}}{2} \tag{1}$$

Compost samples were analysed for water content, pH, electrical conductivity, OM, total N, total P, potassium (K), magnesium (Mg), calcium (Ca), and sodium (Na). Water content, electrical conductivity, and pH were determined in fresh samples. Water content was determined by weight loss after drying at 105 °C [38]. Electrical conductivity and pH were measured using a conductivity electrode or pH metre, respectively, after diluting a sample with distilled water (1:5 sample:water w:v). OM content, also called volatile solids, was determined by loss on ignition at 550 °C for 4 h [39]. OM was converted into organic C by dividing it by 2 [40]. Total N was analysed by the Kjeldahl method [41]. Total P, total K, total Mg, Ca, and Na were analysed by inductively coupled plasma atomic emission spectroscopy (ICP-EOS) after mineralisation with nitric acid and filtering.

2.5 Data processing

Measurements of the total dry matter in compost samples varied greatly and showed inconsistencies in initial calculations (e.g. large increases between two turnings), but the P:ash, Mg:ash, and Na:ash ratios remained stable. Therefore, we considered that the dry matter content had likely become biased between windrow sampling and conditioning of the final samples. Thus, the masses of water, dry matter, and the associated elements (N, P, K, Mg, Ca, Na) in windrows were estimated by assuming ash conservation throughout composting. Wet-weight losses were calculated by adding the water input during turnings and rainfall to the measured wet weight of the windrows.

Moisture and free air space (FAS) are known to be critical factors for managing compost [9]. FAS is the fraction of the total volume that is occupied by air and not by solids or water [9]. It was calculated as the total volume (V_{tot} in m^3) minus the volumes of water (V_{water} in m^3) and dry matter (V_{solids} in m^3) and expressed as a percentage of the total volume of the windrow to facilitate comparisons among treatments and dates:

$$FAS = \frac{\left(V_{tot} - V_{solids} - V_{water}\right)}{V_{tot}} \times 100 \tag{2}$$

The water volume was calculated from the water mass (M_{tot}: total mass of windrow in kg; WC: water content of sample in kg water kg^{-1} wet weight) by assuming a density of water (δ_{water}) equal to 1000 kg m^{-3}:

$$V_{water} = \frac{M_{tot} \times WC}{\delta_{water}} \tag{3}$$

The volume of dry matter was calculated from the mass of dry matter (in kg, calculated from M_{tot} and the dry matter content (DM in kg dry matter kg^{-1} wet weight)) and assuming a density of solids (δ_{solids}) of 1600 kg m^{-3} [16]:

$$V_{solids} = \frac{M_{tot} \times DM}{\delta_{solids}} \quad (4)$$

Means of each parameter were tested for statistically significant differences using Welch's *t*-test. All details of raw data and calculations can be found in El Janati et al. [42].

3 Results and discussion

3.1 Composting processes

3.1.1 Temperature dynamics

Temperature varied during composting (Fig. 3), which reflects the microbial activity of OM degradation and heat loss through passive aeration. All windrows went through mesophilic, thermophilic, and curing phases. For all treatments, windrows had higher temperatures in the centre than near the top or base. In mixtures with DP (T1 and T2), temperatures in the centre of the windrows peaked at 55 °C after 88 days of composting and two turnings. In mixtures with SM (T3 and T4), temperatures in the centre of the windrows peaked at more than 70 °C after 8 days.

Temperature profiles during composting were similar in windrows T1 and T2, as well as in windrows T3 and T4. Adding RP to mixtures T2 and T4 did not change the temperature dynamics, which indicates that P did not limit microbial activity, as shown by Lu et al. [43], who composted pig manure with RP. On the contrary, adding manure clearly accelerated the increase in temperature from the beginning of composting, as observed by Paillat et al. [44]. A rapid increase in temperature was also observed in other green-waste composting experiments [25, 45, 46]. The rapid increase in temperature of mixtures T3 and T4 was due to the high respiration rate of the microbial population, which was enhanced by the increased input of energy, nutrients, and the initial microbial population provided by the SM. As a result, the second temperature peak merged with the

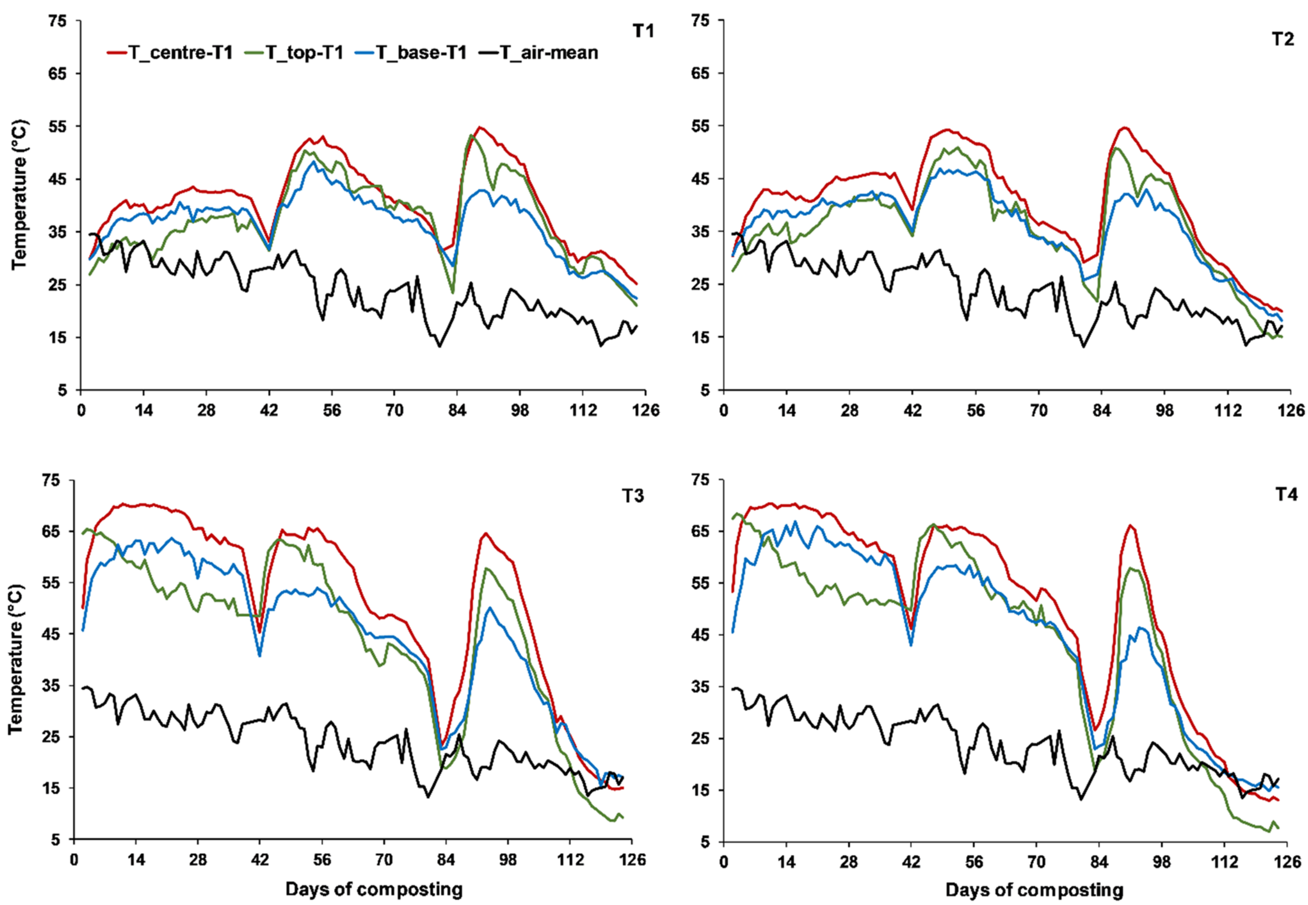

Fig. 3 Temperature dynamics during composting (for all treatments). T1-dry palm leaves, T2-dry palm leaves and rock phosphate, T3-dry palm leaves and sheep manure, and T4-dry palm leaves, sheep manure, and rock phosphate

first peak to form a longer period of higher temperatures. After the first and second turnings, mixtures T3 and T4 had significantly higher maximum temperatures than mixtures T1 and T2. Therefore, adding manure to DP can be considered an option to increase windrow temperature by 20 °C (from ca. 50 °C to ca. 70 °C), which can be used when crop residues with lower contents of pathogens and weed seeds are desired.

3.1.2 Wet weight dynamics

At the end of composting, the wet mass of each treatment was approximately half of its initial wet mass (Table 3). The decrease in wet mass of mixtures T1, T2, T3, and T4 was 63%, 62%, 60%, and 61%, respectively, much of which was due to evaporation of water. The dry matter loss in mixtures was ca. 42% in T1 and 38% in T2, which was significantly ($p < 0.05$) higher than the 33% in T3 and 31% in T4. Thus, DP had similar biodegradability whether composted alone or with SM. In other studies, Adhikari et al. [47] found that a decrease of 39% and 68% in dry matter corresponded to temperatures of 55 °C and 52 °C, respectively, reached during composting of OWPs (i.e. food waste mixed with chopped wheat straw in a 5:1 and 8.9:1 ratio, respectively). Adding RP to mixtures T2 and T4 did not increase the losses of dry matter, total weight, or water. Thus, P did not limit microbial activity, even in soaked DP.

Wet weight loss did not reflect the temperature dynamics, except during the initial period (days 1–39). During this period, the temperature in windrows T3 and T4 was higher than that in T1 and T2, as was the weight loss (42% and 44% vs. 27% and 30%, respectively). Afterwards, T1 and T2 lost more weight than T3 and T4 did, despite the higher temperatures in T3 and T4, so that the final weight loss was similar among the four treatments. It is likely that T3 and T4 lost less heat due to air convection because the fine particles of SM decreased porosity and lost less water due to evaporation because they contained less water.

Table 3 Change in wet weight, dry matter, and free air space throughout the composting period

Composting day	Day 0	Day 39	Day 81	Day 136
Wet weight (kg windrow^{-1})				
T1	1507 ± 6	1206 ± 5	960 ± 4	667 ± 3
T2	1519 ± 6	1157 ± 4	908 ± 3	684 ± 3
T3	1763 ± 6	1178 ± 4	1082 ± 4	866 ± 3
T4	1775 ± 6	1150 ± 4	1039 ± 3	844 ± 3
Dry matter (kg windrow^{-1})				
T1	505 ± 20	385 ± 49	310 ± 63	292 ± 75
T2	495 ± 36	451 ± 33	331 ± 37	305 ± 44
T3	794 ± 48	630 ± 29	583 ± 36	535 ± 31
T4	809 ± 43	634 ± 55	595 ± 51	560 ± 49
Free air space (% total volume)				
T1	74 ± 0	76 ± 2	75 ± 1	81 ± 1
T2	74 ± 0	76 ± 1	79 ± 1	81 ± 0
T3	72 ± 0	79 ± 0	74 ± 1	77 ± 2
T4	71 ± 0	79 ± 1	77 ± 0	78 ± 2

3.1.3 Free air space

In all treatments, the FAS increased from the beginning (ca. 70% of total volume) to the end (ca. 80%) of composting (Table 3). The FAS in mixtures T1 and T2 was significantly ($p < 0.05$) higher than that in mixtures T3 and T4, due to their components, especially manure, which has a high content of small particles. Thus, adding SM to mixtures T3 and T4 filled the pores between DP particles, which reduced their FAS. Haug [9] reported that maintaining proper water content and FAS during composting requires balancing many competing forces. Under arid conditions, increased passive aeration due to high FAS is expected to increase evaporation. Therefore, further experiments would be useful to explore ways to decrease FAS and its influence on composting and the final products.

3.2 Dynamics of chemical composition

3.2.1 Loss of volatile solids

OM content decreased by 40% in all windrows during composting, which indicated OM mineralisation and loss of volatile solids (Fig. 4). During composting of a mixture of DP (soaked for 7 days before composting) and goat manure, Abid et al. [12] reported a similar loss of OM (37%). El Ouaquodi et al. [48] observed a smaller loss of OM (29%) after 14 months of DP composted without initial soaking. Sadik et al. [37] observed a loss of OM of ca. 15% in a 1:1 mixture of DP and cow manure. Therefore, DP may contain compounds that resist degradation. Haug [9] and Paillat et al. [44] mentioned that transformation of OM depends on its degradability. OM with recalcitrant components, such as lignin and cellulose, stabilise the remaining organic compounds, which helps increase soil OM further. In our experiment, soaking may have increased the initial microbial activity by decreasing the electrical conductivity, increasing the N content, and filling the xylem of palm fragments with water. The relatively high initial water content (ca. 60%) and the initial period of 39 days without turning allowed hyphae of fungi to develop. They were observed in all windrows during the first turning, which indicated active degradation of cellulose, lignin, and other polysaccharides [49].

Composting of most OM generally has an initial stage of rapid degradation followed by a longer stage of slower degradation [50–52]. In mixtures T3 and T4, most OM was

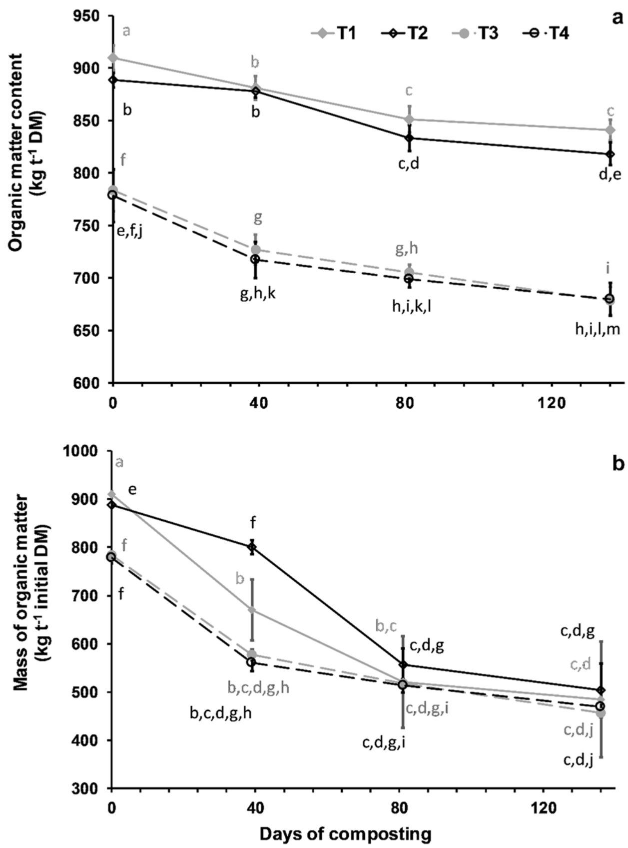

Fig. 4 Dynamics of (**a**) the content and (**b**) mass of organic matter during composting: T1-dry palm leaves, T2-dry palm leaves and rock phosphate, T3-dry palm leaves and sheep manure, and T4-dry palm leaves, sheep manure, and rock phosphate. Letters indicate significant differences ($p < 0.05$) between windrows

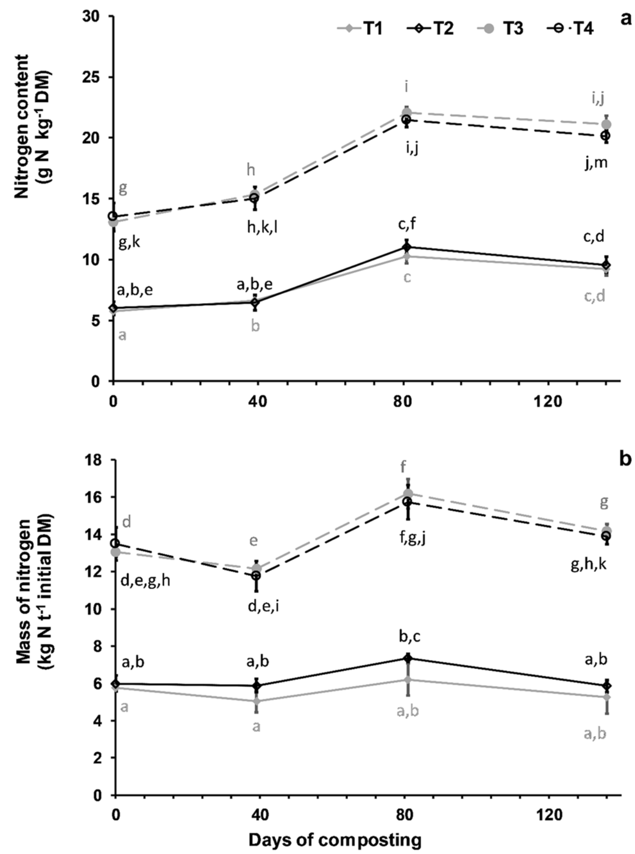

Fig. 5 Dynamics of (**a**) the content and (**b**) mass of nitrogen during composting: T1-dry palm leaves, T2-dry palm leaves and rock phosphate, T3-dry palm leaves and sheep manure, and T4-dry palm leaves, sheep manure, and rock phosphate. Letters indicate significant differences ($p < 0.05$) between windrows

lost during the first stage (39 days) of composting. The OM content of mixtures T1 and T2 decreased slowly during composting, which indicates that DP resisted degradation more than SM.

3.2.2 Nitrogen conservation

Total N contents were significantly ($p < 0.05$) higher in mixtures T3 and T4 than those in mixtures T1 and T2 (Fig. 5). The total N content in all mixtures increased during composting, with a maximum in T3 and T4. The increase in N content, along with a stable N mass, in all mixtures indicates that mineralisation of DP produced enough available C to supply the immobilisation processes of microorganisms. This result agrees with those of Bernal et al. [53] and Paredes et al. [52], who observed that total N content increased due to the concentration effect if leaching is stopped or minimised. These dynamics also suggest the lack of N losses from the windrows, as reported by many studies [44, 46, 51–53] when composting OWPs with high lignin and cellulose contents.

The effect of RP was not significant, despite a small decrease in N mass in mixture T1 of ca. 10% (from $0.58 \pm 0.03\%$ to $0.53 \pm 0.03\%$ initial dry matter) compared to that in T2, whose N was conserved at $0.59 \pm 0.04\%$ initial dry matter. Thus, composting DP and SM with a lower turning frequency decreases N losses.

3.2.3 Dynamics of phosphorus and nutrient contents of the final composts

Compost mixtures with SM (T3 and T4) contained significantly more total P than those without SM (T1 and T2), due to the high P content of the SM added (Fig. 6). Compost mixtures with RP (T2 and T4) had more total P than those without RP (T1 and T3). Adding RP may increase microbial activity and promote P accumulation and preservation, thus increasing the final P content of composts [24, 54]. The final total P content was higher than the initial content in mixture T2, but they were similar in T1, T3, and T4. Adding the same mass of RP to mixtures T2 and T4 led to a lower P

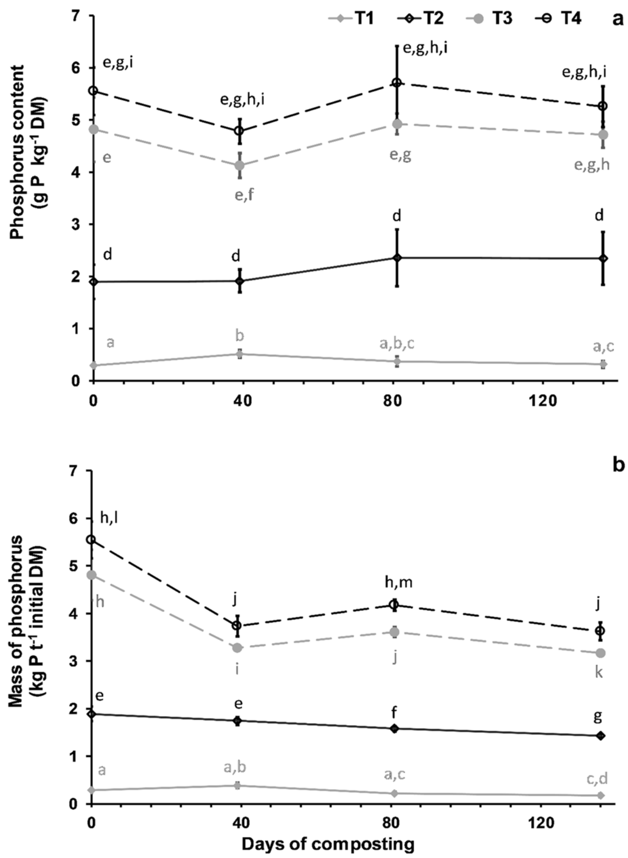

Fig. 6 Dynamics of (**a**) the content and (**b**) mass of phosphorus during composting: T1-dry palm leaves, T2-dry palm leaves and rock phosphate, T3-dry palm leaves and sheep manure, and T4-dry palm leaves, sheep manure, and rock phosphate. Letters indicate significant differences ($p < 0.05$) between windrows

content in T4 because T4 had a higher initial total mass of dry matter.

The total mass of P decreased significantly by ca. 1.5 kg P t^{-1} initial dry matter, as confirmed by the decrease in mean P content ($2.39 \pm 0.36\%$ to $1.60 \pm 0.14\%$ ash measured in the 2×18 samples concerned), from days 0–39 in both mixtures with SM, and was not observed in mixtures T1 or T2. This can be explained either by specific biological processes ("real" P loss) or by measurement artefacts ("false" P loss). However, gaseous P compounds could have been associated with manure [55, 56]. We have no evidence to consider one of the two hypotheses as more probable. The risk of P loss should be studied under more controlled conditions to clarify our hypotheses. In the present study, if the final P content of compost is a critical issue, the risk of losing P from manure during composting with DP can be decreased by adding RP to the initial mixture at a rate of 1.5 kg P t^{-1} initial dry matter (25 kg RP). If the loss of P is confirmed by further studies, composting experiments similar to those described here should indicate whether the loss depends or not on the DP:manure ratio or on characteristics of the manure. Initial and final masses of K, Mg, Ca, and Na did not differ significantly ($p < 0.05$) (Table S4).

3.3 Adapting composting to the needs of circular agriculture

Different ways to apply the composts produced (Fig. 7) can optimise various properties and help composting meet the needs of circular agriculture.

3.3.1 Compost needs in date palm monocropping

Following FAO [57] recommendations, compost is used as an organic fertiliser for young plants, applied per planting hole and supplemented with inorganic fertilisers. Traditionally, 3 kg of compost is mixed with the soil from the hole and then returned to the hole. Our results show that composts T1 and T2 have high OM content, low electrical conductivity, and a pH of 6.5 and should contain more stable compounds. They can provide a long-term increase in soil OM and water-holding capacity. Therefore, larger amounts could be added to increase the expected effects of OM input. El Kinany et al. [58] showed that applying compost to a sandy soil increased the growth of micropropagated date palm plantlets (i.e. fresh and dry biomass, root system, and leaf nutrient content). Applying compost increases aggregate stability and decreases soil density, thus decreasing resistance to root penetration and increasing water-holding capacity [59]. Compost with a high OM content is reported to promote crop growth by influencing the membrane-bound H^+-ATPase in the root system, which increases nitrate uptake [60, 61]. Given the properties of oasis soils, the recommended amounts of compost exceed 30 kg per date palm every 2–3 years [6]. Composts T1 and T2 can be applied either as mulch or incorporated into the topsoil, thus minimising water loss from the soil through evaporation and increasing the soil's humus content [62]. Composts T3 and T4 should be incorporated into the topsoil to supply nutrients to the plant in the irrigated zone. Almadini et al. [63] reported that the amount of fertiliser applied strongly influences date palm production in both old and new oases of Al-Ahsa in Saudi Arabia. Moreover, manure is a scarce commodity in traditional oases and is absent in modern oases [6]; thus, using compost produced on farms can offset this lack of organic inputs and promote the production chain of organic dates.

3.3.2 Compost needs when date palms are associated with other crops

Because annual crops have a short growing season and need nutrients soon after planting, the compost applied must

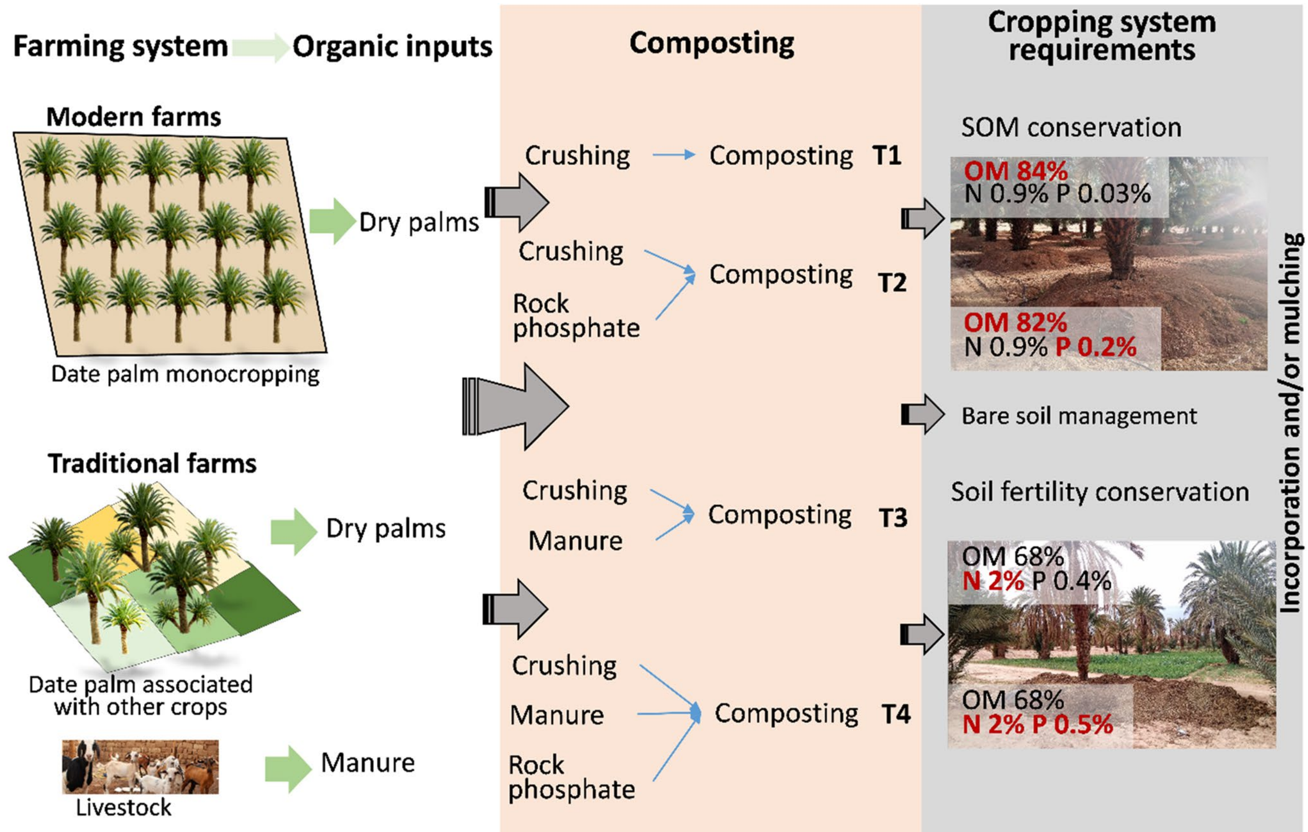

Fig. 7 Adaptation of composting to the needs of circular agriculture of oasis farming systems (practical implications). SOM, soil organic matter; OM, organic matter

provide a sufficient supply of plant-available nutrients. Composts T3 and T4 can be incorporated into the soil during seedbed preparation for these annual crops, particularly cash crops. Each year, farmers apply 2.5 and 2.7 t ha^{-1} of manure to wheat and cumin crops, respectively [6]. Composts T3 and T4 could also be applied to perennial crops at sowing or during growth. Benabderrahim et al. [64] observed that applying DP compost to a loamy sand soil at 30 t ha^{-1} increased both its OM content and water-holding capacity. Using compost to produce forage strengthens the role of livestock in these systems. Maintaining soil water is vital for crop growth and preservation of oasis soils, as soils in arid areas require management to provide sufficient water. Applying compost to the soil as mulch can be an effective way to manage bare soil. All composts produced can be incorporated into the topsoil to increase the formation and stability of soil aggregates.

3.3.3 Compost production to meet OM requirements of cropping systems

El Janati et al. [6] observed that manure is limited and already used in current farming systems, while DPs are insufficiently recycled, and that traditional and mixed farming systems have more C in manure than in DP. Therefore, on the farms that use manure, we suggest combining all available DP leaves, after crushing and soaking, with existing manure in a 70:30 (v:v) ratio to produce composts similar to T3 or T4. Composts T3 and T4 conserved manure nutrients, albeit with a risk of losing some P, which can be compensated by adding RP. In addition, N can be conserved through anaerobic digestion-composting processes [65] and by adding additives to shorten composting times and increase nutrient contents [66].

3.4 Potential implementation of the composting technique

We showed that composting is a tool to upcycle DP to meet the need to manage soil OM and fertility in Moroccan oases. Our results confirmed previous studies showing that composts based on DP are suitable for agricultural use [12, 13, 37, 48]. Here, we discuss some of the technical, economic, and sociological issues of this transition pathway.

Identifying the most relevant composting process first depends on the equipment chosen to produce compostable particles. Equipment categories include chippers, shredders, and grinders. DPs require specific equipment [67]. Composting succeeds when particle sizes vary from 5 mm [12] to 50 cm [48]. Therefore, stakeholders should prioritise socio-economic constraints (e.g. cost, equipment lifetime, maintenance, professional qualifications) and begin sieving feedstock, if necessary. The composting process secondly depends on the feedstock added. The literature shows successful DP composting with feedstock from a variety of sources: urban, livestock, or the food-processing industry. Therefore, stakeholders should maximise short-term agronomic benefits and prioritise the ability to meet needs of production and use operations. The third critical issue is managing salinity. The soaking stage decreased the electrical conductivity of DP. The literature shows that electrical conductivity of DP composts ranges from 1 to 7 mS cm^{-1}, depending on the feedstock. Stakeholders should determine how to reuse the soaking water associated with composting.

Underestimating the role of social values and culture in economic functioning can hinder the spread of innovations [68]. Farm managers and agricultural advisors can help meet the growing demand for organic fertilisers and support the spread of organic farming. In addition to windrow composting, small-scale options such as composting in reusable bags can be tested [69, 70]. “Good practices” for safely harvesting, transporting, and upcycling DP, instead of burning it, could be developed and spread as new policies by institutions. Communication also should consider factors that influence long-term dynamics of the OM added [71].

In regions that produce large amounts of DP, a variety of products can be produced while recycling the DP, whether immediately after harvesting, from the liquid produced after the soaking stage or from the DP after soaking. The strategy can be defined by optimising the combination of feed [7], fibre [72], or fuel [73] products desired, depending on the available technologies and economic opportunities, while maximising the social value of these products in the regions concerned. Attention should be paid to the compatibility between new inputs necessary to produce products and agricultural or horticultural uses of the final compost.

4 Conclusion

For the first time, our study showed that composting is a feasible alternative for appropriate management of DP in the context of circular agriculture in oasis agroecosystems. We designed, experimented with, and discussed the application of four contrasting composting options that can help resolve the paradox of unused organic residues coexisting with soils’ need for organic inputs.

This research provided better understanding of OM decomposition and dynamics of the masses of water, C, N, and P during composting of DP. Our results showed that initial soaking of crushed DP allowed them to be composted without any other additive. They also showed that the quality of final composts could be improved in several ways. Adding manure increased compost temperature, which should increase the sanitation of the initial feedstock. Adding either SM or RP increased the nutrient content of the final compost. Limiting the number of turnings increased the amount of initial N conserved. However, future studies on the effects of water content and lower FAS could help improve the processes.

Discussion of compost uses in a range of cropping systems can help farmers manage available organic resources appropriately by identifying the most suitable composting process and compost uses. The four types of compost met crop requirements for food or feed production. Our discussion highlighted that the composts produced could be used to increase forage production and help improve livestock conservation and sustainable development in such arid agroecosystems, which could increase incomes. Thus, upcycling DP through composting is an effective way to increase the amount of compost produced and increase soil fertility in a circular agriculture model of arid agroecosystems. Moreover, developing harvesting and reuse of DP will facilitate the production of DP-based products, for example for local fuel production.

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Author contribution Conceptualisation and methodology: P.R., A.B., N.A.-C., and M.E.J.; data curation: P.R. and M.E.J.; software and analysis: P.R., N.A.-C., and M.E.J.; writing: M.E.J., N.A.-C., and P.R.; supervision: A.B., P.R., N.A.-C., A.O., Z.T., A.S., and M.C. All authors have read and agreed to the published version of the manuscript.

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Data availability All details of raw data and calculations have been published by El Janati et al. [42]. They are freely available at following address: https://doi.org/10.15454/DFIAFE.

Declarations

Ethical approval Not applicable.

Competing interests The authors declare no competing interests.

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