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Assessment of CO_2 emission of soils with different textures after deinking-paper sludge application

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Deinking paper sludge (DPS) soil amendments have potential as a climate change mitigation strategy. Understanding how DPS application affects carbon mineralization in different soil textures is crucial but has not been well investigated. We performed a 120 days incubation experiment to evaluate the effect of soil texture and DPS amount on CO_2 emissions. Three different textures were tested: silty clay, sandy-silt and sandy with three DPS doses: 0, 30 and 60 $t.ha^{-1}$. Results showed that DPS mineralization without soil seemed very rapid with a high mineralized carbon amount (more than 2.500 $gC.kg^{-1}$DPS), but did not reach the stable phase. For amended soils, soil texture effects are marked at the end of incubation. The cumulative carbon mineralization depended significantly on soil texture and DPS doses with a significant interaction. Among all soils with different dose application, the highest cumulative carbon mineralization was revealed for silty-clay soil by applying 30 $t.ha^{-1}$ as well as 60 $t.ha^{-1}$ of DPS. However, the lowest values occurred for sandy soil. Only this latter achieved the stabilization phase after 120 days and therefore stopped CO_2 emission. The highest potential mineralization rate (C0) was achieved for silty-clay soil by applying the two DPS doses. The mineralization rate (C0*k) was two times higher for this soil than the sandy soil. The kinetic deviation of carbon mineralization applying the highest DPS doses (60 $t.ha^{-1}$) is similar for the four studied soils because of C-decomposition blockage. These findings highlight the necessity to consider the combined effects of the DPS amount and soil texture for assessing C release in DPS-amended soils.
Keywords: Deinking paper sludge, soil texture, mineralization, CO_2 emission, doses.

INTRODUCTION

Climate change is one of the major challenges for humanity. Human activities play a decisive role in the observed increase in atmospheric concentration of greenhouse gases (GHG). The resulting global warming requires the concurrent implementation of measures to reduce emissions, mitigate impacts and adaptation (Durocher, 2015). The Agriculture, Forestry and Other Land Use (AFOLU) sector contributes to anthropogenic GHG emissions and removals, which are defined as all emissions and removals that occur on 'managed land' and are associated with land use, including agriculture (FAO, 2015). For all managed lands, organic and mineral soils, as well as harvested wood products (HWP), must be considered to estimate GHG emissions, CO_2 emissions, and removals due to changes in biomass carbon stock and soil organic matter (FAO, 2015).
The global paper industry generates a significant amount of industrial solid waste, which is treated in one of three ways: primary, secondary, or deinking paper sludge (DPS) (Azevedo et al., 2019).The paper industry is considered as the third largest contributor (50%) of all waste discharged into water (Nunes *et al*., 2008) and as a source of 30% GHG (Azevedo *et al*., 2018). Global production of DPS in the world by pulp and paper mills will be 4.8 million dry tons in 2050 (Mabee, 2001). Tunisia generates 2.423 million tons of municipal solid waste per year, with 10% of that deriving from recycled paper waste (ANGED, 2014).
Currently, the majority of these wastes are disposed by landfill, land-spread or incineration (Ouadi *et al*., 2019). Landfilling of paper sludges emits a large amount of GHG (30%) compared to land application (Faubert *et al*., 2017; Faubert *et al*., 2019). The use of DPS as residual fertilizing matter (RFM) is the most efficient way to reduce around 40% GHG, especially N_2O (Marouani *et al*., 2019, 2020a,b)
Several studies have also shown that using biosolids such as deinking paper sludges (DPS) as soil amendments can improve physical, chemical and biological soil properties

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(Camberato *et al*., 2006; Gagnon and Ziadi, 2012) and nutrient availability. Land application reduces the volume of sludge that is disposed of by incineration resulting in reduced emissions into the atmosphere and has a positive impact on the environment, soil quality and productivity (AEP, 1999). DPS is normally composed of organic material originating from paper fibres (cellulose, hemicelluloses and lignin) and inorganic materials such as limestone ($CaCO_3$), kaolin and talc (Gagnon and Ziadia, 2012). In DPS, carbon content is consistently high, while nitrogen and phosphorus contents are consistently low. Thus, paper sludge can be used in various ways due to its abundant energy and mineral resources (Bajpai, 2015; Jang *et al*., 2018). The improvement of soil properties by these amendments can also help to mitigate CH_4, CO_2 and N_2O emissions (Marouani *et al*., 2020a). Indeed, few studies have evaluated the effect of the use of paper mill biosolids as an amendment on a calcaric soil (Marouani *et al*., 2020b). Furthermore, land applications of paper sludges with high C concentration such as DPS (Marouani *et al*., 2019) cause a temporary immobilization of soil N (Nunes *et al*., 2008).

The regulatory aspect related to the classification of pulp rejects and especially DPS differs considerably from one country to another. In this context, several parameters must be taken into account, such as the composition and characterization of sludges, the processes used and the disposal or recovery processes (Marouani, 2020). Thus, the relevant objective of maintaining the quality of the soil means that the risks of land application involve not only plants and water, but also the soil and even air quality (Girard *et al*., 2005).

In Tunisia, soils characterized by a texture rich in silt and sand and generally with low organic matter content (<1%) occupy a large area of the country (Bouajila *et al*., 2016). This poor content is due to overexploitation, drought as well as the expensiveness and deficiency in farm manure supply (Zoghlami *et al*., 2016). The valorization of industrial waste, particularly paper sludge, is a new alternative, not only to combat the pollution generated by landfilling but also to compensate for the lack of organic matter in the soil and to improve soil quality (Marouani, 2020). In Alberta, optimum receiving soil properties include C: N ratio and texture, which determine the agronomic limitations for the application rate (AEP, 1999). For all provinces, application rates of biosolids take account of major nutrients status of soils, composition of sludge and crops to avoid over-fertilizing and potential contamination of surface and ground water (Camberato *et al*., 2006).

The concentration of soil organic carbon increases with the DPS addition (Bipfubusa *et al*., 2004) and several factors come into play: temperature, soil moisture, and initial composition of the introduced material. The decomposition and mineralization rate of organic soil amendments are related to their easily mineralizable C, nutrient contents, particle size and its biochemical composition (C: N ratio, cellulose, hemicellulose and lignin) (Tian *et al.*, 2015; Marouani *et al*., 2020a).

On the other hand, soil texture is considered as an important factor that influences the distribution of minerals, organic matter retention, structure and the activity of the microbial population, and can influence turnover rates of soil nutrients and biomass activity (Hamarashid *et al*., 2010); Bouajila *et al.*, 2014). Further, the presence of higher fine fraction in soil namely clay and/or loam particles enhances organic carbon content and thus positively affects nutrient equilibrium and microbial growth (Hamdi *et al*., 2018). Furthermore, soil texture plays a key role in carbon storage and strongly influences nutrient retention and availability (Hamarashid *et al*., 2010). Soil organic matter (SOM) content tends to be positively correlated with soil clay concentration among sites (McLauchlan, 2006).

The purpose of this paper is to investigate (1) the impact of different DPS amounts on carbon mineralization, (2) the effect of soil texture on CO_2 emission and (3) the possible relationship between the potential and the rate mineralization carbon under different soils textures.

MATERIALS AND METHODS

Sampling and preparation: The present study was conducted on representative Mediterranean agricultural soils in Tunisia (Fig. 1). Soil samples were collected in 2017 from three different sites, a silty clay calcaric fluvisol located in the Northwest (site 1: Mornag), a kastanozem soil in the centre (site 2: Enfidha) and a gypsisol soil in the south (site 3: Elhicha) of Tunisia. According to the Köppen-Geiger climate classification, these three sites are classified as Csa, BSh and BWh, respectively. The three sites are characterized by an average annual temperature of 18.7°C, 19.4°C and 20.6°C, respectively and with an average annual precipitation of 444 mm, 320 mm and 152 mm, respectively.

In this experiment, surface soil (0-20 cm) was sampled for the plains of Mornag (M) and Elhicha (H) as well as two places for a sloping soil in Enfidha, (EI and EII). The latter correspond to two points on the same slope. Soils samples were air dried at room temperature, gently crushed, passed through a 2-mm sieve, and thoroughly homogenized. Soils differed by their textures, two soils are sandy-silt (EI and EII), while the other two are silty clay (M) and sandy (H) (USDA, 2013).

The DPS used in this experiment is an industrial deinking sludge drained from the wash water and is landfilled in nature. This amendment was collected from a Tunisian paper industry on Tuesday, March 21, 2017; DPS was air-dried in the open air.

Figure 1. Localization of experiment sites (Google Earth, 2021)

Physico-chemical analyses of soil and amendment: The soil properties and the amendments (DPS) were determined in triplicate by conventional methods. Regarding soil analysis, the water pH and electrical conductivity (EC) were determined according to 1:5 (w/v) soil-to-water suspensions at 25 °C. Soil organic matter was measured by the $K_2Cr_2O_7$ titration method after digestion (Nelson and Sommers, 1996). Soil total N content was assayed by the Kjeldahl method (Waring and Bremner, 1964). The exchangeable K and Na contents in soil were extracted with an ammonium acetate solution (1M) and measured by flame photometry (Hanway and Heidel, 1952). The available phosphorus was extracted with Olsen reagent and quantified by molybdenum–blue colorimetry (Olsen *et al*., 1954).

The total Mg, S and Fe were analysed in soils with the same acid extract used for heavy metals according to the partial soil digestion method (Milestone Srl-12, 2017), the determination of these elements' values in ppm was carried out by the spectroscopic method using the ICP-OES device (Ministere de l'agriculture, 2017). Total limestone $CaCO_3$ was determined by using the Bernard calcimeter and the active limestone $CaCO_3$ was assessed using the Drouineau method (Bonneau, 1979).

The DPS analyses were performed. The water pH and electrical conductivity (EC) were determined according to 1:5 (w/v) soil-to-water suspensions at 25 °C. The exchangeable K and Na were extracted with an ammonium acetate solution (1 M) and measured by flame photometry and the total N content was assayed by the Kjeldahl method (Pauwels *et al*., 1992).

The organic matter (OM) was determined using the loss on ignition method (Heiri *et al*., 1999). The samples were dried in an oven at 105 °C for 24 hours, then weighed to determine the dry matter (DM) before placing them in a muffle oven to calcine them for two hours at a temperature of 525 to 550 °C. The total Mg, S and Fe were analysed in the acid extract used for heavy metals according to the partial biological amendment digestion method (Milestone Srl-03, 2017). They

Table 1. Initial physical and chemical properties of different used soils (means ± standard deviation): M (Mornag soil), EI and EII (Enfidha soil) and H (Elhicha soil)

Soils Characteristics	Unit	M	EI	EII	H
Clay	%	48.80	12.30	18.10	5.80
Silt	%	43.20	14.30	18.50	2.60
Sand	%	8.00	73.40	63.40	91.70
Texture	-	Silty-clay	Sandy-silt	Sandy-silt	Sandy
pH-water	-	8.27±0.25	8.90±0.11	9.51±0.11	9.61±0.06
EC	$mS.m^{-1}$	0.54±0.02	1.18±0.99	0.27±0.07	0.17±0.01
OM	%	1.18±0.18	0.56±0.04	0.48±0.08	0.35±0.11
TOC	%	0.68	0.32	0.27	0.20
P	$mg.kg^{-1}$	11.07±2.37	2.41±2.05	1.46±0.86	1.74±0.04
TN	%	0.10±0.14	0.021±0.18	0.033±0.04	0.03±0.07
C :N	-	6.66	15.23	8.19	7.14
Actif $CaCO_3$	%	15.00±2.50	3.33±1.44	10.00±2.50	0.30±0.57
Total $CaCO_3$	%	29.40±0.49	9.64±1.13	24.34±0.74	1.14±0.28
Na_{ech}	$g.kg^{-1}$	3.26±0.11	1.60±0.20	2.00±0.20	0.26±0.11
K_{ech}	$g.kg^{-1}$	9.53±0.3	1.60±0.20	2.66±0.30	0.70±0.11
S	$g.kg^{-1}$	53.96±1.42	28.92±2.85	45.02±1.39	3.40±0.15
Mg	$g.kg^{-1}$	0.38±0.01	0.45±0.02	0.22±0.00	0.04±0.01
Fe	$g.kg^{-1}$	3.03±0.05	0.58±0.50	1.41±0.11	0.00

Data are presented as mean of three replicates (n = 3). EC: electrical conductivity; OM: organic matter. TOC: total organic carbon. P: available phosphorus. TN: total nitrogen. C: N: carbon nitrogen ratio. Actif $CaCO_3$: actif calcareous. Total $CaCO_3$: total calcareous. Na_{ech}: exchangeable sodium. K_{ech}: exchangeable potassium. S: total sulfur. Mg: total magnesium. Fe: total iron.

were analysed by the spectroscopic method using the ICP-OES device (Ministere de l'agriculture, 2017).

Soils and deinking paper sludge characteristics: Characteristics of the basic chemical composition of the soils are given in Table 1. All soils are alkaline, with a pH ranging between 8.27 and 9.61. The four sites are characterized by a medium to low salinity with an EC ranged between 1.18 to 0.17 $mS.cm^{-1}$ for EI and H respectively. In addition, results showed that OM did not exceed 1.18% for all soils, particularly for H, we obtained the lowest OM value (0.35%). The C:N registered for the fours soils revealed that the EI (15.23) is characterized by the highest value following by EII(8.19).

The chemical properties and composition of the DPS are illustrated in Table 2. Analysis showed that the DPS is very rich in OM (45.52%) and organic carbon (22.76%), while it presents a very poor total nitrogen with a rate not exceeding 0.15%.

Table 2. Physico-chemical characteristics of the deinking paper sludge (DPS)

Parameters	Unit	Values
pH-water	-	8.82 ± 0.01
EC	$mS.m^{-1}$	7.21 ± 0.70
OM	%	45.52 ± 5.44
TOC	%	22.76 ± 2.72
TN	%	0.15 ± 0.03
C:N	-	151.73
Na	$g.kg^{-1}$	10.20 ± 0.20
K	$g.kg^{-1}$	3.46 ± 0.64
AP	$g.kg^{-1}$	4.23 ± 1.63
S	$g.kg^{-1}$	3.31 ± 0.13
Fe	$g.kg^{-1}$	0.62 ± 0.03

Data are presented as mean of three replicates (n = 3). EC: electrical conductivity. OM: organic matter. TOC: total organic carbon. AP: available phosphorus. TN: total nitrogen. C: N: carbon nitrogen ratio. Na: exchangeable sodium. K: exchangeable potassium, S: sulfur and Fe: iron.

Incubation experiment: De-inking paper sludge's effect on short-term carbon mineralization was tested by means of an incubation experiment. Two factors, namely DPS doses and soil textures were tested in a full factorial experimental design with four replicates and three levels of DPS: 0, 30 and 60 $t.ha^{-1}$ and three different soil textures: silty-clay for M, sandy-silt for EI and EII, and sandy for H. To determine the effect of soil texture and levels of DPS, we used DPS without adding soil and a control treatment (soil without any addition).

These rates for different soils textures were incubated in 1 litre jars for 120 days in the dark at 35 °C and with a soil-water content (w/w) equivalent to field capacity: 35% for M and EII and 25% for EI and H. The emitted CO_2 was trapped in 10 mL 0.1M NaOH at regular time intervals, 2 days, 4 days then once a week; the vials with NaOH were removed and titrated with H_2SO_4 0.05M in the presence of $BaCl_2$. The CO_2 released by mineralization is expressed in mg $C.kg^{-1}$ of soil (equation 1) and calculated as follows:

$$\text{C released (mg C.kg}^{-1}\text{ of soil)} = 6(V0-V)*Na*20 \quad (1)$$

Where V0 is the volume of blank titration (mL); V is the volume of consumed acid (mL) and Na is the normality of acid ($mol \cdot L^{-1}$). To investigate the kinetics of organic matter mineralization (equation 2), the following exponential equation was used.

$$Ct = C0\ (1- e^{-kt})\ \text{(Jedidi, 1998)} \quad (2)$$

Where Ct is the cumulative carbon mineralized at time t expressed in mg C. kg^{-1}; C0 is the mineralizable carbon potential expressed in mg C. kg^{-1}; k is the constant of mineralization expressed in day^{-1}; t is the incubation time expressed in days. The data was also tested using Curve Expert software and the kinetics parameters were calculated.

Statistical analysis: The means and standard deviations were calculated for all of the parameters. A two-way analysis of variance (ANOVA) was used to evaluate the effect of DPS rates, soil texture and their interaction on CO_2 emission. The differences between the treatment means were compared using Duncan's test at 5% significance level. All statistical analyses were performed using the SPSS (16.0) software package (SPSS Inc., Chicago, IL, USA). Kinetic parameters of carbon (C) mineralization according to the exponential model calculated as $Ct = C0\ (1- e^{-kt})$ by the Curve Expert Professional software program.

RESULTS

Carbon mineralization in DPS incubation: The results of 120 days DPS incubation showed that the release rate of CO_2 revealed a rising trend. According to Fig. 2, the mineralization rate can be divided into two stages. In the first stage of incubation (first to 20th day), the content of CO_2 production indicated a rapid release of CO_2. In the second stage of incubation (from 20 days to the end of experiment), the curve showed that the CO_2 production rate fluctuated slightly and continued to increase through the incubation period. However, this rise did not reach a stable level until the end of incubation. Indeed, the DPS mineralization without soil seemed to be very fast with a considerable amount of mineralized DPS reaching more than 2.500 mg $C.kg^{-1}$ in less than 120 days of incubation.

Modelling the kinetics of carbon mineralization in amended soils: The carbon mineralization data were well fitted to a first-order exponential model (R^2=0.999) (Fig. 3 and Table 3). These results were determined in the same experiment conditions. According to equation 2, the supplement of mineralizable potential C provided by the added doses was determined as Δ (C0) = (C0dose)-(C0control). Kinetic mineralization is explained by C0*k. The kinetic deviation (Δ (C0*k): mg kg^{-1} day^{-1}) is calculated as Δ (C0*k) = (C0*k) dose - (C0*k) control.

Table 3. Kinetic parameters of carbon (C) mineralization according to the exponential model calculated as $Ct = C0 (1- e^{-kt})$ by the Curve Expert Professional software program.

Soils	Treatments	C0 (mg.C.kg^{-1})	k (d^{-1})	C0*k (mg.kg^{-1} d^{-1})	R^2	ΔC0 mg C.kg^{-1} of soil	Δ(C0*k) (mg.C kg^{-1}d^{-1})
Mornag (M)	0	6737	0.0008	5.39	0.96	0	0.00
	DPS30	9017	0.0008	7.21	0.97	2280	1.82
	DPS60	11297	0.0007	7.91	0.98	4560	2.52
Enfidha1 (EI)	0	3139	0.0010	3.14	0.97	0	0.00
	DPS30	5362	0.0010	5.36	0.96	2223	2.22
	DPS60	7636	0.0008	6.10	0.96	4497	2.96
Enfidha2 (EII)	0	2718	0.0010	2.72	0.97	0	0.00
	DPS30	4946	0.0010	4.94	0.97	2228	2.22
	DPS60	7211	0.0008	5.77	0.96	4493	3.05
Elhicha(H)	0	2009	0.0010	2.01	0.96	0	0.00
	DPS30	4248	0.0010	4.24	0.96	2239	2.23
	DPS60	6516	0.0007	4.56	0.96	4507	2.55

0: control (unamended soil), DPS30: 30.ha^{-1} of deinking paper sludge, DPS60: 60t.ha^{-1} of deinking paper sludge, C0: mineralizable C potential (mg C.kg^{-1}), k: mineralization coefficient (day^{-1}), C0*k: mineralization rate mgkg^{-1} day^{-1} and R²: determination coefficient, ΔCo: difference in mineralizable C potential due to amendment, Δ(C0*k): difference in mineralization rate due to amendment.

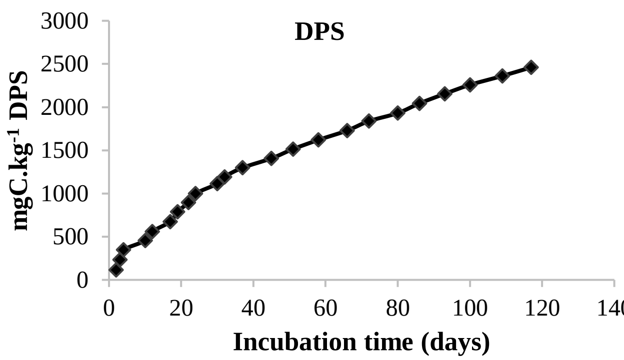

Figure 2. Cumulative organic matter mineralization of DPS without soil

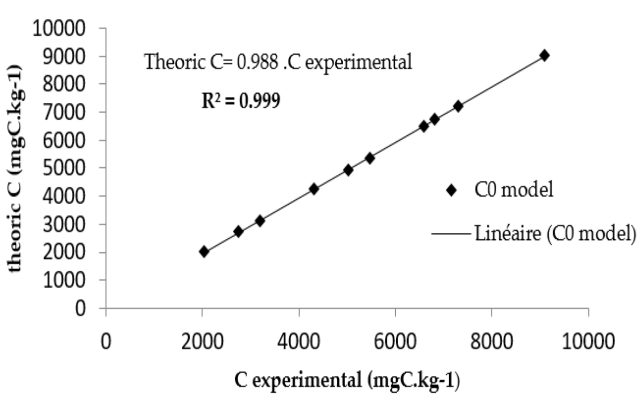

Figure 3. Relationship between the exponential model and the experimental method to determine the values of carbon released (mg of C released.kg^{-1} soil) for the four soils. The data was tested using Curve Expert software and the kinetics parameters were calculated.

***Changes in carbon mineralization according to different DPS doses*:** In our data, we noted that organic matter mineralization was significantly ($P<0.001$) affected by different DPS levels (Table 4). Overall, the treatments exhibited an enhancement in cumulative carbon mineralisation throughout the incubation period (120 days). These rates were higher than those of the unamended soils with 600, 400, 450 and 250 g C.kg^{-1} for the M, EI, EII and H soils respectively (Fig. 4). More interestingly, during the first incubation phase, despite the similar trend of the mineralization curve for the two doses (30 and 60 t.ha^{-1}), the treatment 60 t.ha^{-1} showed a consistent increase of cumulative C mineralization. The highest value (850 g C.kg^{-1}) was achieved for M soil followed by the application of 30 t.ha^{-1} dose (816 g C.kg^{-1}). Nevertheless, we noted the lowest value for the two doses in the case of soil H.

***Changes in carbon mineralization according to different soil textures*:** Generally, regardless of varying textures, we registered a significant positive ($P<0.001$) effect (Table 4) of DPS amendment application on carbon mineralization (Fig. 5). Values did not exceed 600 mgC.kg^{-1} for soil controls, whereas, in the amended ones (30 and 60 t DPS.ha^{-1}) (Fig 5B and 5C), carbon mineralization reached more than 850 mgC.kg^{-1}.

Table 4. Analysis of (ANOVA) for the carbon mineralization

Factors	Carbon mineralization		
	df	F	P
Dose (D)	2	3445.21	< 0.001
Texture (T)	2	1906.80	< 0.001
D*T	4	7.27	< 0.001

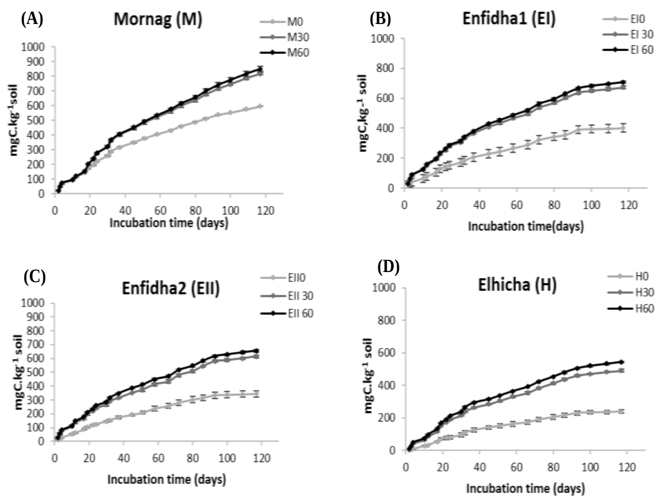

Figure 4. Changes in cumulative carbon mineralization (mg C.Kg^{-1} soil) at three deinking paper sludge rates (0, 30 and 60 t.ha^{-1}) incorporated in four different soils: (A): Mornag (M); (B): Enfidha (EI); (C) Enfidha (EII) and (D): Elhicha (H). Bars over or under the trend lines represent standard errors.

Additionally, the trend curves of various C mineralization differed between soils. After 20 days of incubation, a significant increase in cumulative C mineralization was found in silty-clay soil under unamended conditions, whereas it was noticed 30 days after incubation for other rates.

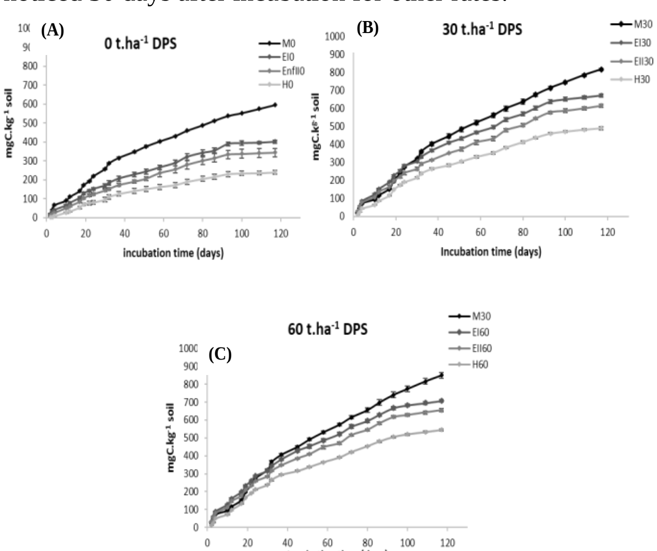

Figure 5. Changes in cumulative carbon mineralization (g C kg^{-1} soil) in four different soils: Mornag (M), Enfidha (EI and EII) and Elhicha (H) at three DPS levels: (A): unamended soil. (B): 30t.ha^{-1} of DPS. (C): 60t.ha-1 of DPS. Bars over or under the trend lines represent standard errors.

More importantly, based on the soil clay percentage, we observed the maximum carbon mineralization for soil with the highest clay content (M: 48.8%), while we obtained the minimum value for soil with the lowest clay content (H: 5.8%). We noted that the silty-clay soil had a rapid carbon mineralization rate (M) followed by sandy-silt (EI and EII) and sandy soils textures (H) (Fig. 5).

Interaction effect of DPS doses and soil texture on carbon mineralization: Significant interaction effect ($p<0.001$) was observed between DPS doses and soil texture on carbon mineralization (Table 4). In all treatments, the results of 120 days' incubation showed that the mineralization rate of the organic carbon had approximately the similar pattern. The trend in CO_2 release have indicated an increase followed by a stabilization until the end of the incubation period (Fig. 6). Among all treatments, the highest cumulative carbon mineralization was found in silty-clay soil (M) when the two DPS doses of 30 t.ha^{-1} and 60 t.ha^{-1} were applied. However, the lowest values were detected under control conditions for sandy soil (H0) followed by EII0 and EI0. More notably, for the majority of the treatments, the greatest CO_2 release was observed 92 days after incubation. Regardless of whether the soil is treated or not, the silty-clay soil has not yet stabilized.

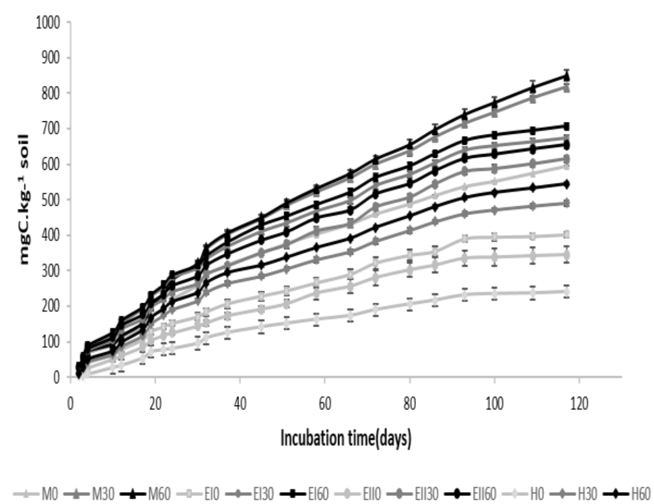

Figure 6. Dynamic of CO_2 emission during incubation period (120 days) under various soils textures (M: silty clay. EI: sandy-silt. EII: sandy-silt and H: sandy) at three levels of DPS (0. 30 and 60t.ha^{-1}). Bars over or under the trend lines represent standard errors.

The control soils have different mineralization potentials. M soil had the highest mineralization potential (Table 3). Whereas, the lowest values were obtained for sandy soils. Indeed, all mineralisation parameters were affected by the application of DPS. The greatest mineralisation rate (C0*k) was revealed for the silty-clay soil (M) followed by EI and EII.

According to Table 3, for all soils of diverse texture, the supplement of mineralizable potential C provided by the added doses (ΔC0) was similar at each defined dose. Further, this gain is proportional to the added dose, reaching the twofold value of the rate from 30 to 60 $t.ha^{-1}$.

According to Table 3, the supplement of mineralizable C potential provided by the added doses (ΔC0) was similar for all the different soils textures at each defined dose. Moreover, this supplement is proportional to the added dose, reaching the twofold value from the 30 to 60 $t.ha^{-1}$ rate.

In the case of kinetic deviation Δ (C0*k), the results showed an increase of values for all soils at rate 30 $t.ha^{-1}$, more particular, this rise was similar for the three light textured soils (EI, EII and H). But, it was found to be the lowest in the silty-clay soil (M).

Furthermore, it was noted that despite the maximum mineralization kinetic obtained for silty-clay soil (M) with C0*k= 7 $mg.kg^{-1}.d^{-1}$, we registered the minimum kinetic deviation (1.82 $mg.kg^{-1}.d^{-1}$) under the effect of the added dose of 30 $t.ha^{-1}$.

Changes of soil organic matter and C:N ratio after DPS incubation: Data revealed that after incubation, the soil organic matter and C:N ratio depended significantly on DPS application doses ($P<0.01$), soil texture ($P <0.01$) as well as the interaction ($P<0.01$) (Table 5).

Regarding the OM, the silty-clay soil (M) recorded the highest level with its two doses 30 and 60 $t.ha^{-1}$. However, the lowest values were obtained for the sandy soil (H) without adding DPS and with 30 $t.ha^{-1}$. In the case of the C:N ratio, data showed the important values applying the highest dose (60 $t.ha^{-1}$). In particular, the sandy soil (H) provided the maximum C:N ratio followed by the sandy-silt soil (EI) with 74.34 and 53.38, respectively (Table 5).

Table 5. Effect of DPS on some soil characteristics after 120 days of incubation.

Soils	Doses ($t.ha^{-1}$)	OM (%)	C :N
M	0	$1.18\pm(0.14)^{b}$	$43.45\pm(0.01)^{bc}$
	30	$1.64\pm(0.06)^{a}$	$45.13\pm(0.09)^{c}$
	60	$1.92\pm(0.06)^{a}$	$45.60\pm(0.10)^{c}$
EI	0	$0.49\pm(0.15)^{def}$	$31.70\pm(0.11)^{d}$
	30	$0.72\pm(0.16)^{cde}$	$46.48\pm(0.12)^{c}$
	60	$0.83\pm(0.14)^{cd}$	$53.28\pm(0.08)^{b}$
EII	0	$0.44\pm(0.14)^{de}$	$25.51\pm(0.19)^{e}$
	30	$0.52\pm(0.10)^{def}$	$30.61\pm(0.18)^{d}$
	60	$0.50\pm(0.17)^{cde}$	$32.65\pm(0.14)^{d}$
H	0	$0.33\pm(0.10)^{f}$	$38.77\pm(0.17)^{cd}$
	30	$0.56\pm(0.27)^{c-f}$	$54.42\pm(0.22)^{b}$
	60	$0.89\pm(0.21)^{bc}$	$74.34\pm(0.18)^{a}$

DISCUSSION

In recent years, the application of DPS to soils, has been found to contribute to the fight against climate change by reducing the emission of greenhouse gases in the long term (Marouani, 2020). However, the effect of soils texture, combined with different DPS doses, on the carbon mineralization has been less studied, thus, poorly understood. The present investigation addressed the research question of how a range of soil textures with different DPS doses could affect CO_2 emission.

In the case of DPS alone, the notably increase of CO_2 emission is the result of the DPS richness in organic matter (45.51%). These results agree with Chantigny et al. (2000a) research, who reported that an increase of CO_2 is related to the intense microbial activity that utilizes SOC as an energy source or possible C loss from microbial decomposition or C-mineralization. Furthermore, data showed that DPS took more than 120 days to be totally degraded. In this regard, Morel (1994) reported that control soils (unamended) release a certain amount of C, being themselves reservoirs of decomposing microorganisms and thus sources of extracellular enzymes that contribute to the biodegradation of organic residues. Compared to the control soil, the introduction of organic matter through adding DPS in the four soils, is the main cause of the increase in CO_2 emissions. In calcareous soils like Fluvisols ((Marouani *et al*., 2020a), such a finding is the result of an excessive carbon supply that stimulates the synthesis of enzymes, resulting in an acceleration of organic matter decomposition (Faubert *et al*., 2016).

Also, we didn't registered a difference between the two DPS doses (30 and 60 $t.ha^{-1}$) at the end of incubation, mainly explained by a nitrogen hunger of soil microorganisms with the 60 $t.ha^{-1}$. These results are in line with Chantigny *et al.* (2000b) and Camberato *et al.* (2006) who reported that the incorporation of a high DPS C:N ratio blocks mineralization and reduces the microorganisms' activities. This decline in microbial activities is related to changes in the soil microbial community or nutrient depletion induced by an excessive C supply. With regard to the environmental DPS impact, the very high C:N ratio can inhibit certain elements in the soil and lead to decline the rate of organic matter mineralization, mitigating the emissions of greenhouse gases (GHG) such as CO_2 and CH4 (Faubert *et al*., 2015), particularly N_2O (Chantigy *et al*., 2013; Marouani *et al*., 2020a).

In the present study, despite the simple effects of DPS doses, the CO_2 emission was under the effect of the soil texture. Our investigation underlined the maximum levels of cumulative CO_2 at the end of incubation for silty-clay soil (M). Our results concur with the observations of McLauchlan (2006); N'Dayegamiye (2007) and Liu *et al*. (2020) who stated that, under incubation conditions, C and N mineralization are widely correlated with higher clay contents soils. Indeed, the clay soil could enhance the CO_2 emission by the dispersion of organic matter, which, in turn, enhance the mineralization. In addition, it is explained by the microorganisms' abundance influenced by the pores size and the amount of air and water flowing through them and the pore space distribution (Olsen, 1981; N'Dayegamiye, 2007). Furthermore, soil texture affects many aspects of gas emissions such as the hydrous functioning of soils, the diffusion of gases and the regulation of aeration conditions, or the protection of organic matter from decomposition (Girard *et al*., 2005). On the other hand, deinking paper sludge (DPS) contains some monovalent ions (e.g. K^+) resulting in dispersion of organic matter and clay particles, and enhance the mobility of dissolved organic matter explaining the increase in CO_2 emission. Moreover, DPS addition seems to be beneficial for soil aggregate formation with the silt and clay particles, which explains the lowest CO_2 release in sandy soil (Larney and Angers, 2012). Our results are in agreement with the study of many researches (Heviaa *et al*., 2003; Hamarashid *et al*., 2010; Blanco-Moure *et al*., 2016), who pointed out that the sandier the soil, the faster the organic resource depletes.

The effect of soil and DPS doses were not only limited to the CO_2 emission but also extended to the mineralization rate between soils. In our case, we noted the lowest mineralization rate for sandy soil, which is mainly attributed to the limited level of organic matter and total nitrogen in this soil. In previous researches, Setia *et al.* (2011) and She *et al*. (2021) underlined that in the fine-textured soil, the decline in the size of active C pool was principally caused by the decrease in biomass of Gram-positive bacteria, suggesting that soil texture alters carbon mineralization by regulating the composition of the soil microbial community.

It can be seen also that the mineralization rate (C0*k) was at a higher level in the silty-clay soil, In the same context, Girard *et al*. (2005) revealed the protective clay effects on C mineralization by adsorption of organic compounds (humic clay complex) or the changes in the microorganisms and enzymes activities. The obtained data can be ascribed to the nature of clay (kaolinite, montmorillonite) and organic matter. Furthermore, we noted that soil texture effects are particularly marked at the end of incubation. These findings taken together indicate that soil microbial communities in clay texture take a longer period to metabolize exogenous organic matter substrates and consequently more time to stabilize their cumulative carbon. Our results concur with the observations of Hamarashid *et al*. (2010), who demonstrated that abiotic factors such as soil texture and chemical components (e.g; pH) had a marked influence on the structure and activity of the microbial population and consequently the carbon mineralization.

In the present study, adding 60 $t.ha^{-1}$ of DPS, the carbon mineralization's kinetic deviation is similar for the four studied soils suggesting that soil texture has no effect on carbon release for this dose, due presumably as the ability of soil microbes to degrade C was temporarily inhibited by the nutrient depletion (Chantigny *et al*., 2000b). Additionally, results revealed that Δ (C0*k) was clearly lower for silty clay soil than the three other soils for 30 $t.ha^{-1}$ of DPS. Such findings are attributed by the lignin and hemicellulose richness of DPS as postulated by (Camberato *et al*., 2006) and (Chantigny *et al*., 2000a). It has been argued that these substances induced a deceleration of carbon mineralization (Zaouchi, 2017). The activity of the microorganisms as well as the extracellular enzymes would be reduced by the micropores formed by the soil aggregates (clay particles) which will protect the organic matter from decomposition (Zhang *et al*., 2019).

Conclusions: Deinking paper sludge is an industrial waste rich in OM but presents an environmental issue; its management by soil application instead of landfilling aims to reduce GHG emissions. The present work was carried out in order to evaluate the effect of different soil textures with different DPS doses on CO_2 emissions. It was noted that the soil application of 30 $t.ha^{-1}$ DPS gave a significant amount of mineralized carbon. The rate of released CO_2 reached its maximum for the silty-clay soil. DPS can therefore constitute a source of carbon emission. Carbon mineralization was found to be significantly affected by different soil parameters (texture, OM). In fact, soil texture as abiotic factor affected gas emissions such as the release of CO_2.

Our findings proved that DPS application have two kinds of impacts: (1) an environmental one, in which choosing sandy soil as an application area reduces CO_2 emissions and thus GHE, and (2) an agronomic one, in which using this product on clay soil improves carbon mineralization, nutrient availability, and soil fertility.

The implications of these findings are that factories and farmers need to understand how to manage industrial waste appropriately, considering the impact of using such materials either on mitigating greenhouse gas emissions or improving soil fertility.

Different forms of management of DPS rich in organic matter are to be considered according to soil textures and environmental or agronomic aim. More research on the synchronization of soil type and amendment amount is required.

Moreover, further research is needed to establish the risks of repeated reject of DPS on phytotoxicity and human health.

Conflict of Interest: The Authors declare that there is no conflict of interest

Authors Contribution Statements: *K.A realized the conceptualization of this manuscript, conducted all the experiments and wrote the manuscript. Note well that N.B.K is the project administration, realized the conceptualization of this manuscript, validated the manuscript, supervised and reviewed it and took care of all the research costs. For K.B, she wrote the original draft preparation and revised the manuscript and reviewed it. While E.M reviewed the* manuscript. And so all authors have read and agreed to the published version of the manuscript.

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