agriculture

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Assessment of Earthworm Viability and Soil Health after Two Years of Raw and Composted De-Inking Paper Sludge Amendment

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Abstract: The improvement of soil fertility properties is a priority for meeting sustainable development goals and world food security. One potential benefit of using paper sludge in agriculture is the reduction of waste and associated environmental impacts. By using paper sludge as a soil amendment, it is possible to divert away this material from landfills and instead use it to improve soil fertility and support the growth of crops. However, it is important to note that paper sludge may contain contaminants harmful to plants and soil health, of which earthworm viability serves as a key indicator. The present investigation aimed to evaluate changes in soil properties after the application of raw and composted de-inking paper sludge for two years. Accordingly, a field study was conducted in Manouba, a semi-arid region of Tunisia with a clay loam soil. The raw de-inking sludge (DS) and composted de-inking paper sludge (DSC) were applied at 30 and 60 t ha^{-1} and 20 and 40 t ha^{-1}, respectively. Soil treatments were compared to unamended soils (C), to determine the optimal sludge treatment and rate for increasing the soil quality. Soil chemical (soil organic matter SOM, total carbon TC, and nitrogen TN, nutrient soil contents organic matter fractioned), physical (porosity and structural stability), and biological parameters (earthworms viability) were assessed. The results showed an increase of soil OM in the DS and DSC amended soils with the lowest rates (30 and 20 t ha^{-1}). The humic fraction was found to be the dominant form. TC and TN were improved in the DS and DSC amended soils with the highest rates: 60 (DS2) and 40 t ha^{-1} (DSC2). Phosphorus and potassium were also increased in a dose-dependent manner. However, the soil porosity decreased in all treatments. The composted de-inking sludge was toxic for epigeic species, which could be explained by the use of litter while composting. Overall, the application of DS and DSC at low rates (30 and 20 t ha^{-1}, respectively) might be a promising alternative for improving soil quality and at the same time ensuring the proper management of these wastes.

Keywords: de-inking sludge; composting; chemical fertility; humic fractions; structural stability; earthworms

Citation: Zoghlami, R.I.; Toukabri, W.; Boudabbous, K.; Hechmi, S.; Barbouchi, M.; Oueriemmi, H.; Moussa, M.; Bahri, H. Assessment of Earthworm Viability and Soil Health after Two Years of Raw and Composted De-Inking Paper Sludge Amendment. *Agriculture* **2023**, *13*, 547. https://doi.org/10.3390/agriculture13030547

Academic Editors: Ilyusya M. Gabbasova and Mikhail Komissarov

Received: 10 January 2023
Revised: 13 February 2023
Accepted: 14 February 2023
Published: 24 February 2023

1. Introduction

Soil fertility is crucial for all farming systems, to improve productivity, as defined in terms of the ability of the soil to supply nutrients to crops. This is an ecosystem conception that integrates the different soil functions, including physical and chemical properties, that promote plant production [1]. Sustained agricultural production in most Mediterranean countries is under threat due to declining soil fertility and loss of topsoil through erosion, which are worsening because of climate change [2], affecting agricultural production and world food security. To restore soil properties, organic matter amendment is a natural solution for enhancing soil fertility, reducing nutrient losses, and improving soil resistance against erosion [3]. At present, animal organic matter (manure) is becoming increasingly expensive and rare, and scientific researchers are currently trying to find a cheaper and environmentally safe alternative. In fact, many studies found that the application of raw or pre-treated organic wastes can enhance the quality and productivity of degraded soils [4].

Organic wastes have a high nutritional potential; therefore, they are receiving consideration for quality control and proper waste management. Usually, these raw materials are either disposed of by burning, dumping, or unplanned landfilling, which create other environmental, social, and economic problems. Within the framework of the circular economy, waste, emissions, and energy leakage have to be minimized by slowing, closing, and narrowing material and energy loops [5]. For instance, organic wastes can be turned into valuable resources, through which their nutrients can be returned to the soil [6].

Many studies have shown the enhancement of soil biological (microbial biomass, enzyme activity), physical (structural stability, density, adsorption complex), and chemical properties (organic matter, nutrient status) after the application of organic wastes such as manure [7,8], municipal solid wastes [9], and sewage sludge [10–14].

Recently, the re-use of industrial wastes, and particularly paper wastes, has received increased interest [15,16]. Despite the increasing use of software tools, the industrial paper sector is enormous, with more than 0.3 billion tons of products produced per year [17]. Paper wastes are estimated to be more than 3 million tons (1% of the products), with an annual rate of increase of 2.5% [15,18]. The manufacture of recycled paper requires the extraction of ink, clay, coatings, and chemicals from paper wastes [19]. This process generates huge amounts of solid wastes, called de-inked paper sludge [20]. According to waste classification and the European List of Waste (2000/532/EC-01.06.2015), paper sludge wastes can be used in several sectors after a proper treatment, including in agriculture. Composting is one of the integrated waste management strategies used for the recycling of organic wastes into a useful product [21]. The process of composting transforms the raw material into a safer and more stabilized material that can be used as a source of nutrients and a soil conditioner in agricultural applications [22]. Ref. [23] demonstrated in their study that the composting of DS effectively decreased the toxicity of organic pollutants, including organochlorines such as polychlorinated biphenyls PCBs. Thus, composting is an interesting tool for safely managing paper sludge and at the same time improving soil quality. In this study, changes in soil properties after two years of raw (DS) and composted de-inking sludge (CDS) amendment at different rates were evaluated, with the aim of finding the optimal treatment and rate for de-inking paper sludge. This study also assessed the impact of raw and composted de-inking sludge amendment on soil earthworm populations, as earthworms are indicators of soil health and can provide insights into the overall effectiveness of the composting process.

2. Materials and Methods

2.1. The Origin of the Soil and Waste Materials

A field-scale trial has been underway since 2017, at the agricultural experimental farm of interprofessional grouping of vegetables (SAM, Manouba) located west of Tunis city center at around 36°48′28″ N 10°6′4″ E (Tunisia). The site is characterized by a semi-arid climate, with a mean annual precipitation of 447 mm and an average temperature of 17.8 °C. In 2017, soil samples were taken from the experimental plot using a Z-pattern sampling path for the initial physico-chemical characterization. The de-inking sludge (DPS) was collected from pulp and paper and wood industries: Tunisie Ouate paper company (Enfidha, Sousse, Tunisia). The compost was formed using different weight ratio percentages (70/30) of DPS and poultry manure, which was obtained from poultry farms in Enfidha (Sousse, Tunisia). The composting process was carried out over 14 months (30 March 2016 to 30 May 2017), at the National Agronomic Institute of Tunisia (INAT) [23].

Table 1 illustrates the physical and chemical characteristics of the soil and sludge samples and compost.

Table 1. Physical and chemical characteristics of the experimental soil and the de-inking paper sludge used in this study.

Parameters	Soil	Raw De-Inking Paper Sludge	Composted De-Inking Paper Sludge
Clay (%)	38.7 ± 1.47	-	-
Sand (%)	38.6 ± 0.85	-	-
Loam (%)	13.5 ± 0.94	-	-
pH (1:2.5)	7.85 ± 0.36	7.45 ± 0.55	7.72 ± 0.43
EC (mS.cm^{-1})	1.08 ± 0.15	1.72 ± 0.52	5.03 ± 0.32
OM (%)	2.82 ± 0.2	43.5 ± 1.43	25 ± 3.26
TC (%)	1.63 ± 0.23	21.7 ± 1.53	12.5 ± 0.80
TN (%)	0.31 ± 0.05	0.23 ± 0.05	1.26 ± 1.17
C/N	5.25 ± 0.12	94.5 ± 5.14	9.92 ± 1.04
K (ppm)	1060 ± 92.12	433.3 ± 18.08	1300 ± 64.62
P (ppm)	34.1 ± 1.42	17.6 ± 1.27	251.8 ± 20.09
Na^+ (ppm)	526.7 ± 31.35	-	-

EC: electrical conductivity, OM: organic matter, TC: organic carbon TN: total nitrogen, C/N: carbon to nitrogen ratio, K: exchangeable potassium, P: available phosphorus, and Na: exchangeable sodium; -: not determined.

According to the USDA textural triangle, the agricultural soil was clay loam (39% sand and 39% clay, Table 1).

2.2. The Experimental Design and Sampling Procedure

Paper sludge amendment was conducted in 2017, after soil sampling. Field treatments were as follows: C: soil control (without amendment); DS1: raw de-inking sludge at 30 t ha^{-1}; DS2: raw de-inking sludge at 60 t ha^{-1}; DSC1: composted de-inking sludge at 20 t ha^{-1}; DSC2: composted de-inking sludge at 40 t ha^{-1}. The experiment was assessed using a fully factorial experimental design, with three replicates. After two years of soil amendment, soil samples were collected in 2019, at the depth of 0–20 cm and subsequently divided into two parts. The first part was dried out, to analyze the physico-chemical properties of the soil and the second part was stored at 4 °C for soil biological analysis.

2.3. Chemical Analysis

pH is determined with a pH electrode in the soil and sludge water extracts (1:2.5). EC was determined using a conductivity meter in the soil and sludge water extracts (1:5).

The total organic carbon (TC) in the soil and sludge samples was analyzed according to [24] (1934). Organic matter (OM) was estimated by multiplying TC by 1.724, according to [25]. Total nitrogen (TN) in soil and sludge was determined according to the Kjeldahl method [26]. Available phosphorus (P) in the soil and sludge samples was quantified using the ascorbic method [27]. Exchangeable potassium (K) and sodium (Na) were extracted from the soil and the sludge samples with an ammonium acetate solution (1 M) and estimated using a flame photometer. Limestone ($CaCO_3$) was determined following the volumetric method [25].

The extraction of humic substances was carried out according to [28]. The absorbance of fulvic and humic acid fractions was measured at 465 and 665 nm, using a UV–visible spectrophotometer. The quotient of absorbance at 465 and 665 nm gave the E4/E6 ratio [29].

2.4. Physical Analysis

Soil aggregate stability was determined according to the method described by [30]. This method combines three disruptive tests that correspond to various wetting conditions and energies: fast wetting, slow wetting, and mechanical breakdown by shaking after pre-wetting [31].

Soil total porosity (*Tp*) can be calculated from the particle density (*Pd*) and bulk density (*Bd*). Soil practical density refers to the mass (*ms)* of a unit volume of solid soil particles (*Vs*).

$$Pd = \frac{Ms}{Vs} \quad (1)$$

Soil bulk density is the ratio of oven-dried soil mass (*mo*) to the bulk volume of the soil, which includes the volume of the solid and the pore spaces between the soil particles (*Vb*).

$$Bd = \frac{Mo}{Vb} \quad (2)$$

The total porosity was calculated according to the following Equation (3) [32]:

$$Tp = 100 \times [(Bd - Pd)/Bd)] \quad (3)$$

2.5. Soil Biological Activity

The quantification of earthworms (species) in soil was performed according to [33] and the ISO 23611-1 standard, adapted to the agro-pedoclimatic context [33]. A solution of formaldehyde (10 L) at different concentrations (0.25%, 0.25%, and 0.4%) was prepared and sprayed three times with an interval of 15 min on a surface of 1 m^2. In the laboratory, earthworms were weighed and identified at the sub-species level.

2.6. Statistical Analysis

IBM SPSS Statistics 23 (New York, NY, USA) software was used for statistical analysis of the data. An ANOVA test was conducted to compare the means of soil treatments for each studied parameter. A post hoc "Duncan's test" was performed at a significance level of 0.05, to determine the degree of difference between the treatments. Pearson product-moment r values estimated the strength of the relationship between all measured soil parameters at $p \leq 0.005$ and $p < 0.001$.

3. Results

Changes in SOM, C/N, and organic matter fractions are represented in Figure 1. As shown in Figure 1a, the SOM increased in the amended soils, showing higher percentages with the lowest rates. More precisely, the soil OM increased by 21% in DS1 (30 t ha^{-1}) and 32% in DCW1 (20 t ha^{-1}) compared to soil control C. According to Figure 1b, humin was the most abundant organic fraction in all treatments, showing a higher proportion in the amended soils compared to C. Paper sludge amendments also increased the TC and TN levels in the amended soils, reaching 1.04 and 011% in DS1 and 1.36 and 0.14% in DSC1, with respect to C (0.92 and 0.09%, Table 2). As a result, the highest C/N ratio was found in the amended soils DSC1, reaching 10.02 (Figure 1a).

Table 2. Changes in soil chemical properties after the application of raw and compost de-inking paper sludge for two years.

	pH (1:2.5)	EC (mS.cm^{-1})	TC (%)	TN (%)	P (ppm)	K (ppm)	Na (ppm)	Total $CaCO_3$ (%)	Actif $CaCO_3$ (%)	E4/E6
C	8.27 ^{a} ± 0.35	0.36 ^{c} ± 0.06	0.92 ^{a} ± 0.26	0.09 ^{a} ± 0.025	105.9 ^{a} ± 6.34	401.3 ^{a} ± 148.3	561.3 ^{a} ± 65.9	20.4 ^{a} ± 1.36	17 ^{b} ± 1.8	3.84 ^{ab} ± 0.27
DS1	8.31 ^{a} ± 0.35	0.23 ^{ab} ± 0.03	1.04 ^{ab} ± 0.3	0.11 ^{ab} ± 0.03	141.7 ^{a} ± 12.1	260.7 ^{a} ± 108.9	497 ^{a} ± 1	20.4 ^{a} ± 0.72	16.8 ^{b} ± 2.08	4.12 ^{ab} ± 0.45
DS2	8.34 ^{a} ± 0.3	0.28 ^{b} ± 0.08	1 ^{ab} ± 0.21	0.1 ^{b} ± 0.02	156.1 ^{a} ± 38.3	404.7 ^{a} ± 202.1	554.7 ^{a} ± 82.4	20.7 ^{a} ± 1.41	17.5 ^{b} ± 1.5	3.54 ^{a} ± 0.3
DSC1	8.71 ^{a} ± 0.24	0.17 ^{a} ± 0.02	1.36 ^{b} ± 0.14	0.14 ^{ab} ± 0.015	136.5 ^{a} ± 31.1	194.7 ^{a} ± 85.4	910 ^{c} ± 46	21 ^{a} ± 0.77	9 ^{a} ± 1.32	6.37 ^{b} ± 1.69
DSC2	8.4 ^{a} ± 0.15	0.21 ^{ab} ± 0.02	1 ^{ab} ± 0.08	0.1 ^{b} ± 0.01	129.4 ^{a} ± 27	163.3 ^{a} ± 78.3	778 ^{b} ± 40	22.4 ^{a} ± 1.17	20.5 ^{b} ± 0.87	6.08 ^{ab} ± 2.63

EC: electrical conductivity. TC: total organic carbon; TN: Total Nitrogen; P: Available phosphorus; K: exchangeable potassium Na: exchangeable sodium; $CaCO_3$: limestone; E4/E6: ratio of fulvic acids/humic acids. Data are presented as means of three replicates (n = 3); C: soil control without amendment; DS1: soil amended with raw de-inking sludge at 30 t ha^{-1}; DS2: soil amended with raw de-inking sludge at 60 t ha^{-1}; DSC1: soil amended with composted de-inking sludge at 20 t ha^{-1}; DSC2: soil amended with composted de-inking sludge at 40 t ha^{-1}. For each parameter, sample mean values with the same letters are not statistically different at $p \leq 0.05$.

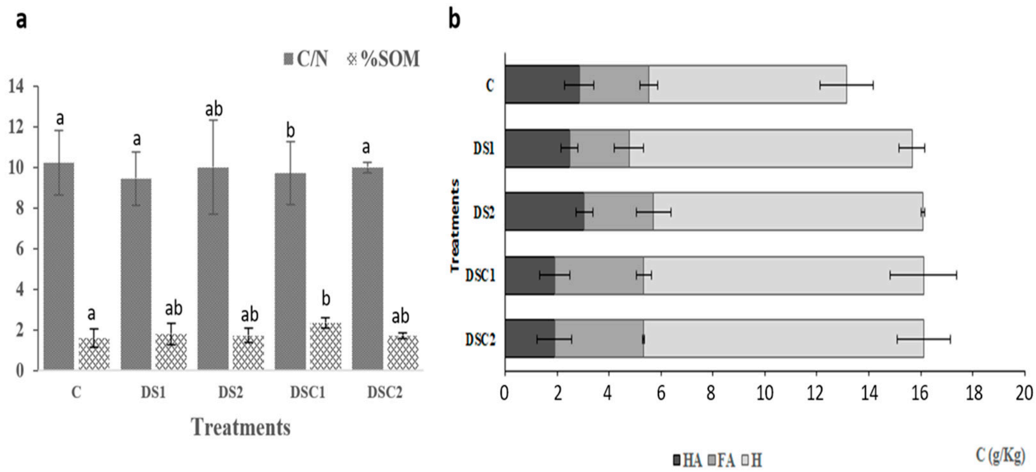

Figure 1. Changes in % SOM and C/N ratio (**a**) and soil humic substances (g C kg^{-1}) (humic acids (HA), fulvic acids (FA), and humin (H)) (**b**) after the application of raw and composted de-inking paper sludge for two years. With C: Control without amendments; DS1: soil amended with raw de-inking sludge at 30 t ha^{-1}; DS2: soil amended with raw de-inking sludge at 60 t ha^{-1}; DSC1: soil amended with composted de-inking sludge at 20 t ha^{-1}; DSC2: soil amended with composted de-inking sludge at 40 t ha^{-1}. For each parameter, sample mean values with the same letters are not statistically different at $p \leq 0.05$.

As shown in Table 2, paper sludge treatments increased the soil pH values, particularly in DSC1 (8.71) and DSC2 (8.4). Similarly, Na showed significantly higher concentrations in the amended soils DSC1 (910 ppm) and DSC2 (778 ppm), with respect to the unamended soil C (561.3 ppm) (Table 2). The available P also increased in the amended soils, reaching 142 ppm in DS1 and 156 ppm in DS2 compared to the soil control (105.9 ppm) (Table 2). On the other hand, the soil salinity (EC) decreased in the amended soils, showing the lowest salinity level in DSC1 (0.17 mS cm^{-1}) with respect to the unamended soil (0.36 mS cm^{-1}) (Table 2). The same trend was observed for K, showing the lowest concentrations in DSC1 (194.7 ppm) and DSC2 (163.3 ppm) (Table 2).

The variation of the soil physical parameters after paper sludge amendment is presented in Figure 2.

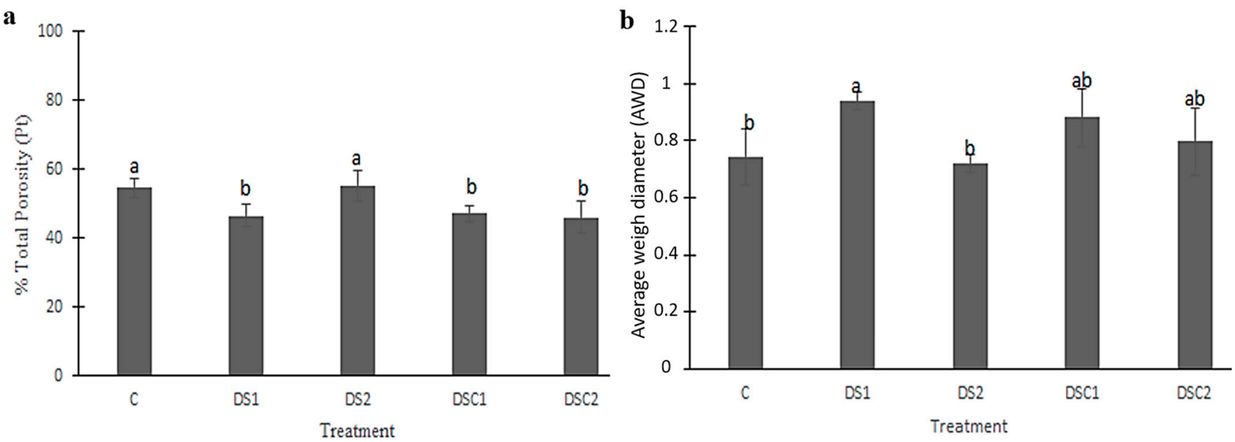

Figure 2. Variation of soil physical parameters (Total porosity (**a**) and the average weigh diameter of aggregates (AWD) (**b**)) after the application of raw and composted de-inking paper sludge. C: soil control without amendment; DS1: soil amended with raw de-inking sludge at 30 t ha^{-1}; DS2: soil amended with raw de-inking sludge at 60 t ha^{-1}; DSC1: soil amended with composted de-inking sludge at 20 t ha^{-1}; DSC2: soil amended with composted de-inking sludge at 40 t ha^{-1}. For each parameter, sample mean values with the same letters are not statistically different at $p \leq 0.05$.

The highest porosity was observed in the amended soil DS2 (55%), showing a non-significant difference with the soil control (53%). (Figure 2a). The AWD increased as follows: DSC2 < DSC1 < DS1, with an increase of 6%, 15.5%, and 21%, respectively, compared to C (0.77) and DS2 (0.74) (Figure 2b).

According to Figure 3, the amended soil DSC1 showed the highest number and mass of endogenic earthworms (4 with a total mass of 5 g), compared to the other treatments. The epigeic earthworms seemed not to survive after 2 years of soil application with composted de-inking sludge. In fact, they were alive only in the control and the soil amended with raw de-inking sludge.

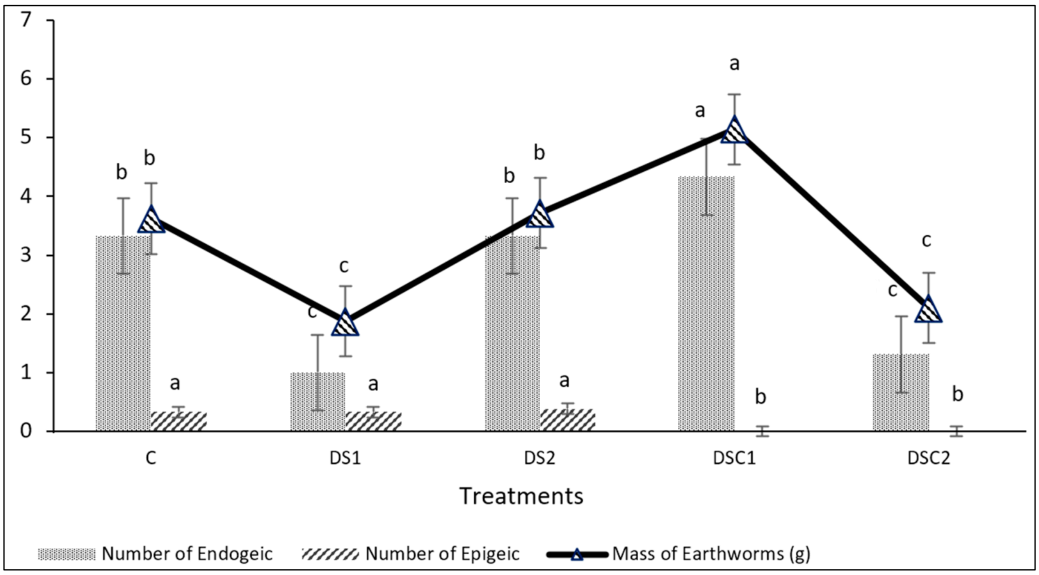

Figure 3. Number and mass of earthworms (epigeic and endogeic) after the application of raw and composted de-inking paper sludge for two years. C: soil control without amendment; DS1: soil amended with raw de-inking sludge at 30 t ha^{-1}; DS2: soil amended with raw de-inking sludge at 60 t ha^{-1}; DSC1: soil amended with composted de-inking sludge at 20 t ha^{-1}; DSC2: soil amended with composted de-inking sludge at 40 t ha^{-1}. For each parameter, sample mean values with the same letters are not statistically different at $p \leq 0.05$.

4. Discussion

Improved management of soil organic matter (SOM) in agricultural soils is essential to sustain their fertility and productivity [34]. Many studies have shown that organic and mineral amendments can increase soil organic matter and its fractions [34–36]. The highest TC, TN, and SOM values were recorded with the DSC1 treatment (1.36%, 0.14%, and 2.35%; Table 2 and Figure 1), which differed from the values observed in the DS1 and DS2 treatments and the control. The increase in soil SOM, TC, and TN was more pronounced in the soils amended with raw and composted paper sludge at 30 t ha^{-1} (DS1) and 20 t ha^{-1} (DSC1). Such results could be related to the high C/N ratio of the paper sludge (14.1%, Table 1). Ref. [16] also reported that the application of DS for two years at 60 Mg ha^{-1} significantly improved soil chemical (organic matter and nutrients status) and physical (stability) properties. The latter authors related the high C/N ratio to the immobilization of soil N, due to high soil microorganism activities. On the other hand, the high proportions of humin indicated good SOM stability in the soil, which was associated to the formation of soil aggregates. The physical occlusion of organic matter in aggregates leads to greater protection from decomposition, through the interactions between mineral and organic surfaces [37].

Favorable soil aggregation is important for improving soil quality, enhancing porosity, and decreasing erodibility [38]. The addition of raw de-inking paper sludge to soil enhanced its stability when applied at a rate of 30 t ha^{-1}. However, as the quantity was increased beyond this rate, the soil stability index (AWD) decreased. In both composted treatments, we observed an improvement of soil stability that influenced the macro-aggregate dynamics. These findings were inversely proportional to the soil porosity, a crucial factor for root zone storage [20]. Indeed, the water-holding capacity of soil is primarily controlled by the relative proportion of clay and various-sized soil aggregate fractions [38]. Unexpectedly, the application of paper sludge had an adverse effect on soil porosity, particularly in the DS1, DSC1, and DSC2 treatments. This decrease in total porosity was linked to a reduction in the available water and air levels for plant roots. A similar outcome was reported by [15], who suggested the use of inorganic materials such as sand, perlite, pumice, and vermiculite, to improve soil aeration. On the other hand, the role of earthworms in shaping soil structure and its associated physical properties has been widely studied. Their feeding and burrowing activities have a significant impact on soil structure, such as aggregation and porosity, and partly determine the physical properties of the soil [39]. In our case, the existence of the epigeic species only in the control and in the raw de-inking sludge amendment could be explained by their environment. In fact, epigeic species of earthworms live in the litter layers and the top centimeters of soil, primarily feeding on fresh surface litter. In contrast, endogeic species reside deeper in the soil and feed on soil organic matter [40]. Thus, it is possible that the application of composted de-inking sludge on the soil surface had a toxic effect on the epigeic species due to the high quantities added. The mass of earthworms (MEW) was strongly and negatively correlated with the average weight diameter of aggregates (AWD). Our hypothesis is that the high percentage of soil porosity can be explained by the high number of the earthworms, and especially the existence of the epigeic species in the control and DS2. The absence of epigeic earthworms in soil treated with compost could be attributed to the presence of litter (straw and wood chips) in the poultry droppings during the composting process [23]. This litter may have been treated with pesticides or insecticides, which are toxic to earthworms [41,42]. Given that epigeic earthworms reside in the upper centimeters of soil, where the amendments were applied, this lethal toxicity can be considered a possible explanation for their absence.

In terms of soil degradation, soil pH slightly increased in the amended soils, reaching 8.7 in DSC1. Ref. [43] also reported an increase of soil pH after the application of raw and composted paper sludge. According to [44], a high pH might be ascribed to the lower mineralization rates in the soil, thus promoting the slow degradation of the organic matter. EC and Na accumulation are some of the main limiting factors for waste reuse in agriculture [45]. In this study, the soil EC decreased with the application of paper sludge, particularly in DSC1. This fact could be attributed to the presence of clay minerals (i.e., kaolinite and montmorillonite) in the paper sludge [23]. These results are consistent with those of [14], who reported that soil organic matter alongside clay minerals form a clay–humic complex that has the capacity to reduce the risk of soil salinization. According to the results, the highest values (>6) of welt ratio (E4/E6) was obtained for the composted de-inking sludge (DSC1 and DSC2), which confirms the results shown by [46], indicating an improvement of soil structure with these amendments. This ratio being higher than 5 indicated that the humic substance was lower than the fulvic acids in the organic fraction of the soil, which is observed in Figure 1b. This implies that the major carbon fraction was not stabilized. Thus, DS2 (E4/E6 = 3) showed a higher degree of humus polymerization that favored organic matter adsorption into the mineral matrix of the soil [47]. This adsorption indicates a strong complexation between the soil minerals and organic acid ligands, especially those associated with aromatic structures [12]. The strong correlation between E4/E6 and exchangeable potassium and sodium (Table 2) indicates the relationship between the humification index and cation exchange.

All treated soils presented an improvement of available phosphorus. Particularly with adding DS2 (60 t ha^{-1}), which shows the importance of the richness of this amendment for organic matter, according to [48]. The addition of raw de-inking sludge released the labile P fraction into the soil, which could affect the soil humic substances. The highest amount of exchangeable sodium was observed in soil amended with composted de-inking sludge, suggesting that the compost with 30% poultry droppings could increase the soil solonetzization. This could lead to reduced productivity and decreased crop yields, as well as other negative impacts on the environment and ecosystem. In fact, it may increase the risk of erosion, as the salt can weaken the soil structure and make it more susceptible to wind and water erosion, as well as possibly decreasing soil fertility by making it difficult for plants to absorb the necessary nutrients and water.

5. Conclusions

This field study highlights the positive effects of de-inking paper sludge amendment, depending on the sludge type (raw or composted) and the applied rate (low or high). Overall, the application of raw (DS1) and composted de-inking paper sludge (DSC1) at low rates (30 and 20 t ha^{-1}, respectively) significantly improved the soil quality. For instance, DS1 and DSC1 showed a higher organic matter (TC and TN) and nutrient status (P and K) compared to the control soil. Subsequently, the soil structural stability and porosity were enhanced. Composting de-inking sludge can be an effective way to reduce waste and improve soil fertility. However, it is important to carefully manage the composting process, to ensure that the resulting material is safe for use as a soil amendment. The use of litter during the composting process may also impact the toxicity of the final composted material. It is possible that the litter used during composting may contain contaminants that could leach into the composted de-inking sludge, resulting in a toxic material that is harmful to epigeic species (i.e., species that live on the surface of the soil). Therefore, it is important to carefully assess the quality of the de-inking sludge before composting and to use appropriate litter materials, to minimize the risk of toxic effects. It may also be necessary to test the composted material for contaminants before using it as a soil amendment, to ensure that it is safe for use. This observation should raise alarm regarding the widespread use of pesticides in conventional agriculture. Therefore, we recommend the use of composted de-inking paper sludge at the rate of 20 t ha^{-1}, as it improved all indexes of soil fertility. However, to gain a clearer understanding of the effect of this practice on soil quality, we suggest conducting a heavy metal analysis of the compost. Further works should assess the effect of paper sludge in relation to plant performance using soils with different types of texture.

Author Contributions: Conceptualization, R.I.Z. and K.B.; methodology, R.I.Z. and S.H.; software, W.T.; validation, M.B., R.I.Z. and W.T.; formal analysis, H.O.; writing—original draft preparation, R.I.Z.; writing—review and editing, K.B., S.H., W.T. and M.B.; supervision, H.B.; project administration, M.M.; funding acquisition, M.M. All authors have read and agreed to the published version of the manuscript.

Funding: We acknowledge the support of the Tunisian Ministry of Industry and The Tunisian Ministry of Higher Education. The APC was funded by the PEJC 3rd edition (2020).

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Acknowledgments: We are grateful to Kamel Arfaoui and Gaith Bouzaien from SAM Manouba for their contribution and help. In addition, we are grateful to Emna Marouani, who provided the compost for our experiment. The authors would like to thank the Foundation for Research Support of the Arid Region Institute of Medenine (IRA) and the staff of Horticultural Sciences Laboratory of National Institute of agronomy of Tunis for their help and encouragement. All the authors also thank the University of Gabes and Carthage.

Conflicts of Interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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