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Turning Waste into Wealth: The Case of Date Palm Composting

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Abstract

This study investigates the economic viability of a new composting station dedicated to the recycling of date palm by-products. A field experiential analysis was performed in the Figuig Oasis (Morocco), providing the first evidence on the agronomic quality of the compost. The compost produced from date palm by-product was compared to cattle manure and unamended soil and can be considered as a good-quality amendment, demonstrating its ability to enhance soil fertility. Second, a socio-economic survey was conducted to explore farmers' perceptions and adoption of sustainable agricultural practices. A total of 201 farmers out of 450 farmers registered in Figuig's municipal administration were surveyed. In terms of fertilisation, farmers preferred locally produced organic fertiliser when available in order to improve soil organic matter content and reduce dependence on chemical inputs. The selling price for the compost was set at 0.14 EUR/kg to reflect the current market price for compost and the willingness of about 38% of the farmers surveyed to buy it. Third, a detailed cost/benefit analysis was performed, with a breakdown of the station's operational and investment expenses. This illustrates the minimum scale needed to generate a viable business model. Financial projections show that increasing production capacity from 350 tonnes/year to 3500 tonnes/year reduces unit production costs while increasing profits. As illustrated by the application of the Ecocanvas framework, the socio-economic analysis reveals the potential to generate positive environmental, economic, and social impacts, as the circular approach could be replicable and scalable in similar oases agro ecosystems.

Keywords: agriculture; business model; circularity; composting; date palm; Figuig

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1. Introduction

Oases are unique agro-ecosystems intensively managed in desert areas and often located in river deltas, alluvial–diluvial plains, and along the edges of alluvial fans, where irrigation is typically sourced from rivers [1]. In Morocco, oases cover about 15% of the national territory (107,324 km^2 out of 446,500 km^2) and are home to 1.6 million inhabitants, representing 5% of the population. They host a large share of the country's phoenicicole heritage, with date palm (*Phoenix dactylifera* L.) cultivation playing a central role in their ecological and socio-economic fabric [2,3].

As of 2019, date palms in Morocco were cultivated over approximately 60,000 hectares [4]. While historically valued for food and carpentry, date palm residues now often accumulate, causing several problems: they occupy arable land, foster pests and diseases such as Bayoud (caused by the soil-borne fungus *Fusarium oxysporum* f.sp. *albedin*is), increase fire hazards, and contribute to visual pollution [5].

Date palm waste in Morocco is estimated to be 104,000 tonnes annually [6]. Rich in organic carbon, it holds significant potential for compost production to enhance soil fertility and crop yields in arid and semi-arid regions [1–5]. Desert-based agricultural systems are characterised by acute constraints in soil fertility, water scarcity, and waste management. These limitations are particularly visible in oasis farming systems, where maintaining productivity under resource scarcity requires innovative solutions. Footprint assessments of Medjool date value chains have underscored the importance of developing circular approaches to close nutrient loops, reduce waste, and sustain production under desert conditions [7]. Within this context, the valorisation of date palm residues through composting emerges as a promising pathway to simultaneously manage agricultural waste and improve soil health.

A growing body of research demonstrates that compost derived from date palm residues has the capacity to improve nutrient availability and support crop productivity in arid agro-ecosystems. For instance, it has been shown that date palm compost application enhanced nutrient release and promoted silage corn growth in desert soils, confirming its agronomic value [5]. Additionally, it was reported that date palm compost improved germination and seedling vigour in barley [8]. Importantly, when composting processes are rigorously monitored following physico-chemical and spectroscopic assessments to confirm compost maturity and safety, the resulting product meets agronomic quality standards [9,10].

Beyond nutrient enrichment, date palm compost influences biological dimensions of soil fertility. Its application was documented, as it increased soil microbial diversity in barley fields, highlighting its potential to sustain soil health beyond short-term nutrient cycling [8]. In parallel, research has shown that combining date palm residues with biochar further improves soil physical properties, including water retention and structural stability—critical levers for resilience in sandy soils with low organic matter content [11,12]. Such results align with broader evidence demonstrating the long-term benefits of organic amendments for soil fertility and sustainability in diverse agro-ecosystems [13].

The objective of this study is to evaluate whether establishing a composting station for date palm waste can serve as a viable circular business model. The research was conducted in three main stages:

- Agronomic assessment: Production of compost from date palm residues and evaluation of its effect on crop productivity in field trials with crop species commonly grown in oases.
- Farmer survey: Collection of local farmers' perceptions and willingness to use locally produced compost to assess market acceptance.
- Socio-economic viability and business modelling: Evaluation of the production capacity, potential pricing, investment and operational costs, and long-term sustainability of the composting station, combined with the development of a circular business plan using the Ecocanvas tool [14] to visualise the potential added value.

Although previous studies have examined the composting of date palm residues—either alone or combined with other organic inputs—in oasis environments [1], this study is, to our knowledge, the first to integrate agronomic validation of compost quality through field trials with a comprehensive socio-economic feasibility assessment, including circular business modelling, within an oasis agro-ecosystem.

2. Materials and Methods

2.1. Date Palm By-Product Compost as Fertiliser for Oasis Crops

The compost used in this study was produced at the Figuig Oasis production plant using the process mentioned in [15]. A full-scale field experiment was conducted to assess the agronomic value of compost derived from date palm by-products. The effects of compost application were compared with those of cattle manure and a control (untreated soil) on two vegetable crops commonly cultivated in the Figuig oasis: pepper (*Capsicum annuum* L.) and eggplant (*Solanum melongena* L.). Growth performance was evaluated through measurements of fresh and dry biomass for both aboveground and root parts. In addition, the effect of compost on seed productivity was evaluated for barley (*Hordeum vulgare* L.), a widely grown cereal in the region.

C. annuum and *S. melongena* trials: The experimental plot covered 51 m^2 and consisted of five rows: two treated with 80 kg of compost, two with 80 kg of cattle manure, and one left untreated as a control. Each row was 0.25 m wide and 17 m long, with 0.5 m spacing between rows. The application rate of both compost and manure was 9.41 kg/m^2. This amount was selected to reflect local agronomic practices in the Figuig oasis, ensuring realistic field conditions and comparability between treatments rather than testing different application gradients. For statistical analysis, all plants were considered, corresponding to $n = 32$ for compost and cattle manure treatments and $n = 16$ for the control.

Planting took place on 22 April 2020, and harvesting occurred on 26 July 2020 (three months after planting). Drip irrigation was applied every three days for three hours to maintain consistent soil moisture. At harvest (flowering stage), both aerial parts (stems and leaves) and root systems were measured. Roots were carefully removed from the soil to assess below-ground biomass. Fresh weight was recorded immediately after harvest using a precision balance. Dry weight was obtained by drying samples at 70 °C for 48 h in a ventilated oven until a constant weight was reached.

Barley trial: This experiment consisted of 30 plots of 2 m^2 each, arranged in three complete randomised blocks of 10 plots. Each plot was sown with 133 g of barley seeds and irrigated every 15 days using a gravity-fed system. Of the 30 plots, 10 received 60 kg of compost, 10 received 60 kg of fresh cattle manure (uncomposted), and 10 served as an unamended control, corresponding to an application rate of 30 kg/m^2. Irrigation was applied every 15 days using a gravity-fed system. This application rate also reflects common local practices, allowing the results to be directly comparable with farmers' current fertilisation methods. Planting took place on 3 December 2022 and harvesting on 30 April 2023 (after five months of cultivation). At harvest, the plants were dry and bearing spikes at maturity, and grain yield was determined separately for each treatment.

All data were expressed as mean ± standard deviation (SD). Differences between treatments were assessed using one-way analysis of variance (ANOVA) followed by Tukey's HSD post hoc test at a significance level of $\alpha = 0.05$. Normality and homogeneity of variances were verified using Shapiro–Wilk and Levene tests, respectively. Statistical analyses were performed using IBM SPSS Statistics software, Version 21.0 (IBM Corp., Armonk, NY, USA).

2.2. Field Surveys to Assess the Uptake of Compost by Farmers

A socio-economic survey was conducted to explore farmers' perceptions and adoption of sustainable agricultural practices [16]. The analysis focused on the palm sector and growers in the oasis environment of Figuig city. The Figuig municipal administration share that there are approximately 450 farmers registered across the different ksours (i.e., fortified districts). We surveyed 201 farmers, which corresponds to 44.6% of the total farming population. The sample size ensures a 95% confidence level with an acceptable error margin (<5%).

The key objectives were to identify the factors influencing the adoption of date palm compost as a fertiliser, assess perceptions of compost compared with other fertilisers, and determine farmers' willingness to pay for the compost. The survey form used for this study is provided in Appendix A (English translation).

2.3. Composting Station Economic Model

The Ecocanvas framework [14] was applied as a predictive tool to develop and structure a circular business model for the Figuig composting station. Rather than limiting the analysis to a description of existing practices, the Ecocanvas was adapted to integrate environmental, social, and economic parameters, enabling an assessment of the potential impacts of managing date palm by-products through composting in fragile oasis ecosystems.

3. Results

3.1. Evaluation of Date Palm Compost as an Amendment

The results indicate that the compost mixed with soil was the most efficient growing substrate for *C. annuum* and *S. melongena*, outperforming the cattle manure and the control (Figures 1 and 2).

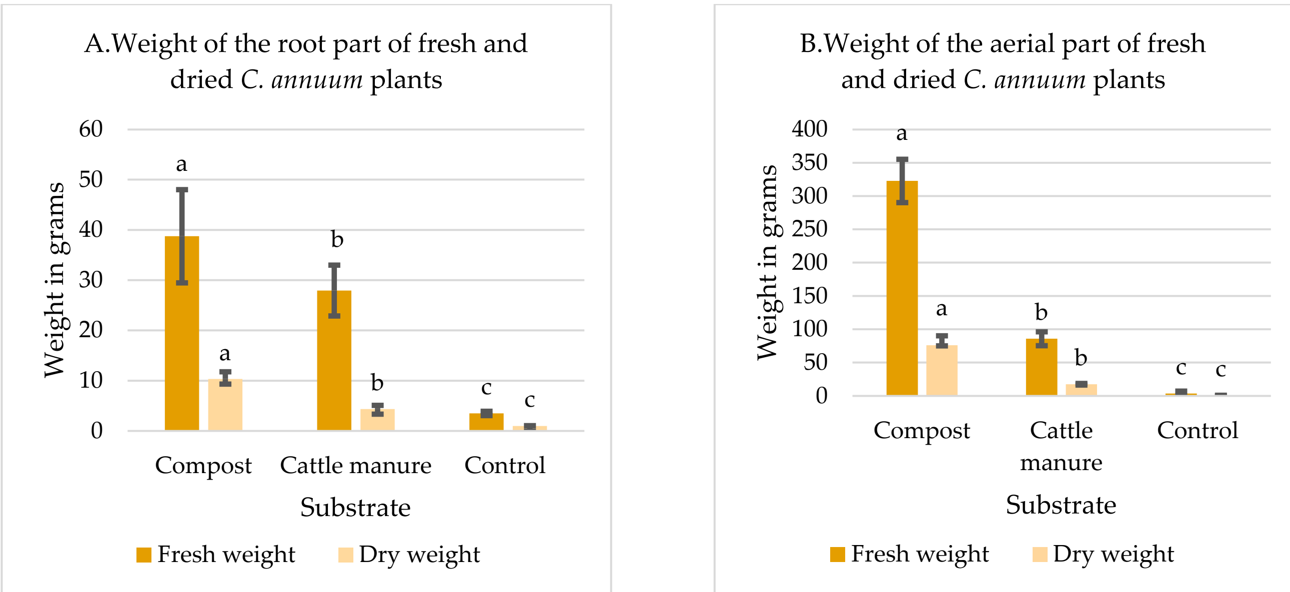

Figure 1. Effects of compost on the growth (grams/plant) of *C. annuum* after 3 months of field cultivation. Bars represent mean ± SD (n = 32 plants per treatment for the compost and the cattle manure; n = 16 plants per treatment for the control). Different lowercase letters above the bars indicate significant differences between treatments (one-way ANOVA followed by Tukey's HSD test, $p < 0.05$).

For pepper plants (Figure 1), compost application significantly improved root and shoot growth compared to cattle manure and the control. Regarding root development (Figure 1A), the fresh root weight was 39.2 g with compost compared to 27 g with cattle manure and 3.92 g in the control. Similarly, dry root weight was 10.8 g with compost compared to 4.34 g with cattle manure and 0.95 g in the control. Aboveground biomass (Figure 1B) also showed significant improvement with compost. The fresh aerial part weight was 332.2 g with compost, while cattle manure resulted in 86.01 g, and the control only 3.63 g. The dry aerial part weight was 75.54 g with compost, 17.68 g with cattle manure, and 0.54 g in the control.

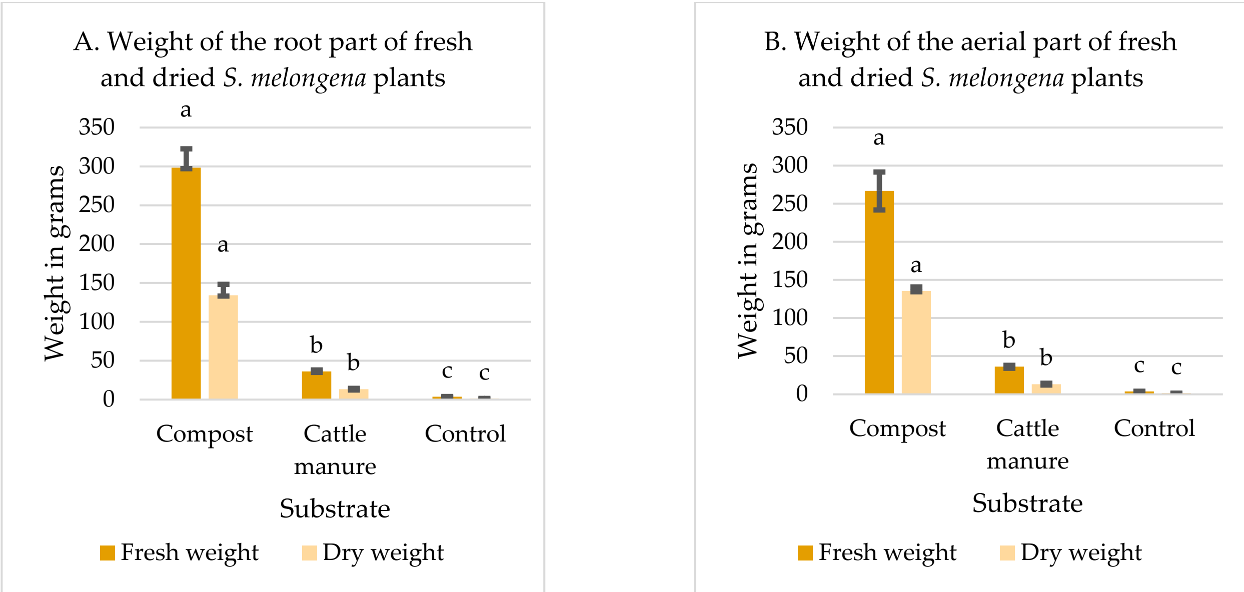

Figure 2. Effects of mature compost on the growth (grams/plant) of *S. melongena* after 3 months of field cultivation. Bars represent mean ± SD (n = 32 plants per treatment for the compost and the cattle manure; n = 16 plants per treatment for the control). Different lowercase letters above the bars indicate significant differences between treatments (one-way ANOVA followed by Tukey's HSD test, $p < 0.05$).

Similar trends were observed for *S. melongena* plants (Figure 2), with compost significantly improving biomass accumulation. In root development (Figure 2A), the fresh root weight reached 290 g with compost compared to 36 g with cattle manure and 3.67 g in the control. Dry root weight was 136.18 g for compost-treated plants, compared to 13.31 g for those treated with cattle manure and 1.46 g for the control. Aerial biomass (Figure 2B) followed the same pattern. The fresh aerial weight was 290 g for compost, 36 g for cattle manure, and 3.67 g for the control. The dry aerial weight was 136.18 g for compost-treated plants, 13.31 g for those treated with cattle manure, and 1.46 g for the control.

As shown in Figures 1 and 2, compost application significantly improved plant growth and biomass accumulation compared to cattle manure and unamended soil.

The harvested grain weight of *H. vulgare* varied between the different substrate treatments (Figure 3). The application of compost resulted in the highest grain yield, followed by cattle manure, while the control treatment (unamended soil) produced the lowest yield. Specifically, compost application significantly increased grain yield compared to the control, producing 472 g/m^2 compared to 257 g/m^2 in the control treatment. Similarly, cattle manure resulted in a significant improvement in grain yield compared to the control, with a harvested grain weight of 396 g/m^2. Furthermore, compost application resulted in higher grain production compared to cattle manure, with yields of 472 g/m^2 and 396 g/m^2, respectively, highlighting its superior ability to improve barley grain productivity.

In conclusion, compost produced from date palm by-product can be considered as a good-quality amendment for the investigated crops that are commonly cultivated in oases environments.

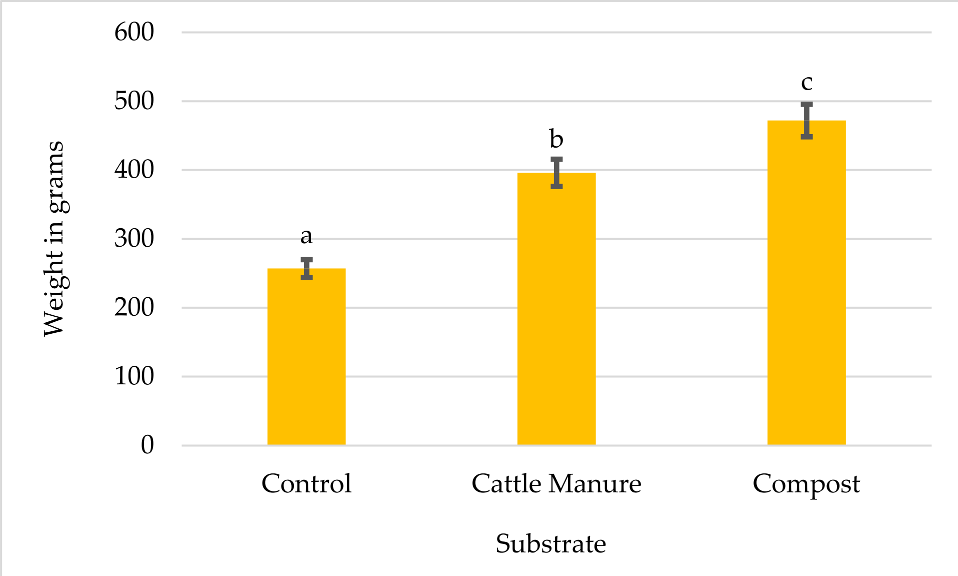

Figure 3. Impact of compost and cattle manure on *H. vulgare* grain production (g/m^2). Bars represent mean ± SD (n = 10 plots per treatment; each plot contained 133 g of barley seeds). Different lowercase letters (a, b, c) indicate statistically significant differences between treatments based on one-way ANOVA followed by Tukey's HSD test, $p < 0.05$.

3.2. Field Survey Findings on the Uptake of Compost by Farmers

A total of 201 farmers were interviewed within Figuig town, which consists of seven ksours. Originally, Figuig was divided into ksours that controlled their own date palm groves. Figure 4 shows their distribution across the ksours, reflecting the size of the different ksours in Figuig. It is clear that the majority of farmers come from Zenaga (74%), followed more or less equally by Loudaghir (6%), Lamâiz (6%), Hammam Foukania (5%), Oulad Slimane (2%), Hammam Tahtani (2%), and Laâbidate (1%).

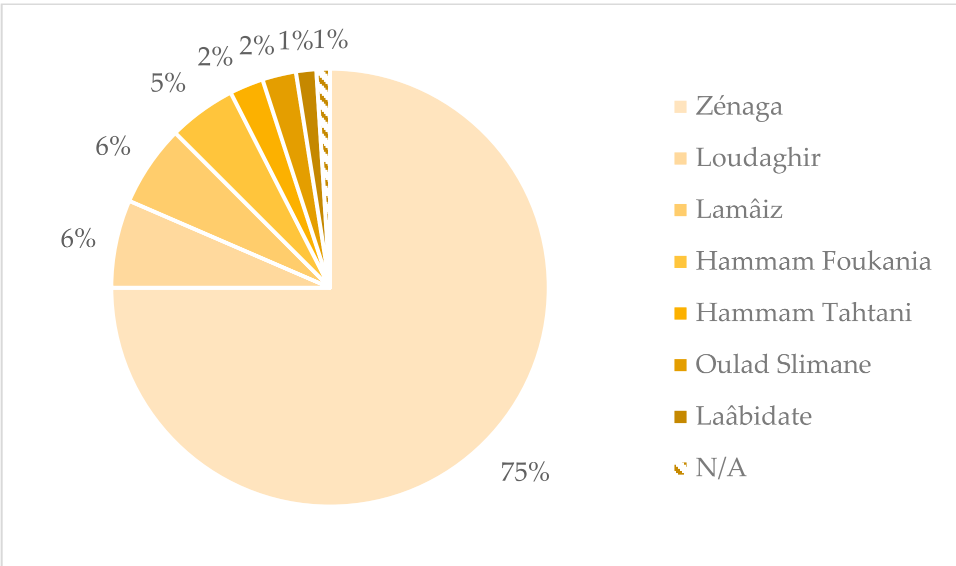

Figure 4. Distribution of interviewed farmers (n = 201) within Figuig Ksours.

This survey was conducted in June 2023. It allowed us to draw a typical portrait of figuigui farmers. They come from old traditional palm groves, are 39 years old on average, and live in Zénaga. They have been farmers their entire lives and have a secondary school degree. Their farms, with an average area of 0.9 hectares, are mainly devoted to the cultivation of date palms, with around 52 trees, although they also grow other crops. They employ at least one seasonal worker and spend an average of three hours a day farming. One of the main challenges they face is pest pressure, especially Bayoud, which they fear the most. This disease is a major constraint, with an average of two infected trees per farm. They consider the overall quality of Figuig's soils to be average, highlighting the challenges associated with the sustainability of oasis farming systems. In terms of fertilisation, they prefer locally produced organic fertiliser when available, often combined with commercial chemical fertiliser.

Farmers use a variety of soil fertility management practices, with all respondents using manure, 30% combining manure with chemical fertiliser, and 7% relying solely on compost, including homemade or industrial composts. The widespread use of manure underlines its critical role in maintaining soil health, while its combination with chemical fertilisers is intended to increase crop yields by providing immediate nutrient availability. The exclusive use of compost by 7% of the surveyed farmers reflects a growing interest in sustainable agricultural practices that improve soil organic matter content and reduce dependence on chemical inputs.

The use of compost remains limited, as it is neither a traditional practice nor readily available on demand. These findings highlight the need for balanced nutrient management strategies and increased awareness of sustainable farming practices to optimise agricultural productivity and maintain soil health.

Farmers choose soil amendments based on various factors, with 94% prioritising availability, indicating a preference for easily accessible options (Figure 5). Soil quality is a consideration for 47% of farmers, highlighting the importance of maintaining soil health. Nutrient content, particularly nitrogen, phosphorus, and potassium (NPK), influences the choice of 36% of the farmers, reflecting the perceived importance of these macro-elements for plant growth. Environmental impact is a concern for 34% of farmers, highlighting a growing awareness of sustainable practices. This awareness is especially crucial in regions like oasis ecosystems, where climate change is exacerbating soil degradation through rising temperatures, erratic rainfall, and disrupted water cycles [17].

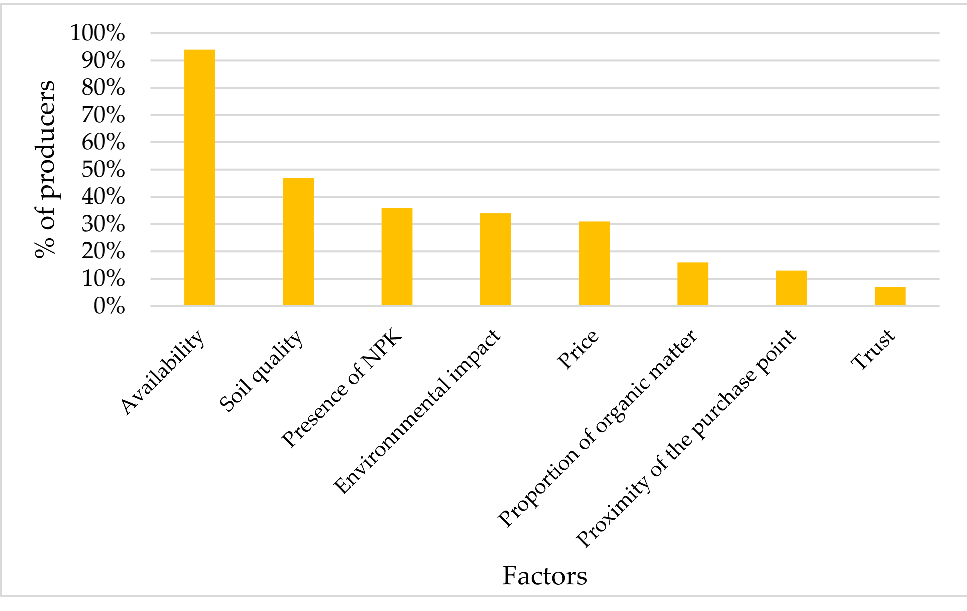

Figure 5. Factors influencing the choice of soil amendments as expressed by Figuig's farmers, (n = 201).

Economic considerations also come into play, with 31% of farmers factoring in cost when choosing soil amendments. Organic matter content, valued by 16% of farmers, is another key factor for improving soil quality, particularly as higher temperatures accelerate the breakdown of soil organic carbon (SOC), weakening soil fertility and resilience [17]. Interestingly, only 13% of farmers are influenced by proximity to the purchase point, suggesting that most are willing to travel farther to secure the right amendments. Trust in the seller matters to just 7% of farmers, indicating that while reliable supplier relationships are important to a small group, the majority prioritise other factors when acquiring soil nutrients.

Among the farmers surveyed, 55% provided an opinion on the price they were willing to pay for compost produced from date palm residues. Their willingness to pay (Figure 6) ranged from 0.02 to 0.57 EUR/kg of compost.

Figure 6. Figuig farmers' willingness to pay for compost made from date palm waste in Figuig station, (n = 201).

3.3. Economic Analysis and Viability Assessment of the Figuig Composting Station

The compost produced in this study was developed in an experimental composting station consisting of three composting lanes, each measuring 5 m × 35 m. Additionally, it was possible to set up a windrow of 100 m^3 on each track, producing 30 tonnes of compost. The production station currently has a production capacity of 350 tonnes of compost per year. Its maximum capacity can be reached after three production batches, each batch consisting of compost production spread over the three tracks described above. To establish the cost structure for this experimental composting station using date palm by-products, initial investment costs were calculated at EUR 238,261. These costs include land acquisition, construction of composting lanes, procurement of equipment (e.g., shredders), and other infrastructure-related costs. Operating costs include consumables, raw materials (by-products and manure), water, grinding fees, and labour costs for two workers. These costs amount to EUR 1916 per 30 tonnes, which corresponds to a unit cost of 0.06 EUR/kg of compost (Table 1).

Table 1. Breakdown of operating costs (in EUR) for the production of 1 windrow of 30 tonnes of compost.

	Unit	Quantity	Unit Price (in EUR)	Total Price (in EUR)
By-product	m^3	75	7	525
Manure	m^3	25	19	475
Grinding costs	tonne	30	14	420
Water	m^3	50	0.4	20
Workforce	workers	2	238	476
Total cost for a windrow of 100 m^3 with 30 tonnes of production				1916
Cost per kg				0.06

The selling price for the compost was set at 0.14 EUR/kg to reflect the current market price for compost and the willingness of about 38% of the farmers surveyed to pay within this price range (0.08–0.14 EUR/kg, see Figure 6). At this price, the sale of 350 tonnes per year generates an annual income of EUR 49,000. After deducting operating costs, the profit is estimated at 26,647 EUR/year. The initial investment of EUR 238,261 can therefore be depreciated over a minimum period of 9 years, which is a considerable period. Two solutions can be envisaged to factor in a faster payback. The first is the involvement of public authorities, which should help such an entrepreneurial venture, based on the important secondary effects and spillovers. The second is growth in scale, so that economies of scale can be reached, reducing the payback period of the initial investment.

Field surveys conducted in 2018 by the National Agency for the Development of Oasis and Argan Areas (ANDZOA) in Morocco estimated that the Figuig oasis contains approximately 259,250 date palm trees [18]. Based on agronomic recommendations provided by local figuigui farmers, each tree requires an average of 15 kg of compost per year to ensure optimal growth. Consequently, the annual compost demand in the Figuig oasis is projected to be around 3889 tonnes. Given this potential demand, it is crucial to project the scalability of the station from an experimental unit to a production facility. Four scenarios are proposed for different production scales (see Table 2):

- Production scale: 350 tonnes/year:
    - Workforce of two people.
    - Three composting lanes.
    - Under these conditions, the initial investment could be recovered in at least 9 years.
- Production scale: 1000 tonnes/year:
    - Increase the workforce from 2 to 6, increasing the operating costs by 953 EUR/year.
    - Increase the number of composting lanes from 3 to 10, requiring an additional EUR 33,357 in investment costs.
    - Under these conditions, the initial investment could be recovered in at least 6 years.
- Production scale: 2000 tonnes/year
    - Invest in more advanced and efficient machinery (shredders and windrow turning) at an additional cost of EUR 238,261.
    - Increase in workforce from 2 to 6 people, increasing operating costs by 953 EUR/year.
    - The initial investment could be recovered in a minimum of 6 years.
    - Increase the number of composting lanes from 10 to 20, requiring an additional investment of EUR 47,652.

    - Under these conditions, the initial investment could be recovered in at least 6 years.
- Production scale: 3500 tonnes/year
    - Invest in modern machinery, adding EUR 47,652 to the capital cost.
    - Maintain 20 composting lanes.
    - Maintain a workforce of six people.
    - Under these conditions, the initial investment could be recovered in a minimum of 4 years.

Table 2. Estimated costs (in EUR) as a function of the production capacity of the composting station.

	350 Tonnes/Year	**1000 Tonnes/Year**	**2000 Tonnes/Year**	**3500 Tonnes/Year**
Investment costs (in EUR)	238,261 3 composting lanes	271,617 10 composting lanes	557,530 20 composting lanes and additional equipment	605,183 20 composting lanes and additional equipment
Operating costs for 30 tonnes (in EUR)	1916 (2 workers)	2869 (6 workers)	2869 (6 workers)	2869 (6 workers)
Total operating costs (in EUR) (B)	22,353	95,633	191,266	334,716
Income after sales at 0,14 EUR/kg of compost (EUR/year) (A)	49,000	140,000	280,000	490,000
Profit (A-B) (in EUR)	26,647	44,367	88,734	155,284
Minimum years return on investment (=investment costs/profit) (in years)	9	6	6	4

Economies of scale play a crucial role in profitability. Financial projections show that increasing production capacity from 350 tonnes/year to 3500 tonnes/year reduces unit production costs while increasing profits. One of the main factors explaining these efficiency gains is the allocation of fixed costs (infrastructure, equipment, installation of composting stations) over a larger production volume. For example, initial investment increases from EUR 238,261 for 350 tonnes/year to EUR 605,183 for 3500 tonnes/year, but profitability increases with a reduction in the payback period from 9 years to just 4 years. In addition, variable costs (labour, transport, energy) increase at a slower rate than production, allowing for an improvement in the profit margin as capacity increases.

The price of amendments is calculated annually per palm tree and reveals significant shifts in the cost-effectiveness of different amendment sources when adjusted for the quantities required per tree (Table 3). In particular, manure, previously considered a low-cost option, becomes more expensive than composted alternatives at EUR 2.5 per tree. Fertiliser, although less costly on a financial basis in this calculation, remains the least environmentally sustainable option due to its significant environmental footprint [7]. With fertiliser currently in short supply, farmers show a preference for natural products over chemical fertilisers, as indicated by 89 out of 201 farmers surveyed. Despite the lower financial cost of chemical fertiliser (Table 3), farmers are aware of its long-term effects, including increased soil salinity and accelerated soil degradation [19]. This awareness positions compost as a viable alternative in line with farmers' long-term sustainability goals.

In this study, the Ecocanvas framework was applied as a predictive tool (Figure 7) to develop and structure a circular business model for the Figuig composting station. Rather than merely describing existing practices, Ecocanvas enabled the anticipation of potential impacts by integrating environmental, social, and economic parameters. Its application provides a comprehensive understanding of how managing date palm by-products through composting can contribute to sustainability in fragile oasis ecosystems.

Table 3. Amending requirement per palm foot.

Amendment	Unitary Price (EUR/kg)	Requirement (kg/year)	Cost (EUR/year)
Commercially available chemical fertiliser (NPK)	0.4	1	0.4
Compost produced at Figuig station	0.14	15	2.1
Commercially available compost	0.14	15	2.1
Cattle manure	0.1	25	2.5

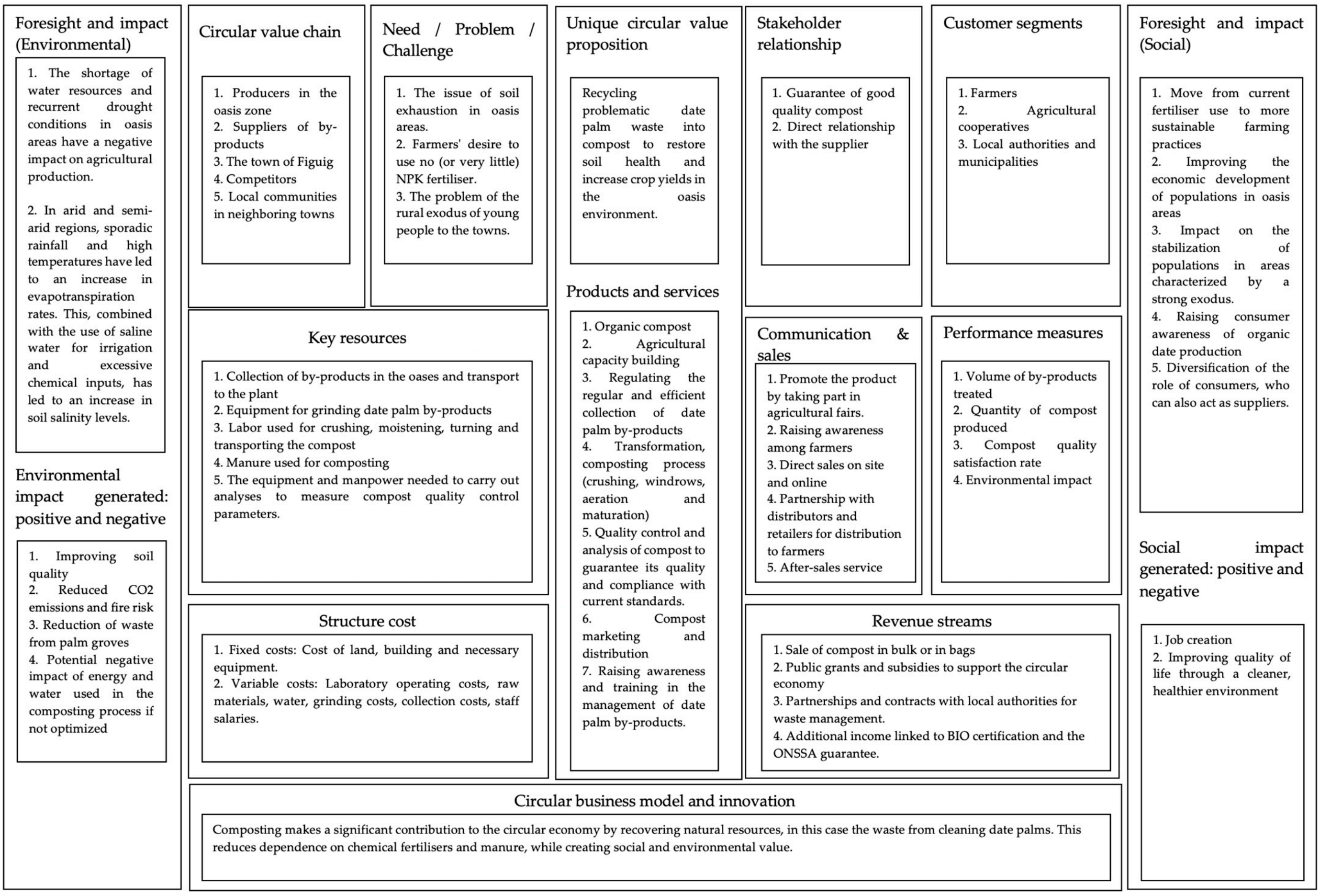

Figure 7. The oasis Ecocanvas of Figuig's compost production facility. Source: Own computation inspired by [14].

The Ecocanvas review reveals the following main dimensions:

- Adaptation of the Ecocanvas to the Local Context

The generic Ecocanvas framework was adjusted to reflect the specificities of the Figuig oasis. Localised parameters were incorporated, including the availability and management of date palm residues, the participation of farmers and cooperatives, and institutional support from local authorities. This adaptation allowed the model to reflect realistic operational conditions and anticipate the station's sustainability potential.

- Integration of Environmental, Social, and Economic Dimensions

The Ecocanvas was used to map the value creation process by identifying how by-product collection, compost production, and distribution interact with broader sustainability objectives:

  - Environmental dimension: Assessing potential contributions to soil fertility restoration, reduced dependence on chemical fertilisers, mitigation of CO_2 emissions from residue burning, and improved waste management.
  - Social dimension: Predicting the creation of local employment opportunities, capacity building through farmer training, strengthened partnerships between cooperatives and institutions, and stabilisation of rural populations by reducing youth migration.
  - Economic dimension: Analysing the market potential for compost in the Figuig oasis, assessing pricing strategies, and identifying collaborative mechanisms to improve market penetration and long-term financial viability.

The Ecocanvas operates not only as a visualisation tool but also as a predictive decision-support framework. It provides a comprehensive understanding of how the Figuig composting station can enhance soil fertility, strengthen local socio-economic structures, and support the transition to a sustainable circular economy in oasis ecosystems.

4. Discussion

This study evaluated the feasibility and sustainability of adopting a circular business model for managing date palm by-products to produce high-quality compost in the Figuig oasis, Morocco.

From an agronomic perspective, the results confirm that the compost produced in Figuig is of high agronomic quality and has demonstrated positive effects on crops commonly cultivated in oasis environments, such as eggplant, pepper, and barley.

The application of compost resulted in significantly higher crop productivity, which can be attributed to several complementary mechanisms. The controlled composting process stabilises organic matter and reduces phytotoxic compounds, producing a safer and more effective soil amendment. In addition, compost enhances humification, improving the cation exchange capacity and gradually increasing the availability of essential nutrients, such as nitrogen, phosphorus, and potassium [5,11]. This slow and sustained nutrient release supports continuous plant uptake throughout the growing season, unlike cattle manure, which often results in variable nutrient release and temporary nitrogen immobilisation during early decomposition.

Furthermore, compost improves soil physical properties, including aggregation, porosity, and water-holding capacity, which together enhance root development and plant access to water and nutrients—critical advantages under semi-arid conditions [13,20]. The application of compost also stimulates beneficial soil microorganisms involved in nutrient mineralisation and plant growth promotion [21,22], thereby fostering a biologically active and resilient soil system. These combined effects on soil fertility, structure, and microbial dynamics explain the superior agronomic performance of compost over cattle manure and chemical fertilisers and underlines the potential of locally produced compost to serve as a sustainable alternative for soil regeneration, water retention, and ecosystem stability [5].

The socio-economic survey highlights a strong willingness among farmers to adopt composting practices, revealing significant potential for scaling up circular agriculture within the region.

The predictive analysis highlights significant potential environmental benefits resulting from the adoption of a circular composting model. By transforming date palm by-products into compost, the station can contribute to improving soil quality through the restoration of organic matter and better nutrient availability, helping to counteract the widespread issue of soil exhaustion in the oasis environment. This approach promotes sustainable soil management by reducing reliance on chemical fertilisers and limiting the associated risks of salinisation and land degradation.

Additionally, composting may prevent the open burning or uncontrolled dumping of palm residues, thereby mitigating fire risk. However, the Ecocanvas also identifies that these environmental gains depend on optimised energy and water management, highlighting potential areas requiring careful monitoring to maximise benefits.

Moreover, by replacing chemical fertilisers with organic compost, the initiative raises consumer awareness of sustainable agricultural practices and strengthens confidence in local organic production systems.

From a social perspective, the Ecocanvas predicts substantial positive impacts associated with the integration of local actors, fostering social cohesion by strengthening partnerships between cooperatives, producers, and local institutions while simultaneously stabilising rural populations in regions vulnerable to youth migration and rural exodus.

At the economic level, the Ecocanvas analysis demonstrates that the systematic collection and transformation of date palm by-products into compost respond to a substantial market demand in the Figuig oasis. With an estimated average selling price of 0.14 EUR/kg, the model anticipates the possibility of covering operational costs while generating revenue for local producers. Furthermore, the tool underscores the importance of strategic partnerships with cooperatives, local authorities, and private distributors to improve compost accessibility and market penetration. These collaborative mechanisms are expected to enhance the station's economic resilience and contribute to the long-term sustainability of the oasis farming system. In addition, the composting station is expected to create local jobs and improve household incomes by generating new economic opportunities in the oasis.

5. Conclusions

This study shows that the recovery of date palm waste, generated each year by the exploitation of the Figuig oasis, into quality compost should make it possible to remedy the problems of soil degradation in oasis environments. The adoption of a circular business model for managing date palm by-products offers significant environmental, agronomic, and social benefits in oasis ecosystems. The Figuig composting station represents a successful integration of sustainable resource management and community-based practices, reducing residue mismanagement, improving soil fertility, and fostering local collaboration through cooperatives and farmer training.

However, achieving long-term sustainability requires scaling up compost production to meet regional demand and fostering wider farmer adoption through targeted awareness campaigns and capacity-building programs. These measures will ensure that the Figuig model can serve as a replicable framework for other oasis regions in Morocco and beyond, promoting sustainable agriculture while addressing environmental challenges in semi-arid agro-ecosystems.

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Informed Consent Statement: Verbal informed consent was obtained from the participants. Verbal consent was obtained rather than written because the majority of participating farmers are illiterate and unable to read or write. Informed consent was obtained orally prior to participation.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

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Appendix A

Farm Survey questionnaire

1. Interviewer Name
2. Farmer's Information
   - Full Name: ______
   - Contact Number: ______
   - Age: ______
   - Place of Birth: ______
   - Current Residence: ______
   - Ksar of Residence: ______
3. Education Level (Select one)
   - ☐ No formal education
   - ☐ Primary
   - ☐ Secondary
   - ☐ Higher education
4. Professional Information
   - Primary Occupation: ______
   - Years of Farming Experience: ______
5. Main Activity Sector (Select one)
   - ☐ Production
   - ☐ Local distribution
   - ☐ Processing
6. Cooperative Membership
   - Member of a cooperative? (Y/N)
   - If yes:
     - Date of cooperative establishment: ______
     - Number of members: ______
     - Cooperative location: ______

    - Main activities: ______

7. Farm Characteristics
    - GPS Coordinates: ______
    - Palm Grove Name: ______
    - Farm Area (m^2): ______
8. Workforce
    - Seasonal Workers: ______
    - Permanent Workers: ______
    - Female Workers: ______
    - Workers aged 16–35: ______
    - Worker Origins: ______
9. Farm Details
    - Number of Date Palms: ______
    - Bayoud-infected Palms: ______
    - Other Crops: ______
    - Crop Type: ______
    - Average Daily Work Hours: ______
10. Financial Information (in MAD)
    - Annual Investment: ______
    - Cost Structure: ______
    - Annual Profit: ______
    - Income Value: ______
    - Does income meet needs? (Y/N)
    - If no, other income sources: ______
11. Soil Amendment Selection Criteria (Select all that apply)
    - ☐ Availability
    - ☐ NPK Content
    - ☐ Environmental Impact
    - ☐ Soil Health
    - ☐ Organic Matter Proportion
    - ☐ Vendor Trustworthiness
    - ☐ Price
    - ☐ Proximity of Purchase Point
12. Soil Analysis
    - Conduct soil tests? (Y/N)
    - If yes:
        - Test Type: ______
        - Frequency: ______
    - Soil Quality Assessment: (Select one)
        - ☐ Depleted
        - ☐ Poor
        - ☐ Average
        - ☐ Good
        - ☐ Excellent
13. Fertiliser Use
    - Type: ______
    - Quantity: ______

- Application Frequency (per year): ______
- Source: ______

14. Date Palm Management
    - Pruning Frequency: ______
    - By-product Storage Method: ______
    - By-product Utilisation: ______
    - By-product Disposal Method: ______
15. Compost Knowledge and Use
    - Familiar with compost? (Y/N)
    - Use compost? (Y/N)
    - If yes:
        - Quantity: ______
        - Source: ______
    - Know SEMO experimental compost station? (Y/N)
    - Willing to:
        - Purchase SEMO compost? (Y/N)
            - Price willing to pay (MAD/kg): ______
        - Sell by-products to SEMO? (Y/N)
            - Expected price: ______
        - Exchange by-products for compost? (Y/N)
16. Additional Comments: ______

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