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RESEARCH

Use of cactus pear pruning waste to improve soil properties and to produce high-quality compost

Loretta Bacchetta · Margherita Canditelli · Giovambattista Platamone ·
Silvia Procacci · Paolo Roberto Di Palma · Oliviero Maccioni ·
Maria Rita Montereali · Chiara Alisi · Cinzia Forni

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Abstract Bio-fertilizers could be a possible solution to help manage bio-waste problems and to maintain soil health conditions, especially in organic farms. Pruning of cactus pear produces from 6 to 10 tons/yearly of cladodes per hectare in specialized Italian orchards, which represents waste and a cost for disposal to farmers. Therefore, the aim of the work was to investigate the effects on soil physical properties, microflora activity, and basil plant growth of powdered pruning waste from cactus pear incorporated in the soil (10%, 20%, 30% 40% w/w). Moreover, we studied a dynamic composting process from fresh cladodes to produce stabilized end-products at the farm level. Our studies demonstrated that holding water ability and bulk density of soil were ameliorated by supplementing dried cladodes. Thus, gravitational and gravimetric water was positively correlated with the increase of added dried cladode in the soil (0.1% and 6.2 g $H_2O \pm 0.3$ in samples of 40% mixed soil versus 68% and 3.3 g $H_2O \pm 0.3$ in control). Furthermore, bulk density was reduced limiting soil compaction. Preliminary results on microbial activity suggested a possible selection/inhibition of some bacterial strains correlated with the increment

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L. Bacchetta (✉) · S. Procacci · O. Maccioni
Bioproducts and Bioprocesses Laboratory, BIOAG Division, SSPT Department, ENEA Casaccia, Via Anguillarese 301, Rome, Italy
e-mail: loretta.bacchetta@enea.it

S. Procacci
e-mail: silvia.procacci@enea.it

O. Maccioni
e-mail: oliviero.maccioni@enea.it

M. Canditelli · P. R. Di Palma
Technologies for the Reuse, Recycling, Recovery and Valorization of Waste and Materials Laboratory, USER Division, SSPT Department, ENEA Casaccia, Via Anguillarese 301, Rome, Italy
e-mail: margherita.canditelli@enea.it

P. R. Di Palma
e-mail: paoloroberto.dipalma@enea.it

G. Platamone
PhD School in Evolutionary Biology and Ecology, University of Rome "Tor Vergata", Rome, Italy
e-mail: gplatamone@outlook.it

M. R. Montereali · C. Alisi
Observations and Measurements for Environment and Climate Laboratory, PROTER Division, SSPT Department, ENEA Casaccia, Via Anguillarese 301, Rome, Italy
e-mail: mariarita.montereali@enea.it

C. Alisi
e-mail: chiara.alisi@enea.it

C. Forni
Department of Biology, University of Rome "Tor Vergata", Via Della Ricerca Scientifica, Rome, Italy
e-mail: forni@uniroma2.it

of dry cladode supplementation. The basil plants grown in 20% mixed soil showed an increased biomass when compared to the control (+21%). Finally, raw cladode proved to be an excellent substrate for aerobic fermentation providing a final product of good quality and high moisture content (65%). These results are particularly relevant in organic agriculture where bio-fertilizers are recommended as economical, eco-friendly solution accessible also to marginal and small farms.

Keywords *Opuntia ficus indica* · Cladodes · Soil properties · Compost · Waste

Abbreviations

AWCD	Average well color development
OD	Optical density
OFI	*Opuntia ficus indica*
OFI soil	Soil supplemented with different percentages of dried cladodes
SBD	Soil bulk density

Introduction

Nowadays, one of the major problems worldwide is the degradation of agricultural land which declines its productivity as a result of modifications of its nutritional properties, amount of organic matter, and erosion (FAO 2015, Timsina et al. 2018; Searchinger et al. 2019). Based on the German Environment Agency (UBA 2015) every year, on a global scale, about 10 million hectares of cropland becomes unproductive, while approximately 25% of the soils used for agricultural productions have significantly reduced quantity of humus and essential nutrients in the last 50 years (Hossain et al. 2020). Another issue is the loss of soil structure that can be disrupted in areas where land use provides insufficient organic matter to the soil or does not maintain its biological activity (Daly et al. 2015). Furthermore, agriculture accounts for 70–85% of water use and the decrease of hydrocolloids in the soil such as organic matter limits the soil water retention reducing the hydrological constants and the field water capacity (Solís-Oba et al. 2020). The recent Farm to Fork strategy, the heart of the European Green Deal, aims to reduce 50% of chemicals in agriculture achieving 25% organic land by 2030 (see https://ec.europa.eu/food/horizontal-top-ics/farm-fork-strategy_en). The challenge is thus to produce enough food reducing the external input, under a circular and sustainable perspective. In this regard, the use of organic amendments might be one of the most effective agronomic practices, especially in organic agricultural system, as a potential solution in maintaining long-term soil fertility, as well as in improving water management (Wilson and Lovell 2016; Dong et al. 2021; Kurniawati et al. 2023).

Indeed, if we consider that nearly 30% of the agricultural goods produced worldwide end up as agro-wastes with an approximately global amount of 2 billion tons biomass (Singh et al. 2021; El-Ramady et al. 2022), there is a great opportunity to obtain soil-improving effects using organic amendments/biofertilizers. This aspect becomes of great importance considering the recent increased cost and restricted affordability of chemical fertilizer, as a consequence of the COVID-21 pandemic and the Russia-Ukraine war (Hall 2023). However, for an efficient use of by-products, different selection criteria must be applied including availability, quality, applicability, sustainability, cost, and beneficial effects on the soil system (Rahmann et al. 2021; Gottschall et al. 2023).

Opuntia ficus-indica ((L.) Mill.) (OFI) is a succulent plant which is widespread in many arid countries including the Mediterranean basin. In specialized organic Italian orchards of cactus pear (Italy is the first supplier in Europe, approximately 4 thousand cultivated hectares, Ochoa and Barbera 2017), severe pruning is applied to stimulate the late yield very appreciated by market (Kumar et al. 2021). This cultural practice produces a waste of 6–10 tons per ha of cladodes and immature fruits yearly, which represents a problem and a cost for its disposal by farmers. Hence, the investigation on how this agro-industrial waste can be managed towards an efficient conversion from wastes to soil value-added products is a prerequisite for sustainable management of the organic cactus pear chain being this raw material is very rich in water, mucilage, and minerals (Bacchetta et al. 2019; Procacci et al. 2021; Bojórqez-Quintal et al. 2021). The presence of hydrocolloids, which is the key factor for the adaptability of *Cactaceae* to arid conditions, makes this biomass particularly interesting as an agricultural by-product. A common practice in the traditional cactus pear cultivation areas is to incorporate part of pruning waste directly in the soil, but not many scientific references are available on this matter, so far.

In 2013, Sáenz Hernández et al. reported a study on the effects of bio-fertilizer from fermentation of a mixture of chopped cladodes and fresh manure on cactus pear growth and yield. The results indicated that the addition of this kind of biofertilizer increased the efficiency and sustainability of crop systems in arid regions. *Opuntia* root development and sprouting were anticipated if compared to the control and water availability and velocity of water infiltration, apparent reduction of soil density was ameliorated. More recently, Rodas-Gaitán et al. (2019) and Cruz-Mèndez et al. (2021) confirmed the positive effects of composting preparation from cactus pear on the physical, chemical, and biological properties of soil. Soil amendments are commercialized in many different compounds and packaging; however, the most common and promising are pellets which combine slow degradation and nutrient release for easy handling for transportation and storage (Sung-inthara et al. 2024). From a sustainable point of view, a new generation of solar air heating and ventilation coupled with an unconventional kiln to dehydrate *Opuntia ficus-indica* cladodes is under development in the traditional area of cultivation (Ciriminna et al. 2019).

Therefore, the aim of the present work was twofold: (1) to investigate the effect of cactus pear powder amendment on soil properties and plant growth as a bio-product for horticultural and floricultural sectors; (2) to evaluate an efficient composting process starting from fresh cladode to produce highly stabilized end-product at farm and industrial level.

Materials and methods

Determination of physical and microbiological parameters on OFI mixed soil

Cladodes of *Opuntia ficus-indica* (cv Gialla) were collected at San Cono (Azienda Spitale, CT, Italy) after normal annual pruning. The biomass, which included cladodes of different ages (1–3 years) and sizes, were washed using tap water, manually dissected, and then dried at 60 °C until constant weight. Sequentially, the dried cladodes were ground with a laboratory blender and stored in an airtight container at room temperature. The soil chosen for the experiments was a commercial potting soil, commonly used for nursery (TerComposti SpA; main characteristics, pH (in H2O) = 8; electrical conductivity (EC = 0.8 dS/m); dry bulk density = 220 kg/mc; total porosity (%) = 82). The air-dried biomass was mixed with soil, in five different percentages by weight: 0%, 10%, 20%, 30%, 40% (g OFI/100 g soil); then, each sample was placed into 5-cm diameter cylinders in three replications for a total of 15 repacked soil samples to be analyzed. To determine gravitational water not retained by colloids and capillary pores, 10 g of each sample was placed in a pot with a saucer and 50 mL of water was added. The samples, fully hydrated (the % of soil humidity was assessed by a tester kit, X0018PF2K7 E2EURO, Consulting Hungary), released the gravitational water in the saucer; the water was measured 60 min after irrigation and expressed by volume (mL). The gravimetric water, that is the fraction of water absorbed by colloids, was assessed using the thermo-gravimetric method (ASTM D 2216–66 standards). Briefly, the procedure was as follows: (1) 10 g of repacked soil samples was placed in a glass container which was previously weighed (W_1); (2) the samples in the container were maintained in an oven at a predetermined temperature of about 105 °C until stable weight; (3) the samples were cooled and weighed together with the container (W_2). The gravimetric water content was obtained by the formula:

$$w = \frac{W_1 - W_2}{W_2 - W_c}$$

W_c	container weight
W_1	container weight and moist soil
W_2	container weight and dry soil

To quantify the incidence of compaction on soil bulk density, compaction tests were carried out using PVC tubes of 4.5 cm diameter and 25.5 cm length. A pressure treatment of 8.9 kPa = 0.090 kg/cm^2 was applied to the repacked soil samples prepared as described before.

Laboratory determination of microbial activity was evaluated on 5 g of the same repacked soil samples (in triplicate) placed in 50 mL of 0.1% sodium pyrophosphate in sterile bottles on an orbital shaker at 180 rpm for 90 min at RT. The soil suspension (containing the bacterial community) was inoculated into Biolog ECO Plates (Biolog Inc., Hayward, CA, USA), according to Sprocati et al.

(2014) to analyze the community-level physiological profile (CLPP). Briefly, soil suspension was diluted 1:10 and dispensed into the 96 wells of the microplates (100 µL per well) containing 32 different substrates in triplicate. The plates were incubated at 28 °C in the dark and read every 24 h in the microplate reader using a double wavelength (OD590-OD750). Kinetic analysis was performed using average well color development (AWCD) as a parameter that captures an integral fingerprinting of carbon sources utilization. AWCD was calculated as the arithmetic mean of the OD values of all the wells in the plate per reading time. Patterns of substrate utilization in each sample were recorded and analyzed with the Microlog software (version 5.0). Heatmap was generated with Excel (Windows Office 13). Data are the mean of six individual OD values.

Evaluation of basil growth on OFI mixed soil

To evaluate whether the integration of OFI powder pruning into the soil is a suitable option for plant growth, an experiment was carried out on basil plant grown on pots (20 cm diameter). Three substrates (treatments) were prepared, each containing commercial potting soil (described before) and increasing amount of powder pruning waste (0%; 10%; 20% w/w) for a total of nine samples disposed in three randomized blocks. Seeds of basil (*Ocimum basilicum* L.) purchased from Agrarian Consortium Dorelli (Rome, Italy) were surface sterilized with 5% sodium hypochlorite solution for 20 min, washed four times with sterile water, and allowed to germinate in the pots. Seedlings were grown in a climatic chamber at 24 ± 2 °C with a photoperiod of 16-h light/8-h dark and weekly watered. After 3 months, the plants were carefully explanted, and the roots were gently washed with running tap water to remove soil residues. Each plant was weighed after the separation of the shoots from the roots. All samples were then lyophilized using a bench freeze dryer (LIO-SPDGT, www.5Pascal.it) and weighed.

Experimental design to compost raw cladodes

The second experiment was carried out using a domestic rotating composter (Fig. 1). The main substrate for the aerated composting process was cactus pear cladodes (65 kg), chopped to obtain 1–2.5 cm pieces. The cladodes were added in the composter every 10 days in 4 different loads. A 20% of the total weight of bulking agent (7.8 kg of *Arundo donax* L.) and 6.1 kg of pellet were initially added to cactus pear to facilitate the aeration of material during the composting process. The percentage of water content was 90% in raw cladodes and 7–8% in the pellet. An initial inoculum (3.4 kg) of compost from agro-industrial waste (see the main characteristics of cured compost used as a starter in supplemental materials, 2S, Table 2S) was added to promote the aerobic fermentation process. The total starting material was 82.3 kg. The composter was manually rotated every 3 days. The process started at the beginning of July and ended in December 2021 (6 months). The evaluation of compost characteristics during the campaign was performed on three replicates as follows: temperature was detected by a long rod thermometer (TC Direct, www.tcdirect.com); the moisture percentage was determined by drying at a constant temperature of 105 °C with a thermobalance (Crystal Therm, Gibertini); electrical conductivity (EC, µs/cm) and pH value were detected using a multiparameter meter (Water Quality Meter) in a solution of 1:3 water/compost. Additionally, in the active phase of composting, during which the highest temperatures of the process

Fig. 1 Composting process (from left to right, above) fragments of cladodes; filling the manual rotating composter; structuring material; (from left to right, below) inoculum, final composition (cladodes, pellet, bulking agent, and inoculum); manual rotating composter ready

are reached, a real-time monitoring system of temperature was realized by ENEA using an *Internet of Things* (*IoT*) solution. The monitoring system is based on a Maduino Zero A9 board, provided by the micro Controller Atmel's SAMD21 (https://wiki.makerfabs.com/Maduino_Zero_A9G.html). A DS18B20 temperature sensor (digital temperature sensor ± 0.5 °C accuracy from − 10 to + 85 °C) was connected to the Maduino board, and through the GPRS/GSM module A9G, the readings are sent every 2 h to the ThingSpeak platform for the real-time visualization. Proximal chemical analysis of compost at the end of the curing phase for C and N was performed by the elemental analyzer (Elementar, vario MACRO), while for P, Fe, K, and Mg was performed by inductively coupled plasma (ICP-OES, Perkin Elmer-Optima 200DV) after carrying out the total dissolution of the compost sample by a microwave-assisted acid digestion procedure. The content of mercury in the compost sample was measured directly using the AMA—254 (FKV, Milestone) spectrometer. All the results were expressed as % of dried weight.

Data handling and analysis

All variables were analyzed statistically, under a completely experimental randomized design. The analysis of variance (one-way ANOVA) was carried out to compare the effects of OFI powder pruning waste supplemented to the soil on its properties and on basil growth (the effect on basil polyphenols contents is provided in supplemental material; see S1). Mean comparison was performed using the Tukey test honestly significance difference test ($P \leq 0.05$). The physical and chemical characterization of OFI compost was performed in triplicate. All data are reported as means ± standard deviation.

Results and discussion

Effect of OFI powder soil mixture on bulk density, water retention, and microbial activity

Due to their chemical composition, cladodes are rich in highly soluble solids and in mucilage, a polysaccharidic compound (Sepúlveda et al. 2007; Bacchetta et al. 2019), which could act as hydrocolloid in soil. This means that OFI organic matter into soil creates a mixture of soil aggregates and residues of plant tissues in which pores and micropores form the basic condition of soil's retention ability (Duvigneaud 1988). Therefore, the generated cohesive forces improve soil absorption capacity of water particles and ions. In this respect, studies on humus demonstrated that an increase of organic matter content by 0.2% in soil generates an average increase of 0.5% utilizable water capacity and 1% pore volume (Meier–Ploeger and Vogtmann 2003). If the ratio of holding capacity vs water is 1 kg of humus to 3 kg of water, this value is approximately six times lower than mineral soil and 15 times lower than dry sand alone (Zemánek 2011). Our studies demonstrated that water holding ability and bulk density of soil were ameliorated by supplementing OFI powder pruning waste. Figures 2 and 3 report the data of gravitational and gravimetric water, determined in not amended soil and the increasing biomass-soil mixture. The amount of water not retained by soil and subject to gravitational force was significantly higher in samples with lower content of OFI dried biomass. In detail, only 0.1% of water was recovered from samples of soil mixed with 40% of OFI powder compared to 68% of the control (0%). The gravitational water determined in samples supplemented with 10, 20, and 30% was 60, 59, and 31% respectively. As we expected, gravimetric water was positively correlated with the increasing of added dried cladode, doubling in OFI 40% (6.2 ± 0.3 g H2O) when compared to control (3.3 ± 0.3 g H2O). An improved soil water holding capacity is a key factor to crop production that contributes to alleviating climate change impacts and reducing water runoff and soil erosion; therefore,

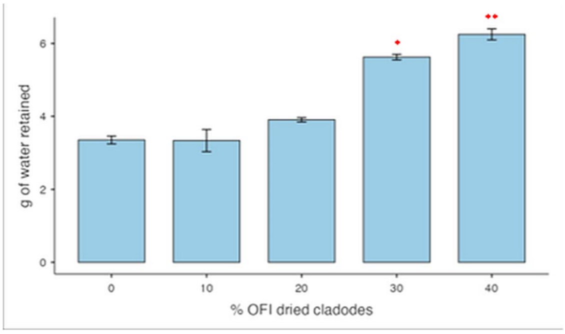


Fig. 2 Gravitational water collected from samples of soil supplemented by 0, 10, 20, 30, and 40% (w/w) of dried cladodes. Data are expressed as mean ± SD of five replications. Significant differences are reported as *$p < 0.1$ and ** $p < 0.01$

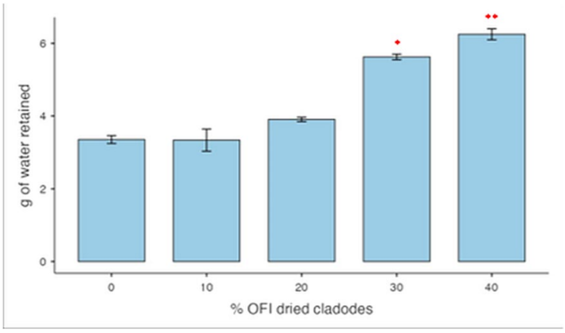


Fig. 3 Gravimetric water collected from samples of soil supplemented by 0, 10, 20, 30, and 40% (w/w) of dried cladodes. Data are expressed as mean ± SD of five replications. Significant differences are reported as *$p < 0.1$ and **$p < 0.01$

Table 1 Soil bulk density in samples of soil supplemented by 0, 10, 20, 30, and 40% of dried cladodes. The data as mean value of three replicates ± standard deviation were calculated in samples without (T0) and after being compressed (T1)

% Dried cladodes in the soil samples	T0 SBD (kg/m^3)	T1 SBD (kg/m^3)
0	0.57 ± 0.01	0.59 ± 0.01
10	0.57 ± 0.01	0.65 ± 0.01
20	0.54 ± 0.03	0.60 ± 0.02
30	0.48 ± 0.01***	0.61 ± 0.01
40	0.42 ± 0.02***	0.54 ± 0.01***

Data are expressed as mean ± SD. Significant differences are reported as ***$p \leq 0.001$

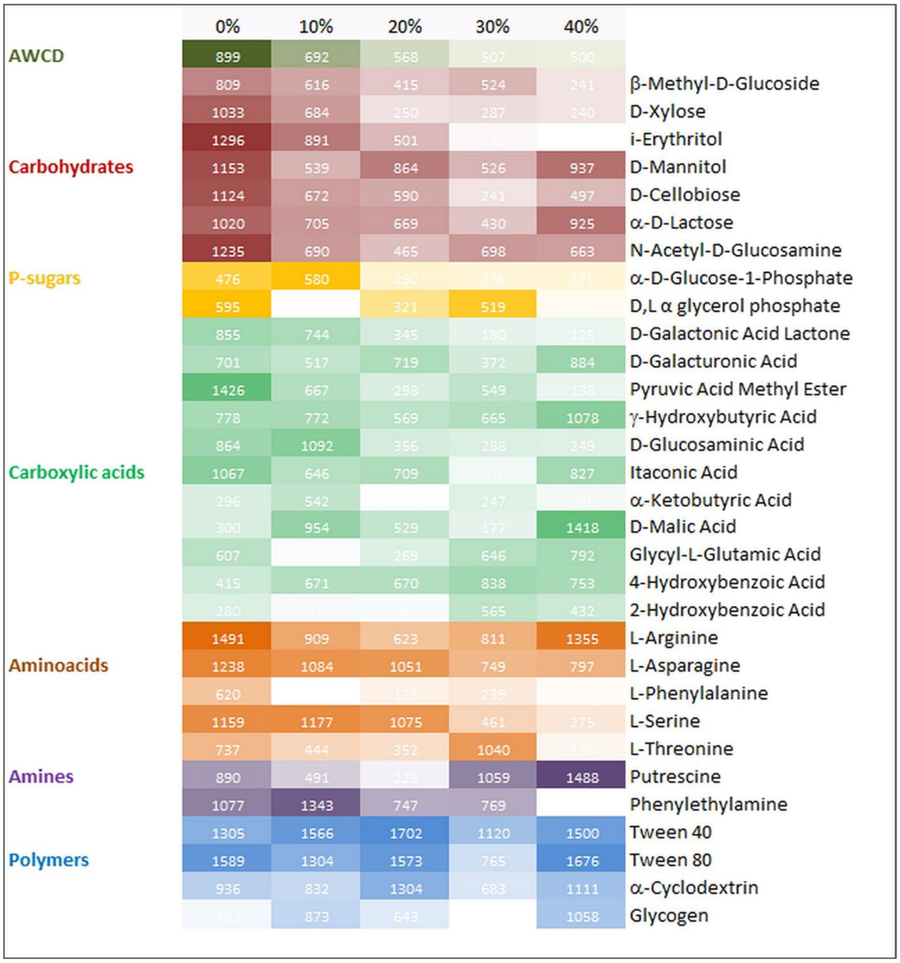
especially in agricultural systems at low input/impacts and in marginal areas, these results could be of particular interest (Kang et al. 2009;Abdallah et al. 2021; Blanchy et al. 2023).

Soil bulk density (SBD) is an indicator of soil quality and compaction and was determined in samples supplemented with increased amount of dried cladodes samples (Table 1). The data were collected before (T0) and after samples were compacted (T1). Because of the effect on soil apparent volume by OFI incorporation, the SBD was negatively correlated with the increment of dried cladodes percentage in the soil. In static conditions, no differences in SBD were detected in samples supplemented with 10% OFI dry cladode and in the control. The highest percentage of dried cladodes integrated into the soil (40%) generated a reduction of at least 30% with respect to the control. The effect of OFI mixture soils on SBD was more evident after soil compression (T1). A significant reduction of this parameter was observed in samples added with 40% of cladodes waste (0.54 ± 0.01 kg/m^3) with respect to the control (0.59 ± 0.01 kg/m^3). Therefore, the supplementation of OFI powder pruning waste affected the apparent volume of soil, causing a reduction of its bulk density, thus preventing the negative consequences of soil compaction. As indicated by other authors (Almendro-Candel et al. 2020), the incorporation of wastes into the soil increases its textural porosity.

Functional diversity analysis of microbial soil communities was assessed by calculating the average well color development (AWCD), used as an indicator of microbial activity in Biolog microplates (Fig. 4). All the different classes of substrates (carbohydrates, P-sugars, carboxylic acids, amino acids, amines, and polymers) contained in the ECOplates were efficiently used by the microbial community from the control and amended soils, indicating a high functional diversity. Among the substrates, very few were below the threshold value (OD 0.2). The control soil (0%) showed the highest AWCD and the ability to readily metabolize all carbon sources, with higher OD values for carbohydrates, P-sugars, and amino acids. The OFI addition to soil seems to progressively reduce the bacteria capacity to metabolize some substrates (i.e., D-xylose, i-erythritol, L-phenylanine, and the P-sugars), suggesting the possible selection or inhibition of some bacterial strains. It would be interesting to study in-depth the microbial dynamics due to the OFI amendment since some antibacterial effect on human pathogens was reported by Blando et al. (2019) although the inhibitory effect is likely linked to the extraction method (Giraldo-Silva et al. 2023). Furthermore, the results by Magarelli et al. (2022) demonstrated that five plant growth-promoting microorganisms (PGPMs) belonging to different genera effectively grew in a low-cost substrate based on OFI cladode juice, thus encouraging further studies on the combination of microbial soil and OFI amendment.

Influence of OFI powder soil mixture on basil plant growth

Different authors showed the beneficial effects of organic and bio-fertilizers from agroindustrial



		0%	10%	20%	30%	40%
AWCD		899	692	568	507	500
Carbohydrates	β-Methyl-D-Glucoside	809	616	415	524	241
	D-Xylose	1033	684	250	287	240
	i-Erythritol	1296	891	501	122	
	D-Mannitol	1153	539	864	526	937
	D-Cellobiose	1124	672	590	241	497
	α-D-Lactose	1020	705	669	430	925
	N-Acetyl-D-Glucosamine	1235	690	465	698	663
P-sugars	α-D-Glucose-1-Phosphate	476	580	190	176	175
	D,L α glycerol phosphate	595		321	519	[illegible]
Carboxylic acids	D-Galactonic Acid Lactone	855	744	345	180	125
	D-Galacturonic Acid	701	517	719	372	884
	Pyruvic Acid Methyl Ester	1426	667	298	549	138
	γ-Hydroxybutyric Acid	778	772	569	665	1078
	D-Glucosaminic Acid	864	1092	356	288	249
	Itaconic Acid	1067	646	709	70	827
	α-Ketobutyric Acid	296	542	[illegible]	247	50
	D-Malic Acid	300	954	529	177	1418
	Glycyl-L-Glutamic Acid	607	[illegible]	269	646	792
	4-Hydroxybenzoic Acid	415	671	670	838	753
	2-Hydroxybenzoic Acid	280	[illegible]	[illegible]	565	432
Aminoacids	L-Arginine	1491	909	623	811	1355
	L-Asparagine	1238	1084	1051	749	797
	L-Phenylalanine	620		178	239	
	L-Serine	1159	1177	1075	461	275
	L-Threonine	737	444	352	1040	128
Amines	Putrescine	890	491	228	1059	1488
	Phenylethylamine	1077	1343	747	769	
Polymers	Tween 40	1305	1566	1702	1120	1500
	Tween 80	1589	1304	1573	765	1676
	α-Cyclodextrin	936	832	1304	683	1111
	Glycogen	483	873	643		1058

Fig. 4 Heatmap showing the effect of OFI treatments (0% control, compared to 10, 20, 30, and 40% OFI addition in soil) on the microbial community, expressed as AWCD and single substrate degradation capacity. Data are the mean of six replications

residues which improved soil physical and chemical properties and increased seedlings germination of basil (Asgharipour and Rafiei 2011; Mininni et al. 2015; Nocentini et al. 2023). Basil plants germinated and grew up without significant morphological differences in OFI powder soil mixture during 3 months of the experiment (Fig. 5); in this trial, we did not consider a supplementation of 30 and 40% of OFI dried waste because we noted a temporary water stagnation. This effect may be due to the relatively high swelling potential of the biomass; i.e., the chemical structure of the mucilage, very rich in polysaccharides including galacturonic acid, favors water retention (Matsuhiro et al. 2006). Thus, the high swelling capacity that characterizes the biomass-soil mixtures may slow down the soil capacity to drain water and limit air circulation; in this condition, root elongation may be hampered and soil aeration reduced (Reynolds et al. 2007). Table 2 reports the data of plant height, raw, and dry weights measured at the end of the experiments. Although the plants showed similar behavior and morphology, those grown in 20% supplemented soil showed an increased stem fresh weight when compared to the control (+21%). Therefore, the root/shoots ratio, even if calculated on dry weight, decreased from 0.91 in the control to 0.67 in plants grown on 20% OFI soil. The root/shoot ratio is one of the measurements to evaluate the overall health of plants; any changes from the value of control (either up or down) would be a useful indication of the developmental stage and environmental influences on plant growth. An enhancement of polyphenols level and antioxidant activity of basil plants grown in dried cladodes mixed soil is also reported as preliminary results in Supplemental Materials (see S1).

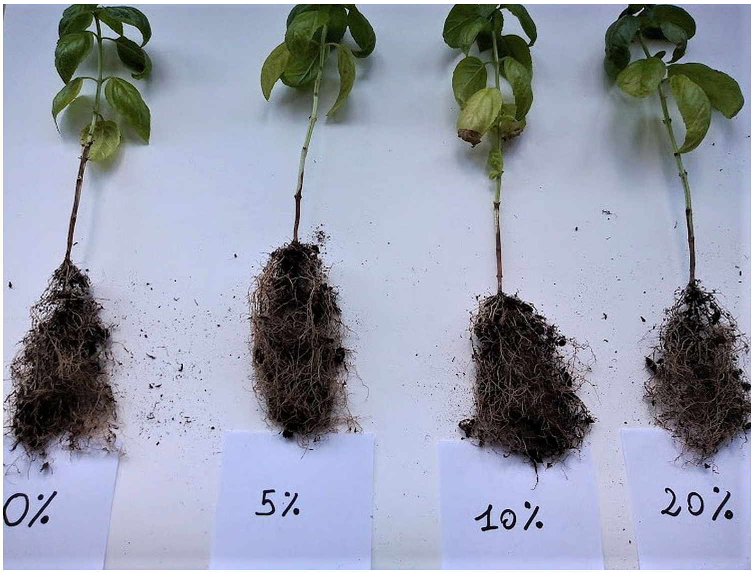


Fig. 5 Growth of basil plant on OFI-supplemented soils

Table 2 Length, fresh and dry weight, and moisture of shoots and roots of basil plants grown in soil mixed with 0, 5, 10, and 20% of dried cladodes

Samples OFI soils	Shoots			Roots			Plant moisture[1] (%)	Root/shoot ratio[2]
	Length (cm)	Fresh weight (g)	Dry weight (g)	Length (cm)	Fresh weight (g)	Dry weight (g)		
0%	18.33 ± 1.5	2.66 ± 0.1	0.37 ± 0.1	11.10 ± 0.2	1.70 ± 0.5	0.3 ± 0.1	80	0.91
5%	18.50 ± 1.5	2.70 ± 0.2	0.44 ± 0.1	11.00 ± 0.1	1.50 ± 0.2	0.41 ± 0.1	80	0.93
10%	16.67 ± 1.7	2.21 ± 0.6	0.32 ± 0.1	8.00 ± 1.0**	1.06 ± 0.2	0.35 ± 0.1	80	1.09
20%	19.17 ± 0.2	3.35 ± 0.4*	0.47 ± 0.1	10.00 ± 0.1	1.22 ± 0.1	0.31 ± 0.1	79	0.67

[1] % Plant moisture was the ratio of the difference between total plant fresh and dried weight divided by fresh weight

[2] Dry weight for roots/dry weight for apical part of plants. Data are expressed as mean ± SD. Significant differences are reported as *$p \le 0.05$ and **$p \le 0.01$ following Tukey post hoc test

Compost from raw cactus pear cladodes: physical and chemical properties

The composting process is considered a sustainable way to recover agro-industrial waste by producing high-value soil amendment due to the environmental, economic, health, and technological benefits it provides (Amuah et al. 2022). This age-old traditional waste minimization practice can be of various types mainly consisting of an aerobic method of decomposing organic solid waste. The result is an end-product rich in organic matter and nutrients that can be used as soil amendment for agricultural and horticultural applications. In our work, a rotating domestic composter was used to develop an affordable, cheap process applied at the farm level. Mature compost was obtained after 6 months of processing, from total starting materials of 82.3 kg of chopped cladodes; 25.85 kg of final product including bulking agent was recovered with the final compost of 18.15 kg. The final product was characterized by 65% humidity and pH 7.6; this high content of humidity depends on the characteristic of cladodes which contain more than 90% of mucilage, a hydrocolloid able to incorporate and maintain water allowing adaptation of cactus pear to arid environments. Among the major factors affecting the composting process, the moisture useful for microbial activity, oxygen, temperature, and nutrients are the key parameters that affect the efficiency of the composting process. In our experiment, the presence of small, chopped cladodes instead of ground ones has facilitated the presence of oxygen, which was necessary for the chemical and biological process. Figure 6 reports the temperature, water content, and pH profiles during the composting test. The temperature profiles of the OFI composting materials showed slight differences between the data obtained by the IoT monitoring system and the spot measurements by needle probe. While the temperature assessed by the IoT system is detected by the temperature sensor installed in the core of the composter, the value measured by the needle probe is a result of the average values in the core and in the composter sides. Considering the two monitoring systems, two temperature peaks of about 40 °C were detected within 2 days of cladodes loading, while the highest temperature (42.8 ± 0.2 °C) was recorded after 29 days from the beginning of the process. As reported by other authors (Guidoni et al. 2018), these values are much lower than those registered in vessel or insulated composters, but comparable with other domestic composters. Fan et al. (2018) and Faverial et al. (2016) reported similar temperature profile in trials where the degradation of the composting material was most intense during the first days of the process. Furthermore, the gases monitored during the composting process, as illustrated in Fig. 6, confirm that the highest oxygen consume and CO_2 production are the consequence of the increased metabolic activity of the microbiota involved (Fig. 7). Although the initial amount of humidity content of OFI cladodes was over the usual range of 55–60% of humidity suitable for a proper composting condition, no bad odors were detected. A hypothesis may be the temperature peak that remained below 45 °C and the low content of proteins of the cladodes; both conditions could lead to less ammonia formation and volatilization. However, the capability of OFI compost to maintain a final water content of 65% after 6 months of process (Table 3) represents very interesting results for potential application in marginal soils under the risk of desertification. The sub-alkaline pH (7.6 ± 0.01) of

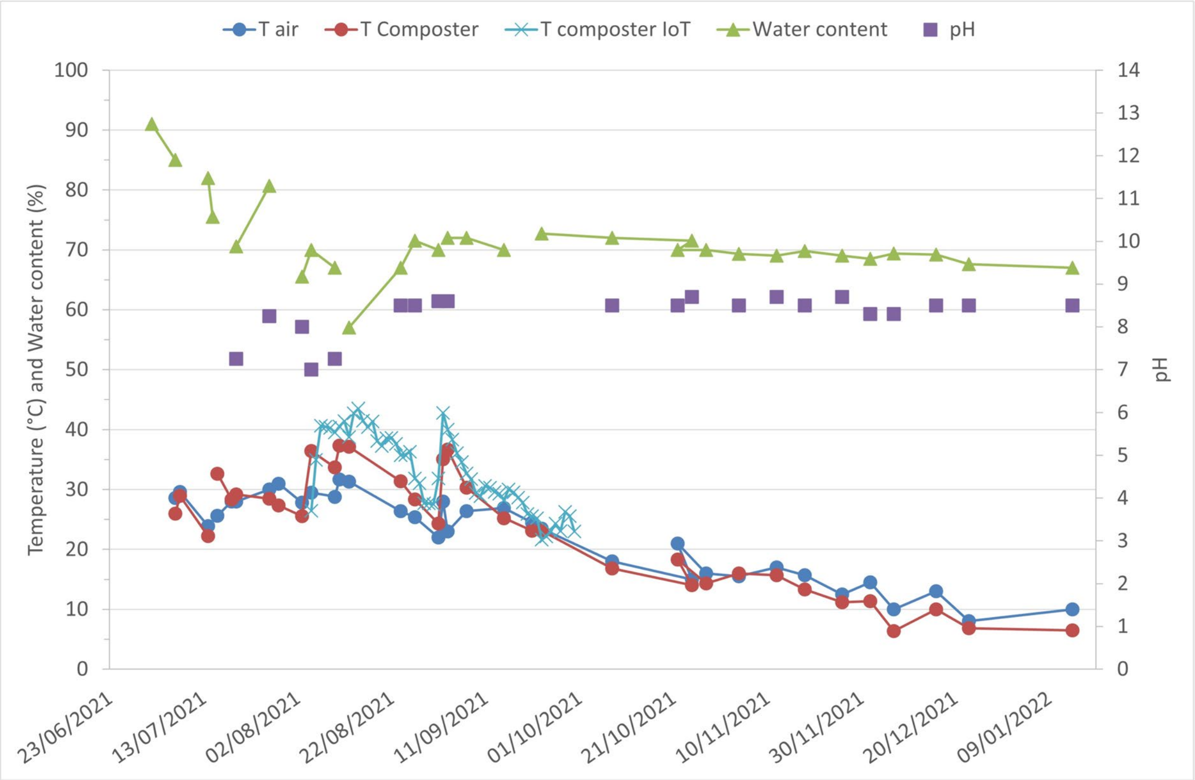


Fig. 6 Temperature, water content, and pH profiles during the composting test. Air composter temperature and measured once a day while composter temperature IoT is read every 2 h and each marker represents the mean daily value

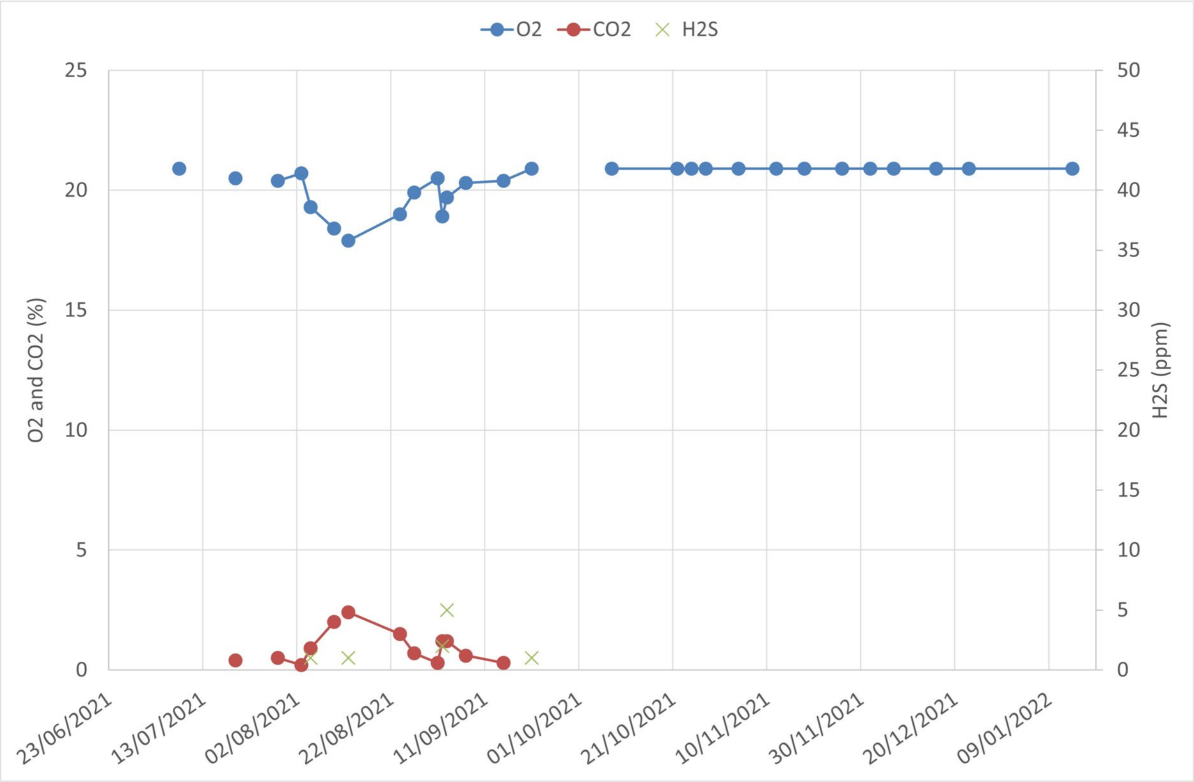


Fig. 7 Process monitoring profile for O_2, CO_2, and H_2S during the composting test

Table 3 Proximal compositions of OFI compost: physical parameters

Humidity.(%)	EC (µs/cm)	pH
65.5 ± 0.2	1822 ± 0.05	7.6 ± 0.01

The table reports the mean values from three replications ± SD

the end-product was probably due to mucilage properties of cladodes, which act as a buffer solution in mitigating pH variations (Bacchetta et al. 2019); the electrical conductivity (1822 ± 0.05 µs/cm) reflects the efficiency of composting process with good mineralization activity of the components. Therefore, analyzing macro- and microelements in compost samples after 6 months of composting (Table 4), nitrogen concentration was 2.6% of dried weight samples, with a C:N ratio of 11.8:1. OFI compost was also characterized by high value of Ca/Mg due to basic composition of cactus pear cladodes as starting material. These soluble salts are mineral nutrients required for plant growth and can help in reducing soil salinity; in appropriate proportions can enhance plant growth and yields (Khater 2012; Gondek et al. 2020). The high K content (3.9%) makes this ready-to-use compost particularly recommendable for crops demanding potassium such as potatoes, Jerusalem artichokes, beets, and turnips. Due to the functions that

Table 4 Proximal compositions of OFI compost: chemical composition

N (%ss)	C/N	P (%ss)	K (%ss)	Ca (%ss)	Mg (%ss)	Fe (%ss)
2.6 ± 0.05	11.8	0.475 ± 0.1	4.9 ± 0.1	5.1 ± 0.1	0.7 ± 0.1	0.212 ± 0.02

The table reports the mean values from three replicates ± SD potassium performs in the plant, the most demanding horticultural crops in terms of quantity and availability of this nutrient are those that must synthesize and accumulate sugars in their fruit or tubers. The values of concentration determined for Cu, Zn, Pb, Cd, Ni, Hg, and Cr(VI) were under the threshold values of the national Directive (75/2010 and 10/07/2013) (see supplemental materials table S3). From the experiences described above with dried cladodes mixed with soil, the OFI compost does not induce any phytotoxic effects on plants (see the results of the official method UNICHIM 10780/2003 in Supplemental Material, table S4). Moreover, we have considered the utilization of organic waste, usually removed by the common agricultural practice of cactus pear, which is not further utilized. In our case, it can be emphasized that the utilization of by-products and compost will not negatively impact soil organic carbon, and thus, the concern, reported by Cocco et al. (2014), about the chance of long-term effects on soil fertility caused by the systematic removal of crop residues should not be taken into consideration.

Conclusions

In this work, we demonstrate the effectiveness of OFI dry cladodes addition to the soil in terms of water retention capacity, i.e., positive effects on gravitational water, and bulk density improvements, both contributing to create suitable conditions for plant growth and soil biodiversity. These effects may provide a positive impact to the efficacy of cultural practices, such as irrigation and fertilization, especially in organic farming, under the perspective of sustainable agriculture. Concerning the latter, the environmentally friendly and locally pursued management of the waste can be foreseen, thus disclosing potential applications in integrating farming. Besides, the cost of crop production might be reduced by decreasing the purchase of external input (e.g., mineral fertilizer), meeting, widely speaking, the concept of zero waste cycle or agro-ecological system to sustain food production and circular bioeconomy. However, further research is required to optimize the use of OFI pruning residue into the soil and to evaluate its potential for widespread application. In terms of retained water, we noted a temporary reduction of soil drainable water capacity when increased percentages of OFI-powered cladodes were used. The OFI residues maintain the typical properties of hydrocolloids with a very high capability to retain water; therefore, the approach to choose the quantity of amendment should be made case by case, also considering the different kinds of soil, relevant to avoid negative effects on soil air and water circulation or modification in the microbial community activity. Further studies considering different plant systems, soil types, and cultivation practices are highly encouraged. Concurrently, the composting process is considered a way to recover agro-industrial waste by producing high-value, stable soil fertilizers and conditioners. In our experience, raw cladode chopped in little pieces proved to be an excellent substrate for aerobic fermentation; the final product is a good quality compost with physical and chemical characteristics comparable to those of similar composts of different origins. However, OFI compost shows the interesting quality of the high moisture content in the final product (65%), which can ameliorate soil fertility and plant growth with useful application in soil desertification prevention.

Author contributions LB wrote the main manuscript text and collaborated to design experimental trials; MC and RP designed the compost trial; GP participated soil tests and statistical analysis; MRM caried out chemical analysis on compost; OM and SP performed chemical analysis on basil plants and phytotoxic test of compost ; CA carried out microbial experiments; CF was supervisor of the experimental activity.

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Data availability The data set that support the findings of this study are available on request from paoloroberto.dipalma@enea.it.

Declarations

Ethics approval and consent to participate Not applicable because the study did not involve humans.

Competing interests The authors declare no competing interests.

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