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Benefits of Circular Agriculture for Cropping Systems and Soil Fertility in Oases

Mustapha El Janati [1,2,*], **Nouraya Akkal-Corfini** [2], **Ahmed Bouaziz** [1], **Abdallah Oukarroum** [3], **Paul Robin** [2], **Ahmed Sabri** [4], **Mohamed Chikhaoui** [5] **and Zahra Thomas** [2]

[1] Department of Crop Production, Protection and Biotechnology, Institut Agronomique et Vétérinaire Hassan II, Rabat 10101, Morocco; hmadbouaziz@gmail.com

[2] Unité Mixte de Recherche Sol Agro et Hydrosystème Spatialisation, Institut National de Recherche pour l'Agriculture, l'Alimentation et l'Environnement, 35000 Rennes, France; nouraya.akkal-corfini@inrae.fr (N.A.-C.); paul.robin@inrae.fr (P.R.); zahra.thomas@agrocampus-ouest.fr (Z.T.)

[3] AgroBioSciences Program, Mohammed VI Polytechnic University, Benguerir 43150, Morocco; Abdallah.OUKARROUM@um6p.ma

[4] Institut National de la Recherche Agronomique, Errachidia 52000, Morocco; sabri_inra2004@yahoo.fr

[5] Department of Soil and Water Resource Management, Institut Agronomique et Vétérinaire Hassan II, Rabat 10101, Morocco; mchikhaoui@gmail.com

[*] Correspondence: mustapha.eljanati@agrocampus-ouest.fr; Tel.: +337-6659-3991

Abstract: Circular agriculture is an effective approach for the management of soil organic inputs that improves soil fertility and cropping system sustainability. We developed a cropping system typology and assessed effects of crop rotation, organic fertilization, and crop residue management on soil fertility properties. Farmers in Drâa-Tafilalet oases in Morocco were surveyed, and soil was sampled and analyzed. In the most common cropping systems (Type I), date palms were associated with cereals, forages, and perennial crops. Type II cropping systems referred to a monocropped date palm of only one cultivar. In Type III, date palm was associated with other crops on part of the utilized agricultural area and monocropped on the other part. In all cropping systems, mean soil organic matter (SOM) content was less than 1.5% and the SOM:clay ratio was less than 12%, which increased the soil degradation risk. Livestock was combined with crops in Type I and III cropping systems and produced 19.4 and 24.2 t of manure per farm per year, respectively. Type I and II cropping systems produced annually 0.98 and 2.1 t.ha^{-1} of dry palms, respectively. Recycling these organic waste products remains a promising option that could produce organic inputs and offset the current lack of manure.

Keywords: circular agriculture; cropping systems; date palm; manure; oasis; organic matter; organic residues; organic waste products (OWPs)

1. Introduction

Oases are a unique agroecosystem intensively cultivated in desert areas. They are created in river deltas, alluvial-diluvial plains, and at the edges of diluvial-alluvial fans, where irrigation water is derived from rivers [1,2]. Oases in the Saharan and pre-Saharan regions are dominated mainly by a perennial date palm (*Phoenix dactylifera* L.) crop, which tolerates extreme arid and continental climates and whose shadow creates a suitable microclimate for the development of other crops [2]. In addition, combining crop clusters and livestock is another strategy used to maintain oasis productivity. It diversifies income sources of family farms and maintains soil fertility through manure application. Forages are fed to animals, some of which are used as draft animals [3,4]. These strategies also provide effective management of scarce natural resources, mainly land and water, since agriculture is the major and most important economic sector in oases [2]. Date palm production contributes 40–60% of the annual agricultural income of oases [5]. However, oasis areas are marked by high social vulnerability, which is expected to increase due to

successive drought years [4,6]. Water scarcity has decreased the amounts of livestock and manure produced, which decreases the main soil organic inputs. Thus, agricultural income has decreased due to reduced crop yield, which has led to population migration and oasis degradation [7,8].

Livestock manure is the main organic product used to fertilize associated crops: cereals, alfalfa (*Medicago sativa*), and cash crops (henna, *Lawsonia inermis*; cumin, *Cuminum cyminum*; and watermelon, *Citrullus lanatus*) [4]. Watermelon has been introduced and expanded in the last decades as a cash crop to increase agricultural income [4]. Its cultivation area nearly doubled from 2012 to 2013 in oases of the Draa valley (670 and 1130 ha, respectively) [9]. However, watermelon requires large amounts of chemical fertilizers and groundwater irrigation to increase its yield, making it an unsustainable crop [9]. To supplement organic matter inputs and increase crop yields, farmers apply chemical fertilizers, especially to cash crops [4], but not all farmers may be able to support this practice because of the cost of chemical fertilizers. In addition, new areas of irrigated date palm have appeared in the last few decades on the edges of old oases [5]. These areas are used to develop intensive systems based on groundwater irrigation, new agricultural practices, and exogenous inputs, such as organic and chemical fertilizers imported from other regions [5]. Consequently, modern and traditional forms of agriculture coexist in oasis regions, as reported by [10]. Introduction of these modern forms of intensive agriculture can aggravate water scarcity and decrease the availability of soil organic inputs, both of which may have serious impacts on agricultural soil fertility.

Soil fertility is assessed by its physical, chemical, and biological properties, which depend on agricultural practices (e.g., crop rotation, organic fertilization, tillage, and crop residue management) [11,12] and environmental conditions (e.g., temperature and rainfall) [13]. Soil organic matter (SOM) is the main indicator of soil fertility, which is strongly influenced by agricultural practices [12,14]. Thus, it is crucial to implement sustainable agricultural practices that support organic matter inputs and preserve soil fertility and oasis sustainability. Crop rotations have shown several positive impacts on soil fertility, such as increasing productivity, nutrient availability [15], and SOM content, especially when legume crops are included [16–19]. In an oasis region of northwestern China, Yin et al. [20] highlighted that the rotation of soft wheat (*Triticum aestivum* L.) and maize (*Zea mays* L.) with straw mulching increased yields by up to 153% compared to those of conventional monocropping of wheat or maize. Crop rotation can also influence soil fertility through crop roots and crop residues incorporated in the soil [17,21,22]. Crop residues (i.e., the aboveground parts not harvested for food and the roots) are composed mainly of organic carbon (OC), as well as macronutrients and micronutrients [23,24]. Incorporating them in the soil may increase soil organic inputs [25,26]. Organic fertilization with livestock manure and compost can also increase SOM content, nutrient cycling [27,28], forage production, and agricultural income [29,30]. It is also an eco-friendly potential source of soil organic inputs [4,28,30]. Therefore, using livestock manure in crop production improves soil organic inputs and crop productivity. However, the rate and amount of organic fertilizers applied in cropping systems depends on their chemical properties and on-farm availability [27,28]. A cropping system refers to a crop rotation and the crop management system of each crop for a homogeneously managed area [31]. Changes in soil and land use, in particular the predominance of cereals in simplified crop rotations, and the absence of both livestock and incorporation of crop residues in the soil decrease soil organic inputs, which decreases SOM and nutrient contents, as highlighted by Liu et al. [32]. Many authors suggested increasing soil organic inputs through agricultural practices as a way to improve soil fertility and crop productivity. Such practices increase agricultural income and the attachment of oasis populations to their land. For all of these reasons, we assumed that soil organic inputs need to be managed through agricultural practices to develop innovative alternatives, especially in an environment of scarce resources and extreme climatic conditions.

Organic waste products (OWPs) refer to organic material of residual origin (from an agricultural, industrial, or urban activity) and spread on agricultural land to recover or recycle fertilizing elements and the organic matter it contains [33]. The pruning of date palms produces large amounts of residues each year [5]. Inappropriate management of these residues causes ecological and plant disease issues and can lead to fires in oases [34,35]. Jarousseau et al. [33] reported that some crop residues often reduce environmental aesthetics and quality since they are usually piled on open fields or burned in most parts of the world.

Since soil organic inputs are the main source of soil nutrients in oasis cropping systems [4], dry date palm leaves (hereafter, "dry palms"), besides livestock manure, are a potential OWP that can provide organic matter pools useful for improving soil fertility and oasis productivity. Recycling and application of OWP in agricultural soils provide an innovative practice that benefits circular agriculture [36], leading to preservation of agricultural soils, restoration of biodiversity [36–38], and sustainability of oasis agroecosystems in our study. Circular agriculture is defined as a facet of the circular economy that targets the challenges of the farm-based rural economy and environmental issues [36]. Thus, circular agriculture suggests an efficient model of managing agricultural residues by integrating them into production processes. It also focuses on sustainable agriculture production and livelihoods, as well as enhancing local food markets [39]. A study conducted in Sri Lanka on circular agriculture showed that some OWP can be recycled and used as soil organic inputs to improve SOM content and alleviate soil-nutrient deficiencies [40]. There is a lack of studies on the management of soil organic inputs and its effect on soil fertility of cropping systems in arid areas, particularly oasis agroecosystems, where resources are limited. In addition, few studies have investigated the potential recycling of oasis OWP in a circular agriculture model to improve soil fertility through organic inputs.

Based on the need for scientific advances on the benefits of circular agriculture for cropping systems and soil fertility in oases, our study provides a new approach to (1) develop a typology of cropping systems based on oasis farm management and the other crops associated with date palms, (2) assess the effects of crop rotation, organic fertilization, and crop residue management on soil fertility, particularly SOM and macronutrient (available phosphorus (P) and potassium (K)) contents, and (3) determine the potential of OWP production (livestock manure and date palm residues) and recycling strategies to improve soil fertility in order to build a framework on circular agriculture in oases.

2. Materials and Methods

2.1. Study Area

Oases represent 1.5% of the total utilized agricultural area (UAA) in Morocco and are home to ca. 1.7 million people, accounting for nearly 5% of the total population of the country [5]. The oasis study area is located in the Drâa-Tafilalet administrative region (30°54′ N, 5°36′ W) in southeastern Morocco. It includes many ksours (i.e., villages) in the provinces of Errachidia, Zagora, and Tinghir, located in the Gheris and Maïder production basins (Figure 1a). Fifteen municipalities in these three provinces (i.e., 19% of these provinces' municipalities) differ in the availability of water resources that are essential to maintain agricultural activities and fulfill basic water needs [41]. In the Gheris production basins, water is used to maintain oases and produce crops, while further down the Maïder production basin, water is conserved to supply drinking water [41]. Intensive crop production in oases is necessary due to the splitting up of plots and extreme climate conditions, particularly the scarcity of water [10]. Cropping systems are intensive in irrigated areas, where irrigation water comes mainly from groundwater and surface water [42].

The area has a dry and continental arid climate with a warm summer (maximum of 43 °C), cold winter (minimum of −3 °C), and mean annual rainfall of 116 mm [43]. It has a mean of 25 rainy days per year, which occur mainly from November to February. The

predominant winds are hot and dry Chergui (north-east) and Saheli (south-west) winds. They average 57.6 km/h, with the highest speeds in March, May, June, and July [43].
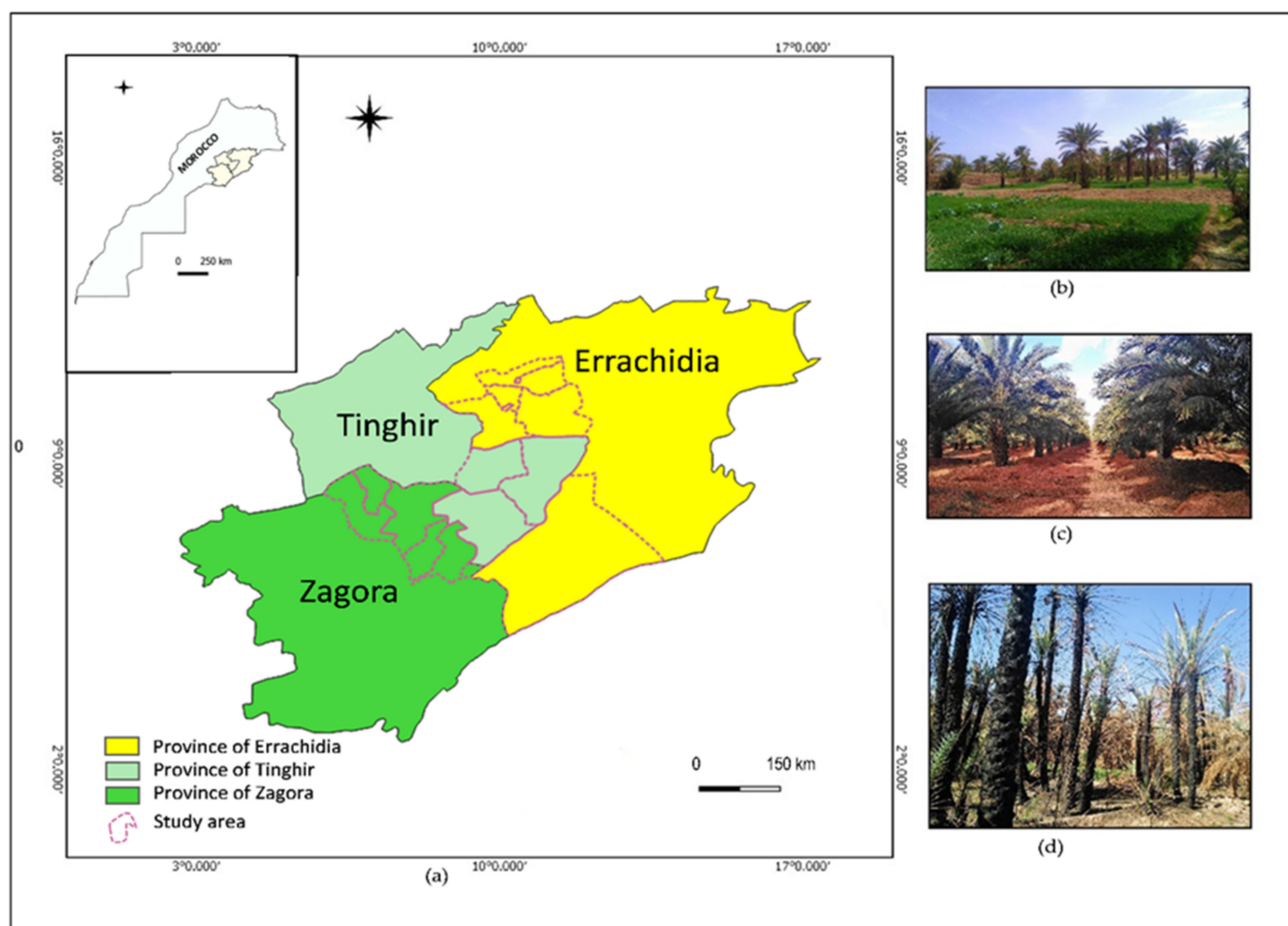
Figure 1. (**a**) The oasis study area, comprising 15 municipalities in the provinces of Errachidia, Tinghir, and Zagora of Morocco; (**b**) (Type I) traditional cropping system of date palm associated with other crops; (**c**) (Type II) modern cropping system of monocropped date palm; and (**d**) fire damage in an oasis caused by inappropriate management of dry palms.

2.2. Surveys

The objective of the survey was to collect data on crop and livestock production systems in order to assess the management and production of OWP in oasis cropping systems (i.e., dry palms and livestock manure). First, our approach was based on understanding characteristics of oasis cropping systems. The scientific literature was reviewed, and researchers from INRA (Morocco's agricultural research institute), managers from ORMVA/TF (agricultural office of the Drâa-Tafilalet region), managers from ANDZOA (Morocco's agency for development of the oasis region), and local experienced farmers were interviewed.

Cropping systems were based on the date palm (the main crop) and associated crops [44]. Farms were chosen randomly to assess a wide variety of farms. Overall, 47 farmers in the study area's 15 municipalities were surveyed. The number of surveys per municipality depended on the number of farms in the municipality and the difficulty in reaching them. The surveys were conducted in the form of one-on-one interviews with farmers. The survey contained three parts:

1.   Identification of general information about the farm (e.g., UAA);

2. Structural characteristics of the farm: (i) crop production (e.g., crop rotation properties, land use, bare soil duration, sowing dates, chemical and organic fertilization, irrigation, crop residue management, yields) and (ii) livestock production (e.g., species, number of head) to estimate the amount of manure produced;

3. Characteristics of the date palm crop (e.g., age, density, cultivars, yield).

2.3. Soil Sampling and Analysis

Soil samples were collected to analyze the relationship between soil properties and agricultural practices for each cropping system. Soil samples from a depth of 0–30 cm were taken and analyzed from each farm surveyed. The number of samples per farm was based on the farmer's description of the number of soil types on the farm. A composite sample of each soil type was taken. In total, 114 samples were sieved to 2 mm and separated for physico-chemical analysis. Four replicates were considered for each soil sample analysis. They were analyzed for particle-size distribution (pipette method [45]), pH of the soil solution (in water, soil:water ratio of 1:5), electrical conductivity (EC) [46], extractable P, according to the Olsen method [47], exchangeable K, using $BaCl_2$ extraction [48], OC, by the Walkley–Black method [49], calcium carbonate using hydrochloric acid [50], and mineral nitrogen (N), by the Kjeldahl method [51]. Samples of dry palms were taken in three replicates per plot for further analysis. They were crushed, dried, and then analyzed for OC and macronutrients (N, P, and K). OC was determined by loss on ignition at 550 °C for 4 h using a muffle furnace [52]. Total N (TN) was measured colorimetrically after combustion with sulfuric acid (the Kjeldahl method) [50]. Total P (TP) was assessed colorimetrically at 690 nm as molybdovanadate phosphoric acid after concentrated HNO_3^- $HClO_4$ digestion, while total K (TK) was determined using a flame photometric method outlined based on APHA standard methods [53]. The SOM:clay ratio was calculated to assess the quality of soil structure, as developed by Johannes et al. [54]. The clay content (%) was calculated from the mean measured particle-size distribution. For acceptable soil structure quality, this percentage should be higher than 17% [54].

2.4. Estimation of Amounts of Manure and Dry Palms Produced

The quantity of manure produced per year per animal was calculated using data from a livestock survey of the Moroccan Ministry of Agriculture [55], which estimated that a cow or sheep/goat produces 9.0 and 0.6 t of manure per year, respectively. We multiplied the number of animals of each species per farm by its annual manure production.

To calculate the quantity of dry palms produced, measurements were made on farms that followed the two methods for cultivating date palms in the study area: modern monocropping or traditional cropping, in which date palm is grown in association with other crops. Production of dry palms was measured from the highest-quality cultivar in the study area, Mejhoul, which is known worldwide for its excellent market value. [5]. The Mejhoul cultivar dominates modern date palm plantations and represented 67% of the planting program of 2.9 million trees by 2020 [43]. The number of dry palms produced by the two methods of date palm production was compared by measuring production in 10 plots of each date palm production method. In each plot, dry palms, which are the oldest ones in the basal layer, were counted on 10 randomly selected trees and then weighed. The total amount of dry palms produced by each date palm production method of the farms surveyed was calculated using the total UAA of the farms, the mean density of date palm, and the number and mean weight of a dry palm. Nutrient inputs (OC, TN, TP, and TK) from dry palms were calculated based on nutrient contents in dry matter (50.1%, 0.4%, 0.03%, and 0.5%, respectively) and the total amount of dry palms produced by each date palm production method.

2.5. Statistical Analysis

Descriptive statistics were performed, and mean parameters were compared by one-way analysis of variance (ANOVA, Student–Newman–Keuls test). Differences were considered significant at *p* < 0.05. All statistical analyses were performed using IBM SPSS 25.

3. Results

3.1. Assessment of Agricultural Practices in Oasis Cropping Systems

3.1.1. Typology of Oasis Cropping Systems

To build a typology of oasis cropping systems, we analyzed the association of date palms with other crops in the study area. Three types of cropping systems were distinguished based on agricultural practices of oasis farms (Table 1).

Table 1. Mean ± standard deviation of agricultural properties of cropping system types (Type I. date palm associated with other crops; Type II. monocropped date palm; Type III. mixed system of date palm associated with other crops and monocropped date palm) and livestock numbers on the surveyed farms. Utilized agricultural area (UAA); date palm (DP); monocropped date palm (MDP); associated date palm (ADP); sheep (S); goat (G); cattle (C).

Type	Farm Number	UAA (ha)	DP Density (Tree.ha^{-1})		Number of DP Cultivars		Livestock (Number)
			ADP	**MDP**	**ADP**	**MDP**	
I	32	2.3 ± 0.8	50 ± 28.4	0	3 ± 1	0	12 ± 9.4 S; 7 ± 5.2 G; 1 ± 1 C
II	3	12.3 ± 4.9	0	138 ± 8.6	0	1 ± 0	0
III	12	8.9 ± 3.7	50 ± 25.7	138 ± 10	3 ± 1	1 ± 0	20 ± 12.8 S; 6 ± 4.7 G; 1 ± 1 C

- Type I (traditional). Date palm associated with other crops: of the 47 farms, 32 followed the traditional system (Figure 1b). On these small farms (mean ± standard deviation (SD) = 2.3 ± 0.8 ha), the mean density of date palm was 50 trees.ha^{-1}; the spaces between trees varied among plots on the same farm and among farms (Table 1). The mean number of date palm cultivars grown per farm was ca. 3. Associated crops were mainly annual crops, such as straw cereals (durum wheat: *Triticum turgidum* L.; soft wheat; barley: *Hordeum vulgare*), maize, faba bean (*Vicia faba*), cumin, and watermelon). There were also some perennial crops, such as alfalfa and henna. Livestock was an important element in this cropping system, especially the prolific and productive local sheep breed, D'man (12 ± 9.4 animals per farm), followed by goats (7 ± 5.2 animals per farm) and cattle (1 ± 1 animals per farm).

- Type II (modern). Monocropped date palm: The three farms of this type (mean ± SD UAA of 12.3 ± 4.9 ha) were entirely monocropped with date palm (Figure 1c). This new type, called "extensions", is established on the edges of traditional oases and based on one cultivar plantation: Mejhoul or Boufeggous. The date palms had higher density (138 ± 8.6 trees.ha^{-1}), with a fixed distance between palm trees and tree rows and drip irrigation from groundwater. This type of cropping system had no livestock.

- Type III. Mixed system of date palm associated with other crops and monocropped date palm: the 12 farms of this type had a mean UAA of 8.9 ± 3.7 ha. On average, 42% of the UAA was planted with date palm associated with other crops (traditional Type III), while 58% was planted with monocropped date palm (modern Type III). Thus, it is a mixed system that combines both traditional and modern systems. In plots of traditional Type III, the density of date palm was the same as that in the Type I cropping system (50 ± 25.7 trees.ha^{-1}), with a variable distance between tree rows. Three cultivars of date palm were grown on each plot. In contrast, the plots of monocropped date palm (modern Type III) had the same density and fixed spacing as those in the Type II system, but only the Mejhoul or Boufeggous cultivar was monocropped, like in Type II. Livestock was also an important element in this system,

especially sheep (20 ± 12.8 animals per farm). The presence of livestock along with cropping systems is crucial for soil fertility in traditional systems, but its absence in modern systems results in flows of organic inputs.

3.1.2. Current Management of Cropping Systems

The results of surveys (Table 2) showed that in both Type I and traditional Type III cropping systems, half of the UAA was dominated by straw cereals rotations (mainly wheat, on 49% of total UAA). Barley occupied 7% and 5% of the UAA in Type I and traditional Type III systems, respectively. Silage maize was planted on less than 3% of the total UAA. Alfalfa occupied the largest percentage of UAA (8%–30%) after wheat in both Type I and traditional Type III systems. The percentage of UAA planted with cumin and henna was 3% and 10%, respectively in Type I systems and 2% and 9%, respectively in traditional Type III systems. Type III systems planted a larger percentage of UAA with watermelon than Type I systems (9% and 3%, respectively), and watermelon was planted on only seven of the farms.

Table 2. Land use, organic and mineral fertilization practices, and crop residue management in each type of cropping systems. Manure (M) and compost (C) are produced by sheep, goats, cattle, or a combination thereof. The application method is incorporated (Inc) and/or mulch.

Cropping System	Crop	Land Use per Farm		Yield	Mineral Fertilization		Organic Fertilization				Crop Residues
		Type I %	Type III %	t.ha^{-1}	N kg.ha^{-1}	P$_2$O$_5$ kg.ha^{-1}	Type	Dose t.ha^{-1}	Freq. per Year	App. Method	
Associated crops in Type I and traditional Type III	Wheat	49	49	1.3 ± 0.6	40 ± 10.5	32.5 ± 17.7	M	2.7 ± 2.1	1	Inc	Exported
	Barley	7	5	0.9 ± 0.4	25.1 ± 8.4	15.0 ± 7.2	M	1.5 ± 1.0	1	Inc	Exported
	Silage maize	2	1	7.0 ± 0.6	35.2 ± 5.4	28.6 ± 13.2	M	2.0 ± 1.7	1	Inc	Exported
	Alfalfa	21	21	3.0 ± 0.9	10.8 ± 6.3	11.8 ± 09.6	M	5.1 ± 1.5	2	Inc, mulch	Exported
	Faba bean	5	4	1.2 ± 0.7	8.0 ± 5.9	5.4 ± 3.7	M	2.0 ± 0.4	1	Inc	Exported
	Cumin	3	2	0.2 ± 0.0	31.5 ± 6.5	27 ± 6.3	M	2.5 ± 1.2	1	Inc	Exported
	Henna	10	9	3.3 ± 0.1	5.8 ± 3.5	3.0 ± 1.1	M	3.3 ± 0.5	2	Inc, mulch	Exported
	Watermelon	3	9	54.1 ± 10.3	64.4 ± 13	68.7 ± 11.1	C	4.2 ± 1.7	1	Inc	Returned to field
	Date palm	ND	ND	2.0 ± 0.6	0	0	M	0.4 ± 0.2	1	Inc	Left on site or burned
Monocropped date palm in Type II and modern Type III	Date palm	ND	ND	13.0 ± 3.5	ND	ND	M-C	6.5 ± 0.6	0.33	Inc	Left on site or burned

Frequency (Freq.); application (App.); not defined (ND).

Type I and III cropping systems had 2–4 rotations (Table 3). These rotations were (i) cereal-cereal, (ii) cereal-faba bean, (iii) cereal-cumin, (iv) alfalfa-cereal, and (v) cash crop (henna, cumin, and watermelon). Alfalfa-cereal rotation was practiced on 91% of the farms. Alfalfa was monocropped on only 6% of the farms. Cereal-cereal and cereal-faba bean rotations were each performed on 45% of farms. Cumin was always rotated with cereals (cereal-cumin). Henna was planted on 28% of the farms. The age of henna cultivation on farms varied from 5–50 years (rotation duration up to 360 months).

The return period for the same cereal, faba bean, or cumin crop to the same field was 2 years. The duration of alfalfa varied from 3–7 years; thus, the return period for alfalfa varied from 4–8 years. Among cash crops, henna was planted the most by farmers. In Type I systems, 31% of farmers grew henna. Cumin and watermelon were planted by 16% of farmers. In Type III systems, henna and watermelon were planted on 25% of farms in February and January, respectively. After the watermelon harvest, the soil remained bare until the next planting, a period of 6 months (Table 3). The soil also remained bare after the harvest of cereals, faba beans, and cumin (in June) until the next sowing in November.

Table 3. Properties of crop rotations in the Type I and traditional Type III cropping systems. Cereals include durum wheat, soft wheat, barley, and silage maize. "Surveyed farms" indicates the percentage of farms with the given rotation out of all farms surveyed. Bare soil (BS) is shown to indicate when it occurred in crop rotations.

Crop Rotation	Surveyed Farms (%)	Cash Crops		Planting Month	Rotation Duration	Bare Soil Duration
		Type I	Type III			
		% Farms	% Farms		Months	Months
Cereal-BS-cereal-BS	45	-	-	November	24	11
Cereal-BS-faba bean-BS	45	-	-	November	24	13
Cereal-BS-cumin-BS	15	16	17	November	24	13
Alfalfa-BS-cereal-BS	91	-	-	March for alfalfa	48–96	6
Alfalfa-BS	6	-	-	March for alfalfa	48–96	0
Henna	28	31	25	February	Up to 360	0
Watermelon-BS-watermelon-BS	15	16	25	January	12	6

Watermelon harvest was staggered, running from late April to mid-June, and produced a mean yield of 54.1 t.ha^{-1}. Henna was cut 3–4 times per year, with a first cut in May and a last cut in November. Mean cumin and henna yields were 0.2 and 3.3 t.ha^{-1}, respectively. The yield of monocropped date palm (13 t.ha^{-1}) was much higher than that in traditional systems (2 t.ha^{-1}). Associated crops were irrigated by surface irrigation, except watermelon, which was irrigated by drip irrigation.

All associated crops were fertilized by organic and chemical fertilizers (Table 2). Chemical fertilizers were applied annually in small quantities. The largest quantities of N and P fertilizers were applied to watermelon, wheat, silage maize, and cumin. For cereals and cumin, the first dose was applied at sowing and the second one during vegetative growth. Watermelon had the highest quantities of chemical fertilizers: 64.4 kg.ha^{-1} of N and 68.7 kg.ha^{-1} of P$_2$O$_5$. Besides chemical fertilizers, watermelon fertilization involved applying compost (ca. 4.2 t.ha^{-1}.yr^{-1}) during soil preparation and just before sowing. This compost was produced on-farm from livestock manure or imported from nomads and other regions. Manure was incorporated into the soil when the seedbed of other associated crops was prepared. A mean of 2.7 t.ha^{-1} was applied to wheat, on average once per year (Table 2). Alfalfa was fertilized mainly by manure twice a year. All farmers incorporated the first dose of manure before sowing and the second dose as mulch in winter. All henna farmers added manure to the soil by incorporating a first application and using it as mulch for a second application. The fertilization of date palm associated with other crops in Type I and Type III systems was based only on annual manure application (mean of 0.4 t.ha^{-1}). For monocropped date palm in Type II and Type III systems, 6.5 t.ha^{-1} of compost or manure was applied every 3 years. Chemical fertilizers were also applied to monocropped date palm.

Some farmers with a small number of livestock buy manure from nomads or other farmers to apply to their associated crops. However, the manure and compost applied to monocropped date palm must be imported from either nomads or other regions outside the oases to prevent the introduction of fungal date palm disease (Fusarium wilt).

Current and potential management of organic matter from crop residues and livestock manure varies in oasis agroecosystems (Figure 2). On all farms that cultivated cereals and faba bean, straw was exported from the fields to feed animals (Table 2; Figure 2). Survey results showed that, after the harvest of cereal grain and straw, farmers graze their sheep and goats on the stubble that remains in the field, which leaves the soil bare. The cash crop harvest is based on removing plants from the ground (cumin) or cutting them at ground level (henna). Thus, residues of cash crops were exported. After the watermelon harvest, residues were left in the field for about 5 months and thus incorporated into the soil during the next plowing. Dry palms were either burned or left in heaps in fields. Under current practices for managing organic inputs, manure was the only on-farm product recycled. Introducing date palm residues in a circular agriculture model provides an alternative for

managing these organic materials and supplements other fertilizer inputs. Dry palms can be collected, recycled, and applied to agricultural soils to meet different cropping system needs. In this way, farmers depend less on external inputs of fertilizers.
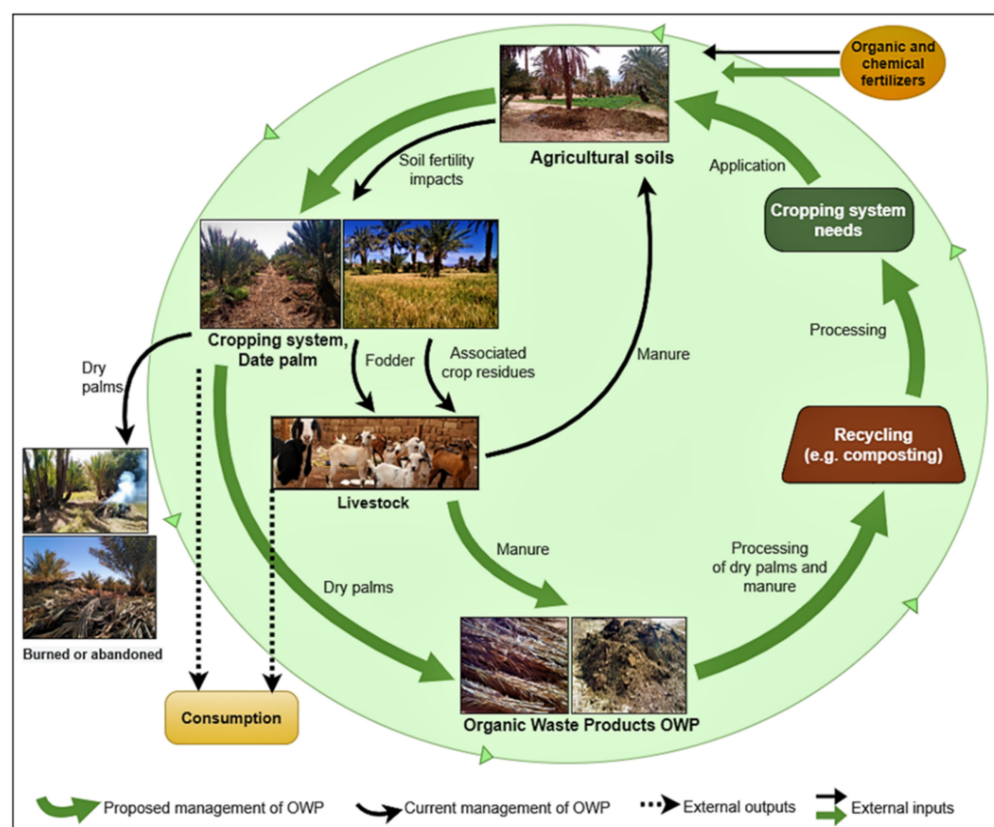
Figure 2. Framework highlighting current and potential management of organic waste products (OWPs) (i.e., associated crop residues, date palm residues, and livestock manure) and their potential application to agricultural soils. Farmers are the main actors who build and maintain this circular agriculture-based model.

### 3.1.3. Soil-Property Analysis of Cropping Systems

Since Type II and modern Type III systems had similar soil properties, they were grouped together. Silty and silty-sandy soils dominated the three cropping systems (Table 4); for example, the percentage of soil samples with a silty-sandy texture reached 60% in Type I cropping systems and 50% in Type III systems. Other textures (sandy-silty and sandy) were also found in these systems. Soils under monocropped date palm in Type II and modern Type III systems had only silty and silty-sandy textures. SOM content differed significantly among cropping systems (Figure 3). Mean SOM content was highest in Type I systems (1.4% ± 0.6%), ranging from 0.8–2.0%, which was a wider range than those of the other two types. In all cropping system types, SOM content was less than 1.5%, and the SOM:clay ratio was less than 17%, with the lowest mean (6.4 ± 3.8%) in Type II and modern Type III systems.

Cropping system types influenced soil P content significantly (Table 4). Soils of all cropping systems were deficient in P, with the most severe deficiency (12.2 ± 4.3 ppm) in Type II and modern Type III systems. Exchangeable K content differed significantly among cropping system types, all three of which exceeded the critical level (up to 146.0 ± 21.6 ppm), with the highest values in Type I and traditional Type III systems (244.8 and 221.0 mg.kg^{-1}, respectively). The EC of soils in Type I and traditional Type III cropping systems (0.1 ± 0.0 mS.cm^{-1}) was significantly lower than that of soils under monocropped date palm in Type II and modern Type III systems (4.3 ± 0.4 mS.cm^{-1}). Soil pH did not differ

significantly among cropping system types. The soil of all three cropping system types was moderately alkaline and strongly calcareous (i.e., high calcium carbonate content).

Table 4. Farm soil properties (soil texture distribution, clay content, SOM:clay ratio, extractable phosphorus (P), available potassium (K), electrical conductivity (EC), calcium carbonate content ($CaCO_3$), and pH) for each cropping system determined from 0–30 cm soil samples taken after harvest. Values followed by different letters within a column are differ significantly at $p < 0.05$, according to the Student–Newman–Keuls test.

Cropping System	Soil Texture Distribution	Clay (%)	SOM:Clay (%)	P (ppm)	K (ppm)	EC (mS.cm^{-1})	CaCO$_3$ (%)	pH
Type I	Silty, Silty-sandy, Sandy	13.4 ± 10.1	10.4 ± 7.9	22.1 ± 10.2 [b]	244.8 ± 71.5 [a]	0.1 ± 0.0 [b]	18.4 ± 10.5	7.6 ± 0.2
Type II and modern Type III	Silty, Silty-sandy	10.9 ± 2.6	6.4 ± 3.8	12.2 ± 4.3 [c]	146.0 ± 21.6 [b]	4.3 ± 0.4 [a]	17.1 ± 7.3	7.7 ± 0.2
Traditional Type III	Silty, Silty-sandy, Sandy-silty	11.8 ± 8.3	6.8 ± 6.0	32.6 ± 13.4 [a]	221.0 ± 53.7 [a]	0.1 ± 0.0 [b]	14.1 ± 9.1	7.7 ± 0.1
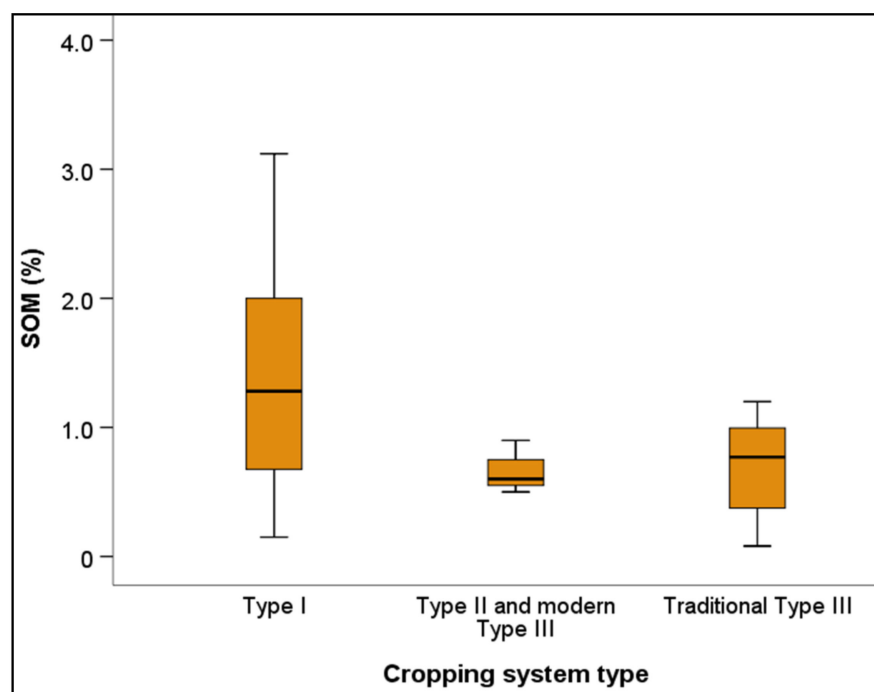
Figure 3. Boxplots of the soil organic matter (SOM) content (%) of soils of cropping system types (Type I represents cropping systems of date palm associated with other crops; Type II and modern Type III refers to monocropped date palm; Traditional Type III represents cropping systems of date palm associated with other crops) determined from 0–30 cm soil samples taken after harvest. Whiskers indicate minimum and maximum values, excluding outliers.

3.2. Potential Amounts of OWP for Recycling-Model-Based Circular Agriculture

Since associated crop residues are exported from the fields to feed animals (Figure 2), they are not quantified as organic materials to be recycled for organic fertilization. We considered livestock manure and dry palms as the main organic materials to be quantified and recycled. We assessed manure and dry palms according to the mean annual amounts produced per farm of each cropping system type.

- Livestock manure production: Sheep and cattle farming produces a large amount of manure each year, given the population of the local D'man sheep breed and the large volume of manure produced per cow. On average, Type I systems (Figure 4) produced less manure (19.4 t.farm^{-1}.yr^{-1}) than Type III systems (24.2 t.farm^{-1}.yr^{-1}). According to the surveys, livestock size, and even the presence or absence of livestock, varied

depending on climate conditions. After successive drought years, there was a lack of fodder and cereal straw, which forced farmers to sell their animals. As a result, manure supply was reduced during dry seasons.

● Date palm residue production: The mean number of dry palms produced annually differed significantly among the modern (Type II), mixed (Type III), and traditional (Type I) systems (19.60, 5.73 and 1.39 t per farm, respectively) (Figure 4). Traditional cropping systems produced significantly more dry palms per tree per year (mean of 16.8) than modern systems (13.0) (Table 5). The mean mass of a dry palm was 1.17 kg, regardless of the system. The surveyed farms in traditional and modern systems contained 118.6 and 100.0 ha of UAA, respectively. Modern systems produced significantly more dry palms (mean of 210.0 t) than traditional systems (116.2 t). Modern systems produced significantly higher amounts of OC, TN, TP, and TK than traditional systems.
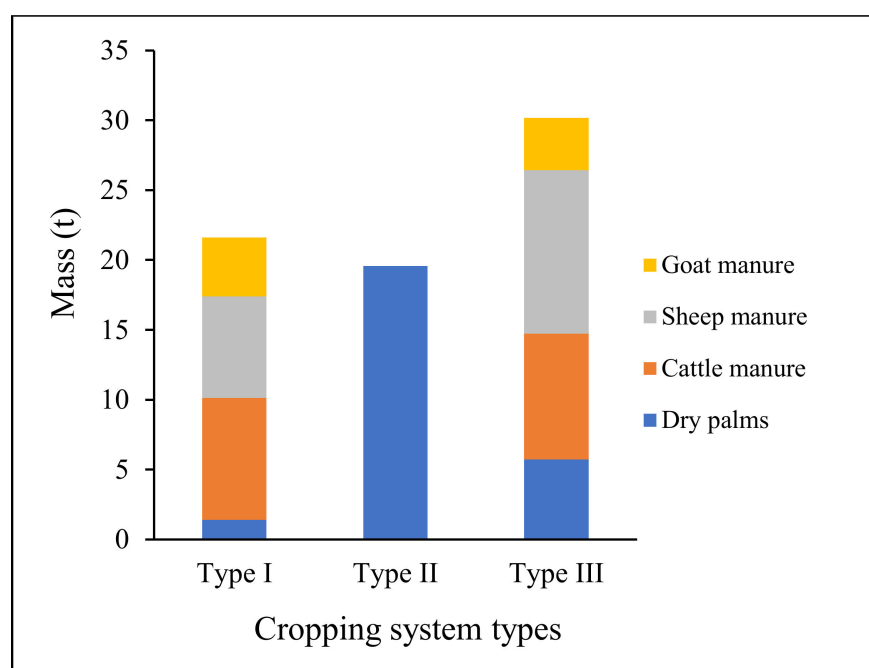
Figure 4. Mean masses of dry date palm leaves and cattle, sheep, and goat manure produced per farm of cropping system Type I (date palm associated with other crops), Type II (monocropped date palm), and Type III (date palm associated with other crops and monocropped date palm).

Table 5. Number, weight, total amount, and potential nutrients (organic carbon (OC), total nitrogen (TN), total phosphorus (TP), and total potassium (TK)) inputs of dry date palm leaves produced annually by the Mejhoul cultivar on the surveyed farms of traditional (date palm associated with other crops) and modern systems (monocropped date palm) of the study area.

System	Number of Dry Palms per Tree	Weight of Dry Palm Leaf (kg)	Total Amount of Dry Palms (t)	OC (kg)	TN (kg)	TP (kg)	TK (kg)
Traditional	16.80 ± 1.68 *	1.17 ± 0.06	116.2 *	58,216.2 *	464.8 *	34.86 *	581 *
Modern	13.00 ± 0.94	1.17 ± 0.10	210.0	105,210.0	840.0	63.00	1050

* significant ($p < 0.05$) difference between systems (Student–Newman–Keuls test).

4. Discussion

4.1. Potential Impacts of Current Agricultural Practices and Management of Organic Input Flows on Soil Fertility

Alongside cropping systems in Type I and Type III systems, farmers used livestock as an integral activity in their production systems. Livestock provided manure that was applied to crops as an organic fertilizer. Janati [4] reported that mixed crop-livestock production is necessary in oases to increase soil fertility and maintain a balance of agricultural income on smallholder family farms. Moreover, livestock farming creates a synergy that increases the value of forage crops [4].

The alfalfa-cereal crop rotation was adopted the most (91% of farms) in Type I and III cropping systems. Alfalfa was the main source of livestock feed. According to Sraïri et al. [8], alfalfa provides 34% of the total energy supply for livestock and occupies 80% of the forage area and nearly 33% of the area irrigated continuously throughout the year in oasis cropping systems. Cereal-cereal and cereal-faba bean rotations provide farmers with subsistence and a source of livestock feed from grain and crop residues. Adoption of cereal and legume (alfalfa and faba bean) rotations indicated that farmers sought to provide their livestock with feed from forage crops, cereal straw, and faba bean husks. Among cash crops, henna was planted most by farmers due to its perennial nature and low production requirements. These rotations were designed for livestock requirements and because there is an economic use for the crops, but farmers may not necessarily consider soil fertility. Yigezu et al. [56] reported that cereal-faba bean rotations provided yields 459 kg.ha^{-1} (48%) higher than those of monocropped wheat and increased the gross margin for the subsequent wheat crop by MAD1258.ha^{-1} (i.e., US$146.ha^{-1}). The wheat-faba bean rotation increases agricultural income and food security of the household. The plots of these crops associated with date palm in Type I cropping systems had higher SOM and nutrient (available P and K) contents than monocropped date palm plots. This difference was probably due to the presence of associated crops, whose roots and production of plant residues help increase SOM and nutrient contents. It may also have been due to the application of manure and chemical fertilizers. However, the SOM content in all cropping system types remained below 1.4%. In field experiments, Haruna and Nkongolo [19] and Gong et al. [21] found that SOM and available P and K contents were significantly influenced by crop rotation. In addition to being deficient in P, calcareous soils may cause P to precipitate, which may ultimately decrease P availability in the soil, as reported by Hashimi et al. [57]. Since the SOM:clay ratio was less than 12%, soil structure quality was degraded, causing impacts on the soil via mechanical stresses, as reported by Johannes et al. [54]. Since SOM content is correlated with other physical soil properties, such as water retention and bulk density, its decrease can decrease soil fertility [54]. In long-term field experiments, Ibno Namr and Mrabet [58] reported that a cereal-cereal rotation with no-tillage and residue mulching increased SOM content significantly. Cultivation of legume crops may improve soil fertility more than that of other crops. Carter [59] found that including perennial forages, such as alfalfa, in a rotation may have many benefits, particularly reduced soil erosion, nutrient loss, and decomposition rate of soil organic pools, since the soil is not repeatedly disturbed. However, in our study, even when alfalfa was present as an associated crop in Type I and Type III cropping systems, the SOM content remained low, perhaps due to the low amount of soil organic inputs, climate, soil type, or other agricultural practices.

Organic fertilization based on applying manure and compost was a common practice that resulted in many flows of these organic inputs on oasis farms. In the traditional (Type I) and mixed (Type III) cropping systems, manure of cattle, sheep, or goats was produced on the farm. Farmers with a large UAA who cannot ensure the necessary amount of manure purchase it from nomads or their neighbors who have small UAA. For the associated crops, only small amounts of manure or compost were applied (no more than 5.1 t.ha^{-1} to alfalfa), due to the small number of livestock, which tends to decrease following successive drought years and water scarcity, as reported by Rignall [7] and Sraïri et al. [8]. Although Type II systems did not produce manure due to their focus on date production, they purchased

it from nomads and incorporated it into the soil around date palms. Compost purchased from industrial composting units was also applied to monocropped date palm (Type II and modern Type III). Ca. 40 kg of compost or manure was applied to each date palm tree every 3 years. These inputs were low given the current quality of the soil, which has a silty or silty-sandy texture, low SOM and nutrient (available P) contents, and moderate alkaline pH (Table 4). Similarly, Janati [4] reported that soils in these desert regions require more manure (30–40 t.ha^{-1}.yr^{-1}) to improve their organic matter and nutrient contents. Maintaining or increasing SOM content is more challenging on non-livestock farms and on mixed crop-livestock farms during drought years, due to the lack of manure production. Until farms of Type II systems were recently landscaped and managed for date palm planting, they were only bare desert soils. Therefore, their soil requires more organic inputs to improve the SOM and supply sufficient nutrients.

Crop residues influence vital soil functions, and incorporating them into the soil as organic inputs is important to improve soil fertility and increase the productivity of cropping systems [33]. Farmers always exported cereal straw and faba bean residues from the field to feed animals. Straw stubble was grazed by animals, and the remaining residues, were removed by wind and water erosion, since strong winds are common in the region, especially in spring and summer [43]. In addition, the burning of dry palms on the edges of plots can cause fires in oases, which have been frequent over the last few decades (Figure 1d). Similarly, natural fires have been observed in date palm oases in San Ignacio, Baja California Sur, and Mexico [60]. Moreover, soils were bare for long periods (up to 6 months), and farmers used no cover crops. Thus, for all of these crops, only the roots remained in the soil. When crop residues were exported, the soil was exposed to erosion (mainly wind erosion), and inputs of organic matter to the soil decreased, which explains the low SOM (less than 1.5%) and P contents, as reported elsewhere in the literature [58,61]. In addition, bare soil increases water evaporation from the soil [61,62], and erosion decreases the rooting zone depth and water-holding capacity, which decreases soil productivity by removing organic matter, nutrients, and fine particles with the topsoil [63,64]. These impacts tend to be more extreme in oases because of the arid climate, soil texture, and degraded soil structure, since these factors make the soil highly erodible [11,64]. Thus, low SOM content in this region was caused mainly by inadequate management of crop residues and applying too little manure or compost. Soil analysis results from our study clearly illustrated effects of these agricultural practices on soil fertility, particularly low SOM content, which led to soil structure degradation. Badraoui et al. [65] also reported low SOM contents (<1.5%) in oasis soils. These results suggest that soil erosion and low SOM content make the incorporation of crop residues into the soil crucial for preserving soil fertility in cropping systems.

The high demand for crop residues caused by exporting them from fields may decrease their availability for maintaining or building SOM. These trade-offs in organic matter can lead to critical soil fertility problems when they persist for a long period. Soil fertility itself can influence the amount of organic residues returned to the soil, since more fertile soils increase crop yields and their residues.

4.2. Circular Agriculture of Date Palm Residues: A Solution for Oasis Sustainability

Our study quantifies date palm residues and their potential application in circular agriculture to increase soil organic inputs. Chehma et al. [66] reported that the age and agricultural practices of date palm trees on farms determine the number of dry palms produced per tree; they observed a mean of 22 per year in Algerian oases, which was higher than that observed in traditional oases in our study (16.8). Similarly, Ali [35] reported that each date palm tree produced 10–20 dry palms per year. The mean mass of dry palms we observed (1.17 kg) was confirmed by Chehma et al. [66], who observed a mean of 1 kg. The small quantity of dry palms produced in the Type I system was due to the few date palms and small total UAA per farm. The large areas and high densities of monocropped date palm trees (Type II) produce a large quantity of dry palms (mean = 2.1 t.ha^{-1} at

138 trees.ha^{-1}). In the traditional system, date palms at a density of 50 tree.ha^{-1} produced 0.98 t of dry palms per year. This difference in date palm density is due mainly to the abandonment of planting new date palm trees to replace those affected by fusarium wilt and successive drought years, as reported by [5]. Fusarium wilt (i.e., "Bayoud disease"), caused by *Fusarium oxysporum* f. sp. *Albedinis*, is one of the main diseases that affects date palm products [67]. Because chemical analyses of dry palms showed high OC, TN, TP, and TK contents, applying them to the soil can offset low manure inputs and help increase the SOM content.

This study suggested that crop rotation can be used to manage crop residues effectively. Crops that produce small amounts of residues, such as cumin and watermelon, can be rotated with crops that produce large amounts of residues, such as wheat, barley, and beans. Mulching around date palms is another practice that can improve soil fertility and reduce water evaporation, particularly given the arid climate of the region [43]. However, according to interviews and field observations, farmers are not adopting this practice. Dry palms are composed of compounds that resist decomposition (i.e., cellulose, hemicelluloses, lignin, and other compounds) [68]. These compounds could be recycled by being processed instead of being burned on the farm, since managing them inappropriately increases fire damage and environmental problems. Moreover, the recycling process must remove pathogens that may be present in the dry palms, in particular the fusarium fungus. Technical and cost issues must also be feasible in order for smallholders to recycle dry palms on their farms. Applying date palm residues to the soil of the same farm on which they were produced decreases the risk of spreading the fusarium fungus. As reported in the literature [68–71], composting date palm residues is an effective management practice. Manure can be added to the residues to produce compost, which can be applied to the soil as mulch [68] or an organic amendment and fertilizer [71,72], depending on cropping system needs (Figure 2). Chemical fertilizers can be applied, along with manure or compost, to maintain desired levels of cropping system productivity, SOM, and nutrient contents, as reported by Hutchinson et al. [73]. Thus, soil organic inputs can be increased, and the small amount of manure applied due to manure scarcity can be overcome, which enhances soil fertility and the sustainability of cropping systems. In addition, Dhaouadi [74] highlighted that using OWP in agriculture can create jobs for processing organic residues into bio-fertilizers that benefit circular agriculture. This enables farmers to be more committed to their soil and oasis heritage.

5. Conclusions

This study established that crop rotation, organic fertilization, and crop residue management are fundamental to follow a circular-agriculture-based model. Alfalfa-cereal, cereal-faba bean, and cereal-cereal crop rotations dominated in the oasis cropping systems of Type I and traditional Type III. Cereal straw and faba bean residues are exported for animal feed. Residues of cash crops are also exported because of their harvesting method. A variety of feed sources is required to meet livestock needs throughout the year. The soils remain bare for up to 6 months per year, which may accelerate soil degradation caused by wind erosion. Amounts of manure and compost applied to the soil lay far below soil requirements; thus, the current annual input of SOM into the soils is insufficient, especially given their texture, low SOM content (<1.5%), and deficient P content. Oasis cropping systems need crop rotations that retain a sustained supply of organic matter and large amounts of active SOM. Traditional and modern cropping systems of date palm farms produce large amounts of dry palms, which can be considered as raw materials to be recycled as organic fertilizers to improve soil fertility and crop yields in arid and semi-arid areas. Since dry palms have high OC content, applying them to the soil can improve SOM and soil nutrient contents. This recycling overcomes manure scarcity and the export of crop residues and promotes innovative agricultural practices and sustainable development in an oasis based on circular agriculture. In this way, farmers increase their agricultural income and become more attached to their land. In addition, quantifying and recycling

oasis OWP prevents fusarium wilt, burning of residues, and hazard natural fires, which causes health and environmental problems.

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