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Integrated Soil Fertility Management by Application of Bulk and Nano-Sawdusts for Enhancing Biomass Yield and Nutrients Content of Maize Plant Grown on Different Soil Types

Karam A.M. Salama[1]; Ahmed M. Mahdy[1*]; Fatma K. Sherif [1]; Hossam M. Ibrahim[2]

[1]*Soil and Water Sciences Department, Faculty of Agriculture, Alexandria University, Egypt*.

[2]*Crop Sciences Department, Faculty of Agriculture, Alexandria University, Egypt*.

*Corresponding author: amahdy73@alexu.edu.eg

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ABSTRACT

A pot experiment was conducted to test the NP-enriched sawdust for replenishment the reduction amounts of mineral fertilizers added to maize plants grown in three different soils. For ensure this aim, specific objectives were investigated to characterize the physical and chemical properties of sawdust nanoparticles (nSD) and the collected bulk sawdust (bSD); to compare the effect of NP-enriched bulk or nano-sawdust supplemented with mineral fertilizer with the conventional mineral fertilization on maize dry matter grown on different soil types. To achieve these objectives, nanoparticles of sawdust were produced, characterized and saturated with 160 mg per liter ammonium and phosphate solutions. The results revealed that the co-application of mineral fertilizers and NP-enriched bSD or nSD significantly increased dry matter production of maize plants grown on the three studied soils. The highest biomass production of maize was noticed at 0.75 mineral co-applied with 0.25 bSD or 0.025 nSD in all studied soils. More biomass production was produced at the different application rates of nSD when it is applied individually or co-applied with mineral fertilizers. The polynomial quadratic model was successfully described the relationship between dry matter production of maize grown on the three studied soils and fertilizer type application rates. The co-application effects of mineral fertilizers and NP-enriched bSD or nSD on element concentrations of maize plants grown on the three studied soils indicated to significant differences in element concentrations of maize as affected by mineral co-applied with bSD or nSD application rates. Also, the highest element concentrations of maize was noticed at 0.75 mineral co-applied with 0.25 bSD or 0.025 nSD in all studied soils. It can be concluded that the more dry matter production and element concentrations at different rates of studied sawdust nanoparticles when it is applied individually or co-applied with mineral fertilizers may due to the entry of nanoparticles through the cell wall. Moreover, bSD and nSD containing more organic carbon and other constitutes that increase the availability of studied elements.

INTRODUCTION

Integrated Soil Fertility Management (ISFM) is a soil management approach referring to combined application of organic and mineral fertilizer inputs to improve yields and fertilizer use efficiency (FUE). Moreover, it is used to reduce water pollution resulting in more nutrients entering water bodies from agricultural practices.

Nitrogen and phosphorus are the most nutrient inputs from agriculture causing eutrophication of lakes and rivers and consequently a sharp decrease in dissolved oxygen and toxicity of aquatic organisms (Du et al., 2005). Many methods are used to remove them from polluted water via different mechanisms, one of them is adsorption or biosorption using biomaterials. Ideal NP-sorbing materials used for this purpose should be free, non-toxic, industrial or agricultural byproducts, generated locally, widely available, and potentially useful as soil amendments once saturated with N or P (De-Bashan and Bashan, 2004). Due to the intensive use and high cost of traditional mineral fertilizers, the suitable solution to overcome this problem is the use of element-loaded sorbing biomaterials and nanofertilizers. Nanofertilizers are modified fertilizers manufactured by chemical, physical or biological methods using nanotechnology to improve their traits and composition, which can enhance the crop productivity (Al-Juthery *et al*, 2018; Elemike et al, 2019, Moustafa et al, 2022).

Recently, the techniques of nanotechnology is widely used in all aspects of science. Nanotechnology has created an emerging and promising research field in developing innovative agricultural technologies in recent years, such as the nanotechnology-based soil amendments that enable better control nutrients release. Use of nano-biomaterials in phosphate and ammonium removal from agricultural wastewater is known nano-biosorption. Nano-biosorption is used for water quality treatment (Lahav and Green, 1998).

Green-synthesized nanoparticles (<100 nm) are promising soil amendments that improve soil fertility management. Nanoparticles have a very high specific surface area (Makris et al., 2006) that allow sorption of huge amounts of phosphate and ammonium (Novak and Watts, 2004). Use of nanomaterials for the removal of nutrients from water will reduce its discharge into water and subsequently eutrophication problem.

Woody sawdust is a biodegradable biomaterial with high percentage of ligno-cellulosic components and could be reused as a source of phosphate and ammonium in the form of NP-enriched compost after phosphate or ammonium saturation (Farag et al., 1994). The broad potential of woody sawdust as biosorbent is due to its chemical constituents that including many function groups and its biodegradability would release more phosphate and ammonium to agricultural soils.

Little research studies has conducted on the use of sawdust as a supplemental source of nutrients to plants and ISFM. Recent research of Mer et al.,(2024) has found activated biochar by co-pyrolyzing sawdust with iron-rich biosolids and poly-aluminum sludge to be a cost-effective adsorbent for removal of organic compounds such as , perfluoroalkyl substances in water.

The application of sawdust nanoparticles in wastewater treatment or wastewater-irrigated soils would increase sorption of nutrients because of its large surface area. It is of considerable interest to study the effect of NP-enriched sawdust application on dry matter production and nutrients content of plants. In particular, the research on the interaction of sawdust particles with P and N is much necessary. Therefore, the aim of this study was to test the NP-enriched sawdust for replenishment the shortage of mineral fertilizers. For ensure this aim, specific objectives were investigated: to characterize the physical and chemical properties of sawdust nanoparticles (nSD) that are produced from mechanically milling and the bulk sawdust (bSD) collected; to compare the effect of NP-enriched bulk or nano-sawdust supplemented with mineral fertilizer with the conventional mineral fertilization on maize dry matter grown on different soil types.

MATERIALS AND METHODS

Sampling:

Soils and Sawdust (SD)

Three soil types were selected: clay soil (*Typic torrifluvent*, from Kafr El-Dawar, Elbohera Governorate, Egypt), sandy soil (*Typic torripsamment*, from El-Bostan, Elbohera Governorate, Egypt), and calcareous soil (*Typic haplocalcids*, from Borg Al-Arab, Alexandria Governorate, Egypt). Soils were collected from a depth of 0–30 cm at each sampling location. Air-dried soil samples were ground and subsequently sieved (<2 mm). The general physical and chemical properties of soils were determined according to standard methods (Jones, 2001)

Three types of wood materials representing *Mangifera indica* (stem wood), *Cinnamomum camphora* (wood-branch), *and Pinus longaeva* (wood-branch) were collected from Alexandria, Egypt during pruning processes. Bark of the woody species was removed, and the wood was transferred to flakes or sawdust in a sawmill in Alexandria. The sawdust was washed several times with distillated water to remove surface impurities, and dried. The dried biomass was stored in a desiccator for further use. Hereafter, the produced nanoparticles from the three wood materials were referred as nSD-MG, nSD-KF, and nSD-CN for *Mangifera indica, Cinnamomum camphora, and Pinus longaeva*, respectively.

Producing of Sawdust Nanoparticles

The woody-sawdust was oven-dried at approximately 50-60 ˚C, and then mechanically ground by a RETSCH RMl00 electrical mortar grinder (Ball mill) to produce nanoscale sawdust particles (<100 nm) according to Elkhatib et al., (2015

Characterization of Sawdust Nanoparticles

The characteristics and element contents of nSD sample were investigated using scanning electron microscopy (SEM), and quipped with Energy-dispersive X-ray spectroscopy (EDX). The nanoparticle surface area was determined using the Brunauer–Emmett–Teller method (Brunauer et al., 1938). All these measurements were carried out by standardized methods that have been routinely used for nanomaterial studies. Size distribution and Zeta potential values of sawdust nanoparticles were measured at normal pH by a Zetasizer.

Greenhouse experiment

Experimental Set-up:

To quantify the effects of N-P-enriched nSD and/or bSD and mineral fertilizers treatments on agronomic performance of maize plants (*Zea mays* c.v. Single hybride 167) were sown as the test crop, greenhouse experiment was conducted using a drainage pot system with a leachate outlet at the bottom that permits drainage collection at an ambient atmospheric pressure at the greenhouse of Soil & Water Department, Agricultural Extension Building, Faculty of Agriculture, Alexandria University. Pots were filled with three different types of soils .Different application rates of bSD, nSD and recommended rates of mineral fertilizers were applied and mixed thoroughly with the soil two weeks before sowing. The treatments included were mineral fertilizer (urea, superphosphate and potassium sulfate), NP-enriched sawdust and their interaction. The NP-enriched sawdust dose was determined by its nitrogen content, on the basis that 50 % of its organic N will be released. The doses of NP-enriched sawdust equivalent to 0, 0.25, 0.50, 0.75 and 1.0 as a fraction of recommended rate (RR) of fertilizer for maize by Ministry of Agriculture in Egypt . NP-enriched sawdust were spreaded on the soil surface and then mixed into the soil for each pot. Likewise, mineral fertilizer was applied as a percentage of RR for maize. The mineral N was applied twice before sowing and 21 days after sowing of maize plants. The P and K fertilizers were applied before sowing. Seeds of maize were sown as the test crop. The seedlings were thinned to 2 seedlings per pot. Pots were irrigated using tap water, and the amount of water applied was controlled.

The soils were sampled post-harvesting. The plant shoots were harvested, and immediately washed with running tap water and rinsed three times with de-ionized water.

The application of mineral and/or NP-enriched sawdust fertilizers to the soil was as follows:

T1: Soil + 0% NPK + 0 % NP-enriched sawdust
T2: Soil + 0.25 from RR of NPK + 0 % NP-enriched sawdust
T3: Soil + 0.50 from RR of NPK + 0 % NP-enriched sawdust
T4: Soil + 0.75 from RR of NPK + 0 % NP-enriched sawdust
T5: Soil + 1.0 from RR of NPK + 0 % NP-enriched sawdust
T6: Soil + 0% NPK + 0.25 RR as NP-enriched sawdust
T7: Soil + 0% NPK + 0.50 RR as NP-enriched sawdust
T8: Soil + 0% NPK + 0.75 RR as NP-enriched sawdust
T9: Soil + 0% NPK + 1.0 RR as NP-enriched sawdust
T10: Soil + 0% NPK + 0.025 RR as NP-enriched sawdust nanoparticles
T11: Soil + 0% NPK + 0.050 RR as NP-enriched sawdust nanoparticles
T12: Soil + 0% NPK + 0.075 RR as NP-enriched sawdust nanoparticles
T13: Soil + 0% NPK + 0.10 RR as NP-enriched sawdust nanoparticles
T14: Soil + 0.25 from RR of NPK + 0.75 RR as NP-enriched sawdust
T15: Soil + 0.50 from RR of NPK + 0.50 RR as NP-enriched sawdust
T16: Soil + 0.75 from RR of NPK + 0.25 RR as NP-enriched sawdust
T17: Soil + 0.25 from RR of NPK + 0.075 RR as NP-enriched sawdust nanoparticles
T18: Soil + 0.50 from RR of NPK + 0.050 RR as NP-enriched sawdust nanoparticles
T19: Soil + 0.75 from RR of NPK + 0.025 RR as NP-enriched sawdust nanoparticles

Biomass Dry Matter

The above-ground shoots were harvested after 45 days of sowing date. Plants tissues were washed to remove any adhering particles. The samples were oven dried and weighed. Plant tissues were dry-ashed for analysis of total phosphorus and potassium, and wet-ashed for analysis of total nitrogen (Jones, 2001).

Dry matter production of shoot was expressed on dry weight basis. Concentrations of nutrient in plant tissue was expressed by mg/kg dry weight basis.

The polynomial quadratic model was used in the form

$\mathbf{Y_i = a + bX_i + CX^2_i}$ (Thabet and Balba, 1994)

Where Y_i is the expected dry matter yield corresponding to nSD application rate X_i at each soils type, **a** is the intercept and b, C are the linear and quadratic coefficients, respectively.

Maximum dry matter Yield (Y_{max}) and Maximum applied nSD (X_{max})

The maximum dry matter yield and maximum applied nSD for all soil types were calculated as follows:

$\mathbf{Y_{max} = a - (b2/4C)}$, $\mathbf{X_{max} = -b/2C}$

Where Y_{max} is the maximum dry matter yields corresponding to maximum nSD application rate (X_{max}) at each soil type, a is the intercept and b, C are the linear and quadratic coefficients, respectively.

Statistical and mathematical analyses

The three-ways analysis of variance (ANOVA) was carried out to determine the statistical significance of the treatment effects on crop dry matter and nutrients concentration with the Fisher's least significant difference procedure at a significant level of 0.05 (SAS Institute, 1994).

RESULTS AND DISCUSSION

Characterization of Soils and Sawdust Nanoparticles

Soils: Some physical and chemical characteristics of the three soils studied are presented in Table (1). Data presented in Table (1) indicated that the studied soils are different in all chemical and physical characteristics that enabling soil factor was considered for interpretation and discussion.

Sawdust Nanoparticles

Carbon and Nitrogen contents of Sawdust Nanoparticles: C/N ratio of the three studied sawdust nanoparticles was the basis for selection the best nSD for further research study. The values of carbon, nitrogen and C/N ratio presented in Table (2) for the studied sawdust nanoparticles indicated that nSD-MG was more biodegradable than nSD-CN and nSD-KF and it was the best N-P saturated biosorbent used as a supplemental source with the mineral fertilizer for maize plant.

SEM, EDX, size distribution, specific surface area, and zeta potential: Study the structure and surface morphology and elemental features of the biosorbents are important in studying the inorganic pollutants biosorption particularly biosorption mechanism (Akar and Tunali, 2005; Tunali et al., 2006; Panda et al., 2007; Pino et al., 2006). SEM and EDX are powerful tools for examining the structure of surface morphology and elemental features of the biosorbents. SEM images and Zetasizer analysis can also be used to judge whether good dispersion has been achieved or whether agglomeration is present in the system. The size distribution of Zetasizer analysis refers to size average 98 nm (< 100 nm) (Fig.1). SEM and EDX analyses of nSD-MG before and after phosphate and ammonium saturation are shown in Fig.(2) The SEM images of nSD-MG samples clearly showed that the representative single particle size dimension lies in the range 1-100 nm .After saturation with phosphate and ammonium, a coating layer of adsorbed nutrient on the surface of the nSD-MG was observed which ascertained adsorption of studied nutrient by nSD-MG (Fig.2B**)**.The EDX elemental analysis of nSD-MG illustrated in Figure (2) confirmed these results by occurrence of nitrogen (2.88%) and phosphate (3.94%) peaks in saturated nSD-MG. The EDX analysis revealed that nitrogen, calcium, potassium, iron and phosphorus elements represent little percentage of the total elements of saturated nSD-MG (Fig.2B).

The specific surface area (SSA) of nSD-MG (16.94 m^2g^{-1}) is much higher than that of the bulk bSD-MG sample (2.33 m^2g^{-1}) .Indeed; the high SSA could potentially supply nSD-MG with highly reactive surface sites for nutrient retention. These results coincided with the results of Wahab et al.,(2010) and Gogoi et al.,(2018), Ali et al.,(2021) , they reported that bulk sawdust have a lower surface area (1.43 $m^2.g^{-1}$) than fine dusts. In addition, other observations were found for moringa seed waste (Ajava and Fakayode,2013), its bulk SSA was 177 $mm^2.g^{-1}$. Also, Mnisi and Ndibewu,(2017) reported bulk SSA was 1.79 $m^2.g^{-1}$ for moringa , and it was recorded in other study that SSA was 2.97 m^2g^{-1} (Adesina, et al,2013).

Table 1: Some physical and chemical characteristics of studied soils.

Characteristics	Units	Kafr El-Dawar	El-Bostan	Borg Al-Arab
pH		8.13 ± 0.05	7.69± 0.05	8.08 ± 0.06
EC	dSm^{-1}	2.66 ± 0.11	3.84± 0.12	2.92 ± 0.06
$CaCO_3$	%	5.79 ± 0.06	2.40± 0.30	356.80±2.60
Sand	%	59.64 ± 0.42	868.2±5.10	740.00± 3.70
Silt	%	14.13 ± 0.15	25.10± 0.30	101.50± 1.90
Clay	%	26.23± 0.07	106.70±2.20	158.50± 3.20
Texture		S.C.L	L.S	S.L
O.M[†]	%	0.85 ± 0.02	1.00± 0.04	4.60 ± 0.15
Olsen-P	mg kg^{-1}	24.75 ± 0.25	2.89± 0.14	18.70 ± 0.80
CEC	Cmol(+)kg^{-1}	39.13 ± 0.98	8.70± 0.20	26.00 ± 2.02

[†] : pH measured in sample/water suspension(1:2.5) by pH-meter instrument(CRISON); EC: electrical conductivity; O.M: organic matter ; CEC: cation exchange capacity ;
S.C.L: sandy clay loam; L.S.: loamy sand; S.L.: sandy loam

Table 2. Characterization of Sawdust Nanoparticles

Characteristics	nSD-MG		nSD-CN		nSD-KF	
	Before	After	Before	After	Before	After
C,%	55	55	51	51	46	46
N,%	2.76	2.78	1.45	1.47	1.08	1.10
C/N ratio	19.93	19.78	35.17	34.69	42.59	41.82

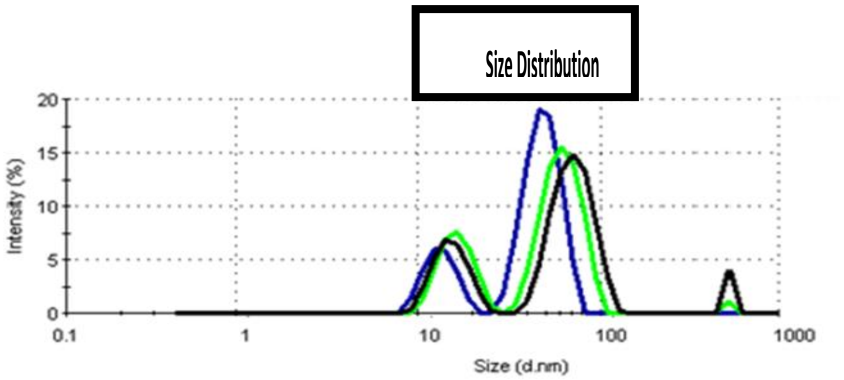
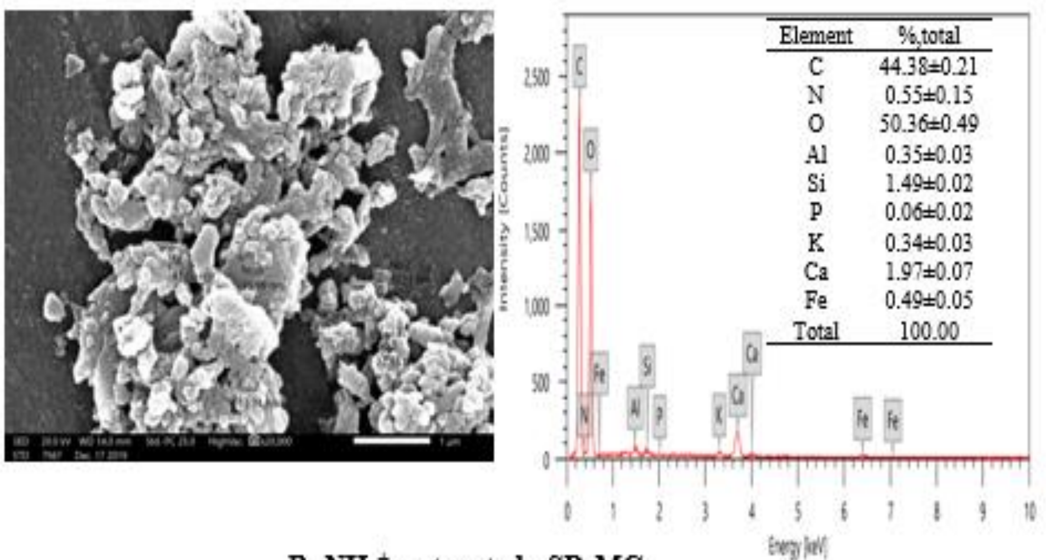


Fig.1: Size distribution of nSD-MG biosorbent used in the study

A: Unsaturated nSD-MG



B: NH_4^+ -saturated nSD-MG

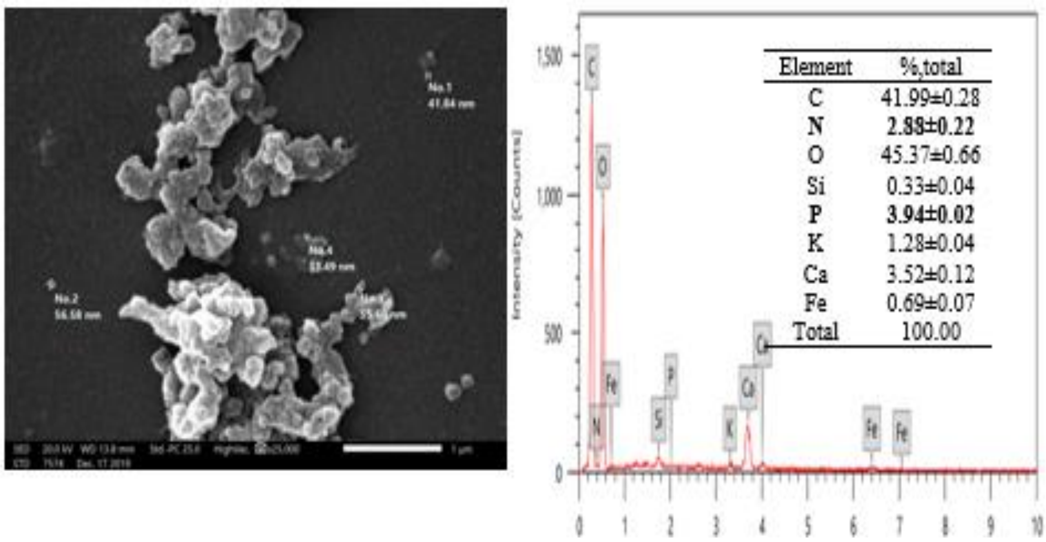


Fig.2: Scanning electron microscopy (SEM) image and energy dispersive X-ray (EDX) elemental distribution of un-saturated and saturated nSD-MG

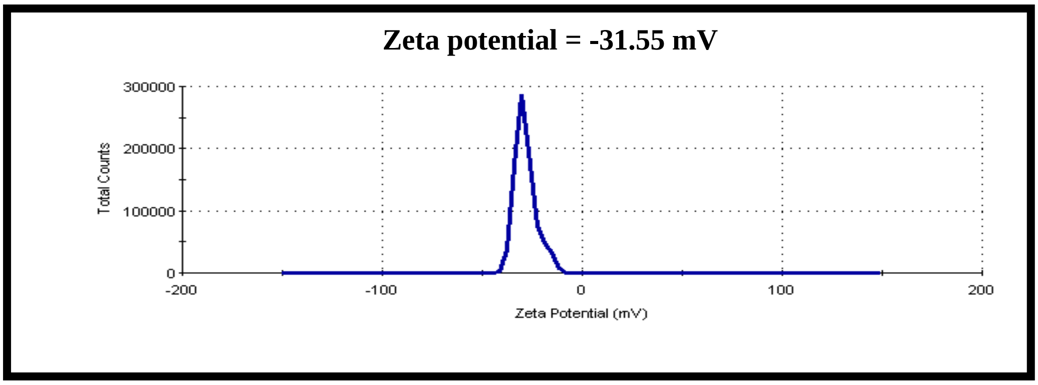


Fig.3: Zeta potential of nSD-MG biosorbent used in the study

In the electric double-layer in soil, an electric potential across the layer called “zeta potential”. The magnitude of zeta potential reflects the quantity of charges absorbed by the solid (Hunter 1988; Shaw 1991). Based on the above concept, the zeta potential characteristics of a nSD-MG was studied (Lin and Liu,1996). The research showed that zeta potential of nSD-MG was -31.55 mV that indicating more surface charge on particles and increase the sorptive capacity of nSD-MG (Fig.3). Abidi et al.,(2019) studied the removal of dye from textile industries effluents by clay adsorbent as affected by zeta potential and reported that zeta potential measurements allowed the determination of the electrical charge and of the dye behaviour at the clay-water interface.

Dry matter production of Maize

Mineral fertilizer effect: The effects of mineral fertilizers on dry matter production (above-ground shoot) of maize plants grown on the three studied soils are shown in Fig. (4). Significant differences in total biomass production of maize as affected by mineral fertilizer application. Application of mineral fertilizer at a rate of 0.25 of recommended rate for maize to the three studied soils resulted in the lowest values of biomass production. It was noticed that the biomass production of maize plants grown on clay soil was more than calcareous and sandy soils (Fig.4). Increase of the mineral fertilizer application rate to 0.50, 0.75, and 1 as a fraction from recommended rate applied to maize plants significantly increased biomass production in the three studied soils (Fig.4).

Clearly, the soil type, mineral fertilizer rates and their interaction significantly affected the biomass production (Fig.4). These results are in agreement with the findings of Battisti et al., (2023) indicating that shoot growth was enhanced by N-P starter fertilization occurred 1 day earlier in all studied systems. However, a response to N-P starter fertilization at harvest was recorded in mineral-fertilized systems only. López-Carmona et al.,(2019) showed that maize plant response to whole rhizosphere microbial communities in terms of growth and nutrition is strongly associated with N and P fertilization balance. Laub et al.,(2023) stated that at realistic application rates, maize yield in integrated soil fertility management is best sustained by a combined application of farmyard manure and mineral N. Mustafa et al.,(2022) indicated that priming of cucumber seeds in nanofertilizers solutions enhanced plant growth parameters under salt stress. The study of Mahdy, (2009) that conducted to study the effects of combination of mineral and organic fertilizers on maize yield revealed that application of 25% mineral and 75% organic fertilizer significantly increased dry matter yields of grain and stover of maize and this increase was due to beneficial changes in soil N, P, K and organic matter dependent soil properties.

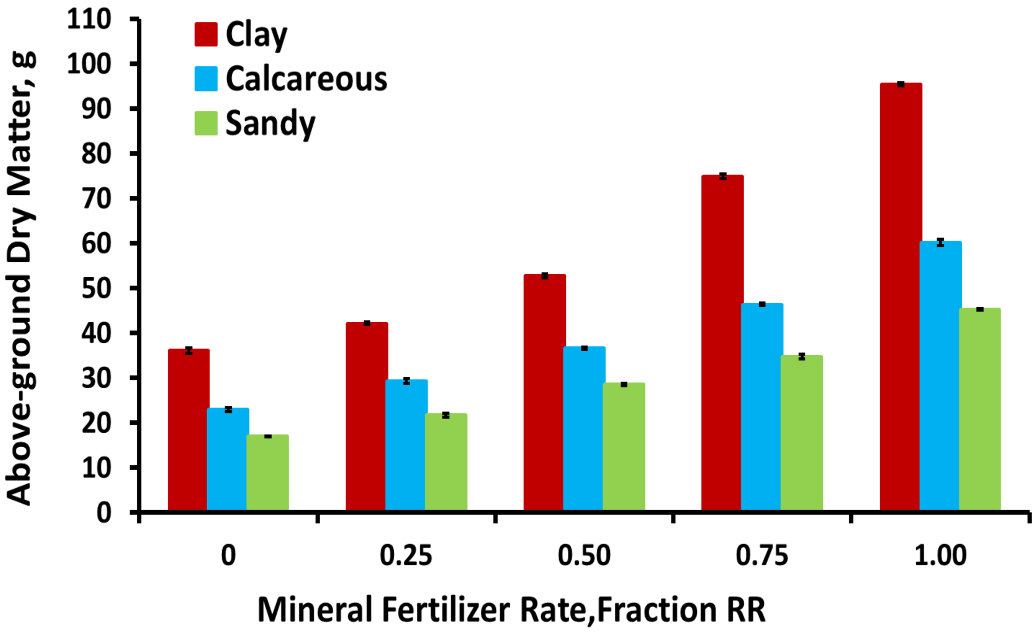


Fig.4: Effect of mineral fertilizer (N-P) as a fraction from RR on above-ground dry matter production of maize grown on the three studied soils.

LSD $_{0.05}$ Soil (S) = 0.23; Rate (R) =0.30; F-test: S ***; R ***; S X R ***

Almutairi et al.,(2021) conducted field experiments over two consecutive growing seasons (2018 and 2019) to determine the individual and interactive effects of various organic and mineral fertilizer treatments on the fruit quality of the Wonderful pomegranate under various irrigation conditions. They reported that the co-application of mineral and organic fertilizers had a significant effect on fruit quality, with 75% mineral + 25% organic fertilizer improving all of the physical and chemical properties of the fruit in both experimental seasons. Moreover, they concluded that the co-application of organic and mineral fertilizers produced better quality pomegranate fruit than mineral fertilizer alone under deficit irrigation conditions.

Bulk sawdust of Mango (bSD-MG) effect: In similar, the effects of NP-enriched bSD-MG application rates on dry matter production of maize plants grown on the three studied soils are shown in Fig.(5). Significant differences in biomass production of maize as affected by bSD-MG application rates. Application of bSD-MG at a rate of 0.25 as a fraction of mineral fertilizer RR for maize to the three studied soils resulted in the lowest values of biomass production and the recorded values were lower than that recorded at the same rate of mineral fertilizer as shown in Figs.(4 and 5). It was noticed that the biomass production of maize plants grown on clay soil was more than calcareous and sandy soils (Fig.5). The increase of the NP-enriched bSD-MG application rate to 0.50, 0.75, and 1 as a fraction from RR applied to maize plants significantly increased biomass production in the three studied soils (Fig.5). Moreover, the soil type, NP-enriched bSD-MG rates and their interaction significantly affected the biomass production (Fig.5). These results are in agreement with the findings of Mahdy,(2009); López-Carmona,et al.,(2019); Almutairi et al.,(2021) ;Battisti et al.,2023 ; Laub et al.,(2023). The study of Chen et al.,(2024) was conducted to evaluate the combined effects of annual maize straw-derived organic amendments and mineral N fertilizer amendment on soil organic carbon and total N accumulation and thermal stability in bulk soils and physically isolated soil aggregate fractions in a long-term field experiment on the North China Plain. They suggested substitution of annual above-ground litter with biochar with or without mineral N fertilizer was the most effective way for soil organic matter build up and stabilization under a wheat/maize system in the North China Plain, while manure, compost and biogas residue resulted in little to no increases of soil organic matter in bulk soils and physically isolated aggregate fractions compared to straw amendment.

Nano sawdust of Mango (nSD-MG) effect: The NP-enriched nSD-MG application rate was reduced to one-tenth of the mineral fertilizer or NP-enriched bSD-MG application rates in all studied soils to compare the effect of nanoparticles (low rates) with mineral and bSD-MG rates (10 fold rate) on dry matter production of maize (Fig.6).

In comparison with NP-enriched bSD-MG, it was noticed that nSD-MG application rates significantly increased dry matter production of maize with values more than bSD-MG and very close to values produced from mineral fertilizers (Fig.6) in all studied soils. Application of nSD-MG at a rate of 0.025 as a fraction of mineral fertilizer RR for maize to the three studied soils resulted in the lowest values of biomass production. However, increase of the NP-enriched nSD-MG application rate to 0.050, 0.075, and 0.10 as a fraction from RR applied to maize plants significantly increased biomass production in the three studied soils (Fig.6). Moreover, the soil type, NP-enriched nSD-MG rates and their interaction significantly affected the total biomass production (Fig.6).

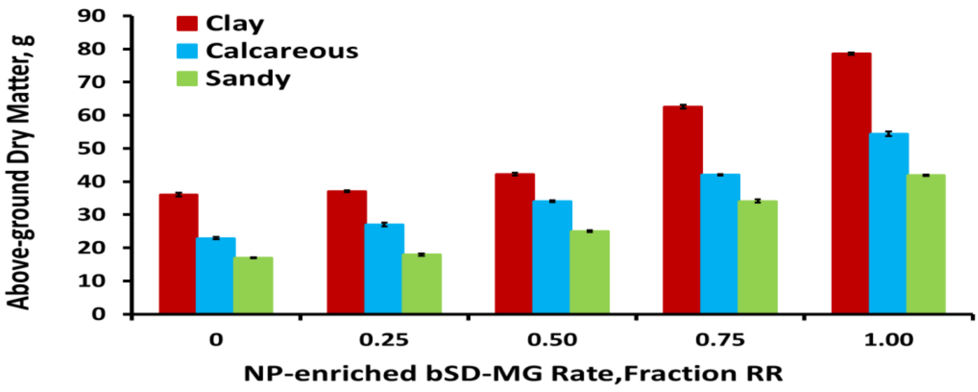


Fig. 5: Effect of NP-enriched bSD-MG as a fraction from RR on above-ground dry matter production of maize grown on the three studied soils.

LSD $_{0.05}$ Soil (S) = 0.24; bSD-MG Rate (R) =0.33; *F-test*: S ***; R ***; S X R ***

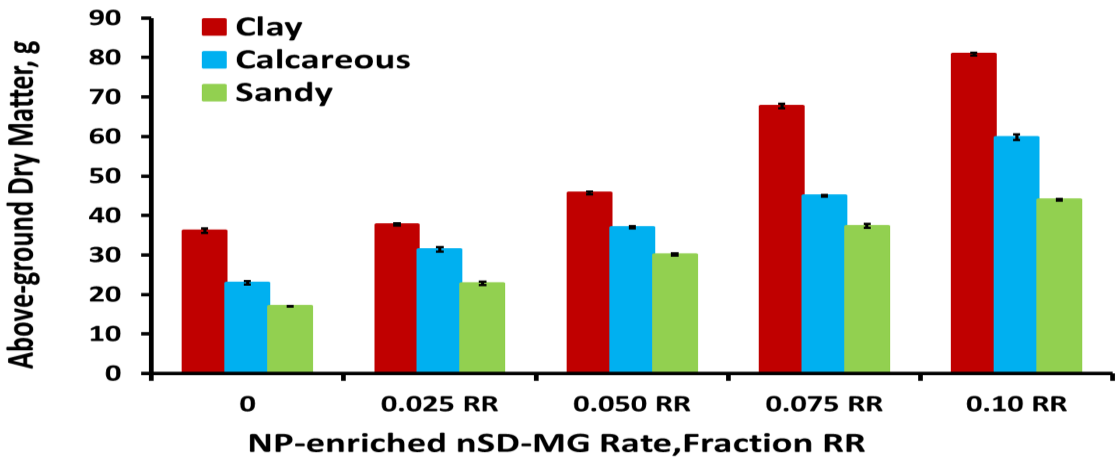


Fig.6: Effect of NP-enriched nSD-MG as a fraction from RR on above-ground dry matter production of maize grown on the three studied soils.

LSD $_{0.05}$ Soil (S) = 0.21; nSD-MG Rate (R) =0.30; *F-test*: S ***; R ***; S X R ***

Interaction effects of fertilizer and soil types: Figure (7) shows the comparison between fertilizer types studied (mineral, bSD-MG, and nSD-MG) on dry matter production of maize plants in all studied soils. It was noticed that dry matter production of maize fertilized with mineral type was very close to that produced from nSD-MG and more than that produced from bSD-MG. The order was mineral ≥ nSD-MG > bSD-MG (Fig.7) in all studied soil. Also, dry matter production of maize plants grown in clay soil (Fig.7A) was more than calcareous (Fig.7B) and sandy (Fig.7C) soils. Significant differences in total biomass production of maize as affected by soil type, fertilizer type, Fertilizer rate and their interactions (Fig.7).

Co-application effects of fertilizer types

Mineral and bSD-MG: The co-application effects of mineral fertilizers and NP-enriched bSD-MG on dry matter production of maize plants grown on the three studied soils are shown in Fig. (8). Significant differences in biomass production of maize as affected by mineral co-applied with bSD-MG application rates. Application of bSD-MG at different rates of 0.25, 0.50 and 0.75 as a fraction of mineral fertilizer RR for maize to the three studied soils resulted in more values of biomass production in comparison with mineral fertilizer only (Fig.8). For example, the recorded values at 0.75 bSD-MG added to 0.25 mineral was 45.45 g per pot but, the value at 0.25 mineral only was 42.19 for plants grown in clay soil. For sandy and calcareous soils, the values at 0.75 bSD-MG + 0.25 mineral were 25.29 and 30.96 g per pot, respectively, but the values were 21.74 and 29.36 at mineral fertilizer only (Figs 4 and 8). However, the highest biomass production of maize was noticed at 0.75 mineral co-applied with 0.25 bSD-MG in all studied soils. Soil type, NP-enriched bSD-MG rates, mineral fertilizer rates, and their interaction significantly affected the biomass production (Fig.8). These results are in accordance with the findings of Mahdy,(2009) revealing that combination of organic and mineral fertilizers in field experiment improved soil fertility, yields and nutrient concentration in the crops compared to mineral fertilization only. Other research studies demonstrated the positive effects of combination between mineral and organic amendments on dry matter yields of various plants (Pincus et al.,2016; López-Carmona,et al.,2019; Almutairi et al.,2021 ;Battisti et al.,2023 ; Laub et al.,2023;Chen et al.,2024)

Mineral and nSD-MG: The co-application effects of mineral fertilizers and NP-enriched nSD-MG on dry matter production of maize plants grown on the three studied soils are shown in Fig. (9). Significant differences in biomass production of maize as affected by mineral co-applied with nSD-MG application rates. Application of nSD-MG at different rates of 0.025, 0.050 and 0.075 as a fraction of mineral fertilizer RR for maize to the three studied soils resulted in more values of biomass production in comparison with mineral fertilizer only (Figs 4 and 9). For example, the recorded values at 0.075 nSD-MG added to 0.25 mineral was 51.55 g per pot but, the value at 0.25 mineral only was 42.19 for plants grown in clay soil. For sandy and calcareous soils, the values at the same treatment were 28.47 and 35.73 g per pot, respectively, but the values were 21.74 and 29.36 at mineral fertilizer only (Figs 4 and 9). However, the highest biomass production of maize was noticed at 0.75 mineral co-applied with 0.025 nSD-MG in all studied soils. For example, the values were 100.24, 65.71, and 50.85 g per pot for clay, calcareous, and sandy soils, respectively.

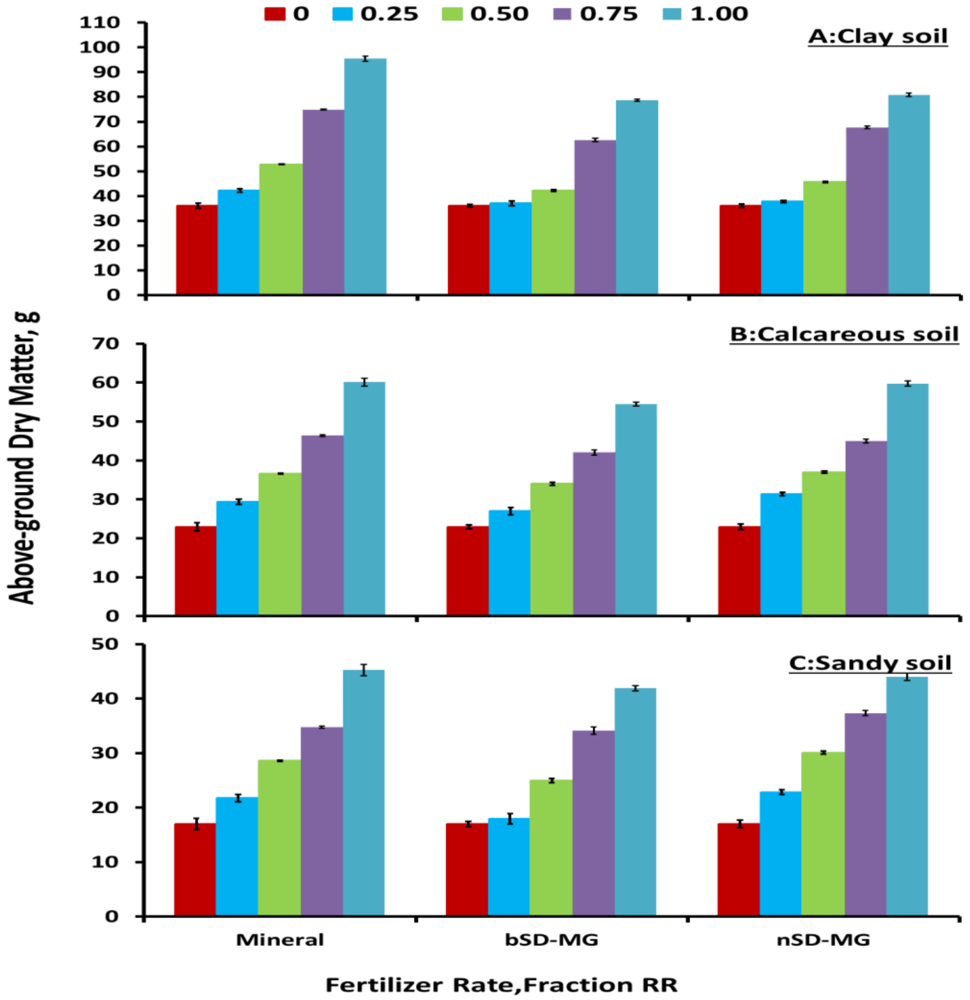


Fig.7: Effect of fertilizer type application as a fraction from RR on above-ground dry matter production of maize grown on the three studied soils.

LSD $_{0.05}$: Fertilizer (F) = 0.30; Soil (S) = 0.23; Rate (R) =0.30
F-test: F ***; S ***; R ***; F X S ***; F X R ***; S X R ***; F X S X R ***

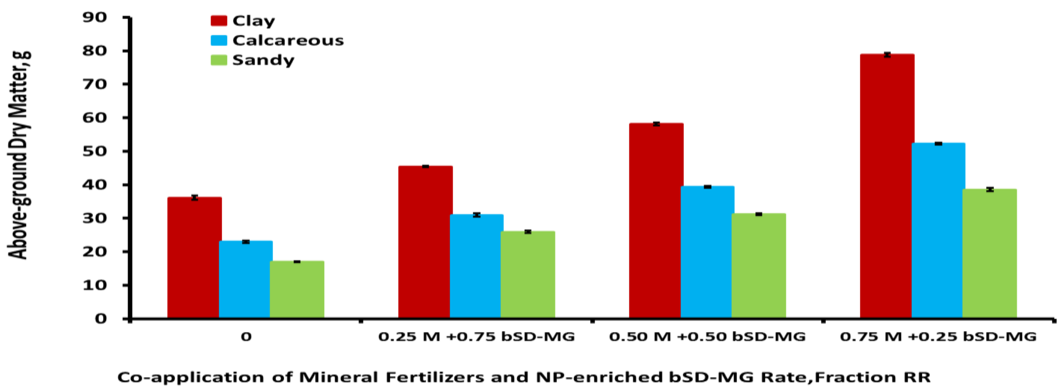


Fig.8:Co-application Effect of mineral and bSD-MG fertilizers on dry matter production of maize grown on the three studied soils.

LSD $_{0.05}$: Fertilizer (F) = 0.30; Soil (S) = 0.23; Rate (R) =0.30
F-test: F ***; S ***; R ***; F X S ***; F X R ***; S X R ***; F X S X R ***

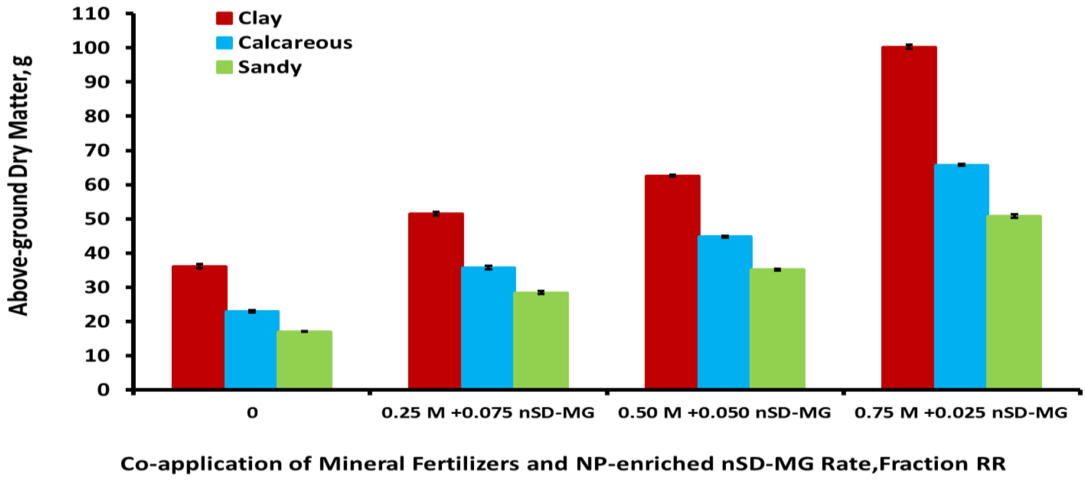


Fig.9:Co-application Effect of mineral and nSD-MG fertilizers on dry matter production of maize grown on the three studied soils.

LSD $_{0.05}$: Fertilizer (F) = 0.30; Soil (S) = 0.23; Rate (R) =0.30
F-test: F ***; S ***; R ***; F X S ***; F X R ***; S X R ***; F X S X R ***

Soil type, NP-enriched nSD-MG rates, mineral fertilizer rates, and their interaction significantly affected the total biomass production (Fig.9).

In conclusion, the more biomass production at different rates of studied sawdust nanoparticles when it is applied individually or co-applied with mineral fertilizers may be discussed if the entrance pathways of nanoparticles are known. The pore diameter of cell wall (5–20 nm) is a very important factor for entry of nanoparticles (Fleischer *et al.*1999). Hence, any nanoparticles less than the pore diameter of cell wall can enter and reach to the plasma membrane (Moore2006; Navarro *et al.*2008). Further, formation of complexes between nanoparticles and root exudates can transport them into the plant (Kurepa et al.2010). After entering the cell, nanoparticles may be transported via plasmodesmata from one cell to cell (Rico et al. 2011). In the cytoplasm, nanoparticles can interfere with different metabolic processes (Moore 2006; Lin and Xing, 2008).

Polynomial Quadratic Model Application

The polynomial quadratic model was used to describe the relationship between dry matter production of maize grown in the three studied soils and fertilizer type application rates (Table 3). The method of the least squares was used to calculate the values of B_0, B_1 and B_2 of the polynomial model. Thus 15 polynomial quadratic models were established to express the relationship between dry matter production of maize grown in the three studied soils and fertilizer type application rates (Table 3). Moreover, the maximum yield for each treatment was calculated.

The calculated dry matter values in the three studied soils were close to the experimental values as shown from the values of standard error of estimates (SE) and determination coefficient (R^2). Therefore, the polynomial quadratic model accurately described the relationship between dry matter production of maize grown in the three studied soils and fertilizer type application rates.

The maximum dry matter production of maize plants grown on the three studied soils is presented in Table (3). In clay soil, the maximum dry matter production of maize was noticed at the treatment of M + nSD-MG with the value of 37.05 g per pot followed by 35.42 g per pot at bSD-MG treatment (Table 2). While, in calcareous soil, the maximum dry matter production values were 21.53 and 19.61 g per pot at bSD-MG and mineral fertilizer treatments, respectively. In sandy soil, the maximum dry matter production values were 19.12 and 15.30 g per pot at M + bSD-MG and bSD-MG treatments, respectively (Table 3). In general, the order of maximum dry matter production of maize plants grown in the three studied soils was: clay > calcareous > sandy soils.

Element concentrations in maize plants

Fertilizer type effects: The effects of mineral fertilizers on nitrogen, phosphorus, and potassium concentrations in maize plants grown on the three studied soils are presented in Table (4). Significant differences in element concentrations of maize as affected by mineral fertilizer application. Increase of the mineral fertilizer application rate from 0.25 to 0.50, 0.75, and 1 as a fraction from RR applied to maize plants significantly increased element concentrations in the three studied soils (Table 4).

Table 3: Polynomial quadratic models expressing the relationships between fertilizer type application rates and dry matter production of maize plants grown in the three studied soils.

Equations		Y_{max}	R^2	SE
Clay				
Mineral (M)	$Y = 2.8933X^2 -.2273X+35.139$	34.71	0.99**	0.004
bSD-MG	$Y= 3.2424X^2 -.3956X+40.868$	35.42	0.98**	0.002
nSD-MG	$Y= 2.6433X^2 -.9227X+36.331$	34.87	0.96*	0.005
M + bSD-MG	$Y= 2.8292X^2 -.0788X+33.604$	33.60	0.99**	0.002
M + nSD-MG	$Y= 5.5483X^2 -.4003X+39.523$	37.05	0.98*	0.003
Sandy				
M	$Y= .7772X^2+2.3195X+14.032$	12.28	0.99**	0.004
bSD-MG	$Y= 1.1283X^2-0.175X+15.314$	15.30	0.98**	0.003
nSD-MG	$Y= .1248X^2+6.1021X+10.584$	14.57	0.99**	0.002
M + bSD-MG	$Y= -0.4025X^2+8.988X+8.7225$	59.12	0.99**	0.003
M + nSD-MG	$Y= .0492X^2+5.5772X+11.076$	3.59	0.97*	0.006
Calcareous				
M	$Y=1.2255X^2\ 1.7828X+20.267$	19.61	0.99**	0.002
bSD-MG	$Y=1.2636X^2\ 0.2196X+21.543$	21.53	0.99**	0.003
nSD-MG	$Y=1.0779X^2\ 2.2552X+20.597$	19.42	0.99**	0.005
M + bSD-MG	$Y=1.2275X^2\ 3.5062X+18.433$	15.93	0.99**	0.003
M + nSD-MG	$Y = 2.0367X^2 +3.55X+18.153$	16.61	0.98**	0.004

*, ** significant at the 0.05 and 0.01 probability levels, respectively.
Y: is the dry matter production of maize plants grown on studied soil fertilized with different fertilizer types, g per pot; X: fertilizer application rate, as a fraction from recommended rate; Y_{max}: maximum dry matter production, g per pot

Clearly, the soil type, mineral fertilizer rates and their interaction significantly affected the three element concentrations (Table 4). In similar, the effects of NP-enriched bSD-MG application rates on element concentrations of maize plants grown on the three studied soils indicated that there were significant differences in element concentrations of maize as affected by bSD-MG application rates (Table 4). Application of bSD-MG at 0.25 , 0.50, 0.75, and 1 as a fraction of mineral fertilizer RR for maize to the three studied soils resulted in lower values of element concentrations in comparison to the recorded values of mineral fertilizer. It was noticed that the three element concentrations of maize plants grown on clay soil was more than calcareous and sandy soils (Table 4). Moreover, the soil type, NP-enriched bSD-MG rates and their interaction significantly affected element concentrations (Table 4).

In comparison with NP-enriched bSD-MG, it was noticed that nSD-MG application rates significantly increased element concentrations of maize with values more than bSD-MG and very close to values produced from mineral fertilizers (Table 4) in all studied soils. Application of nSD-MG at a rate of 0.025 to the three studied soils resulted in the lowest values of N, P, and K concentrations. However, increase of the NP-enriched nSD-MG application rate to 0.050, 0.075, and 0.10 to maize plants significantly increased element concentrations in the three studied soils (Table 4). Moreover, the soil type, NP-enriched nSD-MG rates and their interaction significantly affected the element concentrations (Table 4).

For comparison between fertilizer type studied (mineral, bSD-MG, and nSD-MG) on element concentrations of maize plants in all studied soils, it was noticed that element concentrations of maize fertilized with mineral type was very close to that produced from nSD-MG and more that produced from bSD-MG. The order was mineral ≥ nSD-MG > bSD-MG (Table 4) in all studied soil. Also, element concentrations of maize plants grown in clay soil (Table 4) was more calcareous and sandy soils. Significant differences in element concentrations of maize as affected by soil type, fertilizer type, Fertilizer rate and their interactions (Table 4).

Co-application effects of mineral and NP-enriched bSD-MG or nSD-MG: The co-application effects of mineral fertilizers and NP-enriched bSD-MG or nSD-MG on element concentrations of maize plants grown on the three studied soils are presented in Table (4). Significant differences in element concentrations of maize as affected by mineral co-applied with bSD-MG application rates.

Table 4: N, P, and K concentration in maize plants grown in the studied soils.

Rate, fraction from RR	N			P			K		
	Element concentration, %								
	Mineral (M)								
	Clay	**Sandy**	**Calc.**	**Clay**	**Sandy**	**Calc.**	**Clay**	**Sandy**	**Calc.**
0.00	0.08	0.03	0.05	0.04	0.02	0.03	1.88	1.42	1.77
0.25	0.38	0.22	0.31	0.77	0.16	0.21	2.38	1.74	1.85
0.50	0.56	0.33	0.42	1.08	0.33	0.57	3.67	1.99	2.25
0.75	0.88	0.44	0.53	1.18	0.74	1.18	4.11	2.88	3.08
1.00	1.53	0.78	1.15	1.25	0.72	1.16	6.13	3.02	3.15
bSD-MG									
0.00	0.08	0.03	0.05	0.04	0.02	0.03	1.88	1.42	1.77
0.25	0.22	0.16	0.24	0.43	0.11	0.15	1.96	1.58	1.68
0.50	0.37	0.22	0.32	0.51	0.15	0.21	2.36	1.88	1.95
0.75	0.60	0.31	0.44	0.76	0.34	0.62	2.86	2.62	2.74
1.00	0.87	0.52	0.85	1.11	0.65	0.95	3.12	2.74	2.82
nSD-MG									
0.00	0.08	0.03	0.05	0.04	0.02	0.03	1.88	1.42	1.77
0.025	0.35	0.18	0.27	0.64	0.14	0.18	2.11	1.65	1.77
0.050	0.51	0.25	0.38	0.87	0.27	0.47	2.81	1.94	2.15
0.075	0.84	0.35	0.46	0.93	0.68	1.08	3.45	2.77	2.81
0.10	1.36	0.61	0.95	1.22	0.68	0.99	3.96	2.91	2.95
M + bSD-MG									
0.00	0.08	0.03	0.05	0.04	0.02	0.03	1.88	1.42	1.77
0.25 M +0.75 bSD-MG	0.46	0.38	0.42	0.53	0.28	0.34	2.50	1.88	2.02
0.50 M +0.50 bSD-MG	0.65	0.52	0.58	0.86	0.38	0.65	3.80	2.12	2.44
0.75 M +0.25 bSD-MG	1.82	1.33	1.48	1.33	0.75	1.28	4.55	3.11	3.22
M + nSD-MG									
0.00	0.08	0.03	0.05	0.04	0.02	0.03	1.88	1.42	1.77
0.25 M +0.075 nSD-MG	0.67	0.46	0.58	0.68	0.38	0.47	2.68	2.11	2.33
0.50 M +0.050 nSD-MG	1.18	0.88	0.97	1.12	0.52	0.74	3.96	2.55	2.74
0.75 M +0.025 nSD-MG	1.96	1.41	1.65	1.76	0.95	1.48	4.81	3.22	3.51
LSD 0.05									
Soil (S)		0.07			0.05			0.10	
Fertilizer (F)		0.09			0.07			0.12	
Rate (R)		0.11			0.10			0.11	
ANOVA					*F-test*				
S		***			***			***	
F		**			**			*	
R		**			**			*	
S X F		*			*			*	
S X R		*			*			*	
F X R		***			**			**	
S X F X R		**			**			**	

*, **,*** significant at the 0.05 and 0.01 and 0.001 probability levels, respectively.

Application of bSD-MG at different rates co-applied with mineral fertilizer to the three studied soils resulted in more values of the three element concentrations in comparison with mineral fertilizer only (Table 4). For example, the recorded values of N at 0.75 bSD-MG added to 0.25 mineral was 0.46% but, the value at 0.25 mineral was 0.38% for plants grown in clay soil. For sandy and calcareous soils, the values were 0.38 and 0.42%, respectively, but the values were 0.22 and 0.31% at mineral fertilizer only (Table 4). However, the highest element concentrations of maize was noticed at 0.75 mineral co-applied with 0.25 bSD-MG in all studied soils. Soil type, NP-enriched bSD-MG rates, mineral fertilizer rates, and their interaction significantly affected the element concentrations (Table 4). Similarly, the co-application of NP-enriched nSD-MG and mineral fertilizers on element concentrations of maize plants grown on the three studied soils are presented in Table (4) and it was noticed significant differences in element concentrations of maize as affected by mineral co-applied with nSD-MG application rates. Application of nSD-MG at different rates of 0.025, 0.050 and 0.075 to the three studied soils resulted in more values of element concentrations in comparison with mineral fertilizer only (Table 4). For example, the recorded values of N at 0.075 nSD-MG added to 0.25 mineral was 0.67% but, the value at 0.25 mineral only was 0.38% for plants grown in clay soil. For sandy and calcareous soils, the values of N at the same treatment were 0.46 and 0.58, respectively, but the values were 0.22 and 0.31% at mineral fertilizer only (Table 4). However, the highest element concentrations of maize was noticed at 0.75 mineral co-applied with 0.025 nSD-MG in all studied soils. For example, the values were 1.96, 1.41, and 1.65% for clay, sandy and calcareous soils, respectively. Soil type, NP-enriched nSD-MG rates, mineral fertilizer rates, and their interaction significantly affected the element concentrations (Table 4).

In conclusion, the more element concentrations at different rates of studied sawdust nanoparticles when it is applied individually or co-applied with mineral fertilizers may due to the entry of nanoparticles through the cell that wall depends on the pore diameter of the cell wall (5–20 nm) (Fleischer et al.1999).

Hence, nanoparticles or nanoparticle aggregates with diameter less than the pore size of plant cell wall could easily enter through the cell wall and reach up to the plasma membrane (Moore2006; Navarro et al.2008). Moreover, bSD-MG and nSD-MG containing more organic carbon and other constitutes that increase the availability of studied elements.

Many researchers have studied the combination of mineral and organic fertilizers added to soils.

The study of Mahdy,(2009) revealed that combination of organic and mineral fertilizers in field experiment improved soil availability of macronutrients(NPK) and the increase in these nutrients was associated with their uptake by maize plants. Other research studies demonstrated the positive effects of combination between mineral and organic amendments on nutrient contents and dry matter yields of various plants (López-Carmona,et al.,(2019); Almutairi et al.,(2021); Battisti et al.,2023; Laub et al.,(2023); Chen et al., 2024). Other research studies concerning with addition of organic residues amendments such as, Heil and Barbarick (1989) and Mahdy et al., (2007) who observed an increase in dry matter production with application of alum-sludge residues. Ippolito et al. (1999) and Mahdy et al, (2009) reported that application of bulk water treatment residuals (WTRs), with a constant application rate of biosolids, significantly increased dry matter yield of blue grama, maize and western wheat grasses. Moreover, the co-application of biosolids and WTRs produced more total plant dry matter than the single application of biosolids.

CONCLUSIONS

The co-application effects of mineral fertilizers and NP-enriched bSD-MG or nSD-MG on dry matter production of maize plants grown on the three studied soils revealed significant differences in biomass production of maize. The highest biomass production of maize was noticed at 0.75 mineral co-applied with 0.25 bSD-MG or 0.025 nSD-MG in all studied soils. The more biomass production at different rates of studied sawdust nanoparticles when it is applied individually or co-applied with mineral fertilizers may be due to the entry of nanoparticles through the cell wall . The polynomial quadratic model was successfully described the relationship between dry matter production of maize grown in the three studied soils and fertilizer type application rates. The co-application effects of mineral fertilizers and NP-enriched bSD-MG or nSD-MG on element concentrations of maize plants grown on the three studied soils indicated to significant differences in element concentrations of maize as affected by mineral co-applied with bSD-MG or nSD-MG application rates. The highest element concentrations of maize was noticed at 0.75 mineral co-applied with 0.25 bSD-MG or 0.025 nSD-MG in all studied soils. It can be concluded that the more element concentrations at different rates of studied sawdust nanoparticles when it is applied individually or co-applied with mineral fertilizers may due to the entry of nanoparticles through the cell that wall. Moreover, bSD-MG and nSD-MG containing more organic carbon and other constitutes that increase the availability of studied elements.

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الملخص العربي

الإدارة المتكاملة لخصوبة التربة عن طريق استخدام حبيبات نشارة الخشب العادية والنانوية لتحسين إنتاجية الكتلة الحيوية ومحتوى العناصر الغذائية لنبات الذرة المنزرع فى أنواع مختلفة من التربة

كرم أحمد محمد سلامه[١]، أحمد محمد مهدى[١]، فاطمة كمال شريف[١]، حسام محمد إبراهيم[٢]

[١] قسم الاراضى والمياه– كلية الزراعة– جامعة الاسكندرية.

[٢] قسم المحاصيل– كلية الزراعة– جامعة الاسكندرية.

تم إجراء تجربة أصص لاختبار نشارة الخشب المخصبة بـــعنصرى النيتروجين والفوسفور لتعويض نقص المضاف من الأسمدة المعدنية إلى نباتات الذرة المنزعة في ثلاث أنواع أراضى مختلفة. ولتحقيق هذا الهدف، تم وضع مجموعة من الأهداف المحددة وهى توصيف الخواص الفيزيائية والكيميائية لحبيبات نشارة الخشب العادية (bSD) والخشب النانوية (nSD) التي تم إنتاجها بواسطة الطحن الميكانيكي؛ مقارنة تأثير كلا النوعين من النشارة المضافة مع الأسمدة المعدنية مقارنة بالتسميد المعدني التقليدي المضاف بمفردة على محصول الذرة المنزع في أنواع مختلفة من التربة. ولتحقيق هذه الأهداف تم إنتاج الحبيبات النانوية من نشارة الخشب وتم تشبعيعها بـــ ١٦٠ ملجم لكل لتر من محاليل الأمونيوم والفوسفات. أوضحت النتائج أن التطبيق المشترك للأسمدة المعدنية مع bSD أو nSD المخصب بـــعنصرى النيتروجين والفوسفور أدى إلى زيادة كبيرة في إنتاج المادة الجافة لنباتات الذرة المنزعة في الأراضى الثلاثة المدروسة. لوحظ أن أعلى إنتاج للكتلة الحيوية للذرة عند المعاملة ٠,٧٥ معدنى مع ٠,٢٥ bSD أو ٠,٠٢٥ nSD في جميع الأراضى المدروسة. زيادة إنتاج الكتلة الحيوية عند إضافة المزيد من الحبيبات النانوية بمفردها أو مع الأسمدة المعدنية. تم بنجاح وصف العلاقة بين إنتاج المادة الجافة للذرة المنزرعة في الأراضى الثلاثة المدروسة ومعدلات استخدام الأسمدة المختلفة. أشارت نتائج الاضافة المتزامنة من الأسمدة المعدنية و bSD أو nSD المخصب بـــعنصرى النيتروجين والفوسفور أن تركيزات العناصرفى انسجة نباتات الذرة المنزعة في الاراضى الثلاثة المدروسة بها اختلافات كبيرة ومعنوية. كما لوحظ أن أعلى تركيز للعناصر فى أنسجة النبات عند المعاملة ٠,٧٥ معدنى مع ٠,٢٥ bSD أو ٠,٠٢٥ nSD في جميع الاراضى المدروسة. زيادة إنتاج المادة الجافة وتركيز العناصر عند معدلات مختلفة من نشارة الخشب النانوية عند إضافتها مفردة أو مع الأسمدة المعدنية قد يكون بسبب دخول الحبيبات النانوية عبر جدار الخلية. علاوة على ذلك، احتواء bSD وnSD على المزيد من الكربون العضوي ومكونات أخرى تزيد من توفر العناصر المدروسة.

الكلمات المفتاحية: نشارة الخشب؛ الحبيبات النانوية؛ المادة الجافة؛ الذرة؛ العناصر الغذائية.