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Impact of nano slow-release fertilizers on growth and sustainable productivity of field crops

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Impact of nano slow-release fertilizers on growth and sustainable productivity of field crops

Abstract: The prepared nanofertilizer loaded with carbon nanotube was subjected to thermogravimetric analysis to assess its nitrogen released pattern. The in-vitro incubation was performed for forty days at field moisture condition to study the nutrient contents release rate of the developed nanofertilizer and compared with convectional chemical fertilizer. A pot experiment with 'Habanero' pepper plant was performed to study the efficiency of the developed nanofertilizer in the growth advancement of 'Habanero' pepper. The post effect of the developed nanofertilizer application in the soil was also conducted. The release pattern of nitrogen from both developed nanofertilizer and conventional fertilizer showed a significant reducing tendency with time while the release of nitrogen contents was high-rise for the developed nanofertilizer than conventional one. The analysis of pot experiments showed a higher accumulation of nitrogen contents in the plant grown with the developed nanofertilizer compared to the convectional fertilizer. The post effects of fertilizers application in the soil revealed a better pH, moisture, cation exchange capacity, and nitrogen available under soil treated with the developed nanofertilizer was higher compared with the soil treated with the conventional fertilizer. The developed nanofertilizer therefore, potentially improved the nutrients contents use efficacy and positively influenced in crop growth enhancement.

Key words: nanofertilizer, urea, nanomaterials, soil treatment, carbon nanotubes

Vpliv počasi sproščajočih se nano gnojil na rast in trajnostno pridelavo poljščin

Izvleček: Pripravljeno nano gnojilo, opremljeno z ogljikovo nano cevko, je bilo podvrženo termogravimetrični analizi za oceno vzorcev sproščanja dušika. V razmerah vlažnosti poljske kapacitete je bila v obdobju štirinajst dni izvedena in vitro inkubacija za spremljanje sproščanja hranil pri uporabi nano gnojil v primerjavi s konvencionalnimi mineralnimi gnojili. Vzpostavljen je bil lončni poskus za preučevanje učinkovitosti nano gnojil na pospešeno rast 'Habanero' čilija. Izvedena je bila tudi analiza učinka nano gnojil na tla v lončnem poskusu. Sproščanje dušika se je s časom zmanjševalo pri obeh načinih gnojenja a je bilo pri nano gnojilih večje kot pri konvencionalnih gnojilih. Analiza lončnega poskusa je pokazala večjo akumulacijo dušika v rastlinah pri gnojenju z nano gnojili. Učinki gnojenja na tla so pokazali izboljšanje parametrov tal kot so pH, vlažnost, kationska izmenjalna kapaciteta in dostopnost dušika v primerih gnojenja z nano gnojili v primerjavi s konvencionalnimi mineralnimi gnojili. Nano gnojila so izboljšala učinkovitost izrabe hranil in so pozitivno vplivala na pospeševanje rasti poljščin.

Ključne besede: nano gnojila, urea, nanomateriali, obravnavanje tal, ogljikove nano cevke

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1 INTRODUCTION

Agriculture is the major source of food and feed for both human beings and animals. Owing to the rapid increase in the world population, increased in agricultural produce will be required to meet up with the foods needed globally (Subramanian et al., 2015). However, achieving and sustaining global food security is a huge challenge that necessitate agriculture practice to be modified. On this basis, transformation and sustainable farming practices are called for to meet the global food demand and ensure long-term food security. Development and adoption of agriculture practices to produce adequate food is essential in order to meet up with the demands of a growing population globally. Application of fertilizer is being practiced in agricultural field to produce enough food for increasing population (Chhipa et al., 2017). The use of fertilizer is therefore used to enhance and sustain crops production. Thus, application of various fertilizers in the farming system is unavoidable for the increasing and sustaining crops production (Subramanian et al., 2015; Chhipa et al., 2017). Nevertheless, the detrimental of the conventional fertilizers commonly being used by the farmers have many challenges not only to the agriculture sector also to the environment. Moreso, uncontrolled utilization of the conventional fertilizers inflicts more costs on the farmers and considered to be a hurdle to agriculture sustainability chain disturbances, as well as various environmental problems (Seleiman et al., 2021). It has been generally discovered that more than 60% of the total amount of chemical fertilizers applied has been estimated to remain unused as they hoard in the soil through leaching and mineralisation (Bhardwaj et al., 2022).

Prospective agricultural sustainability can be accomplished via productivity improvement and control of nutrients, facilitated by the successful application of technologies like nanotechnology. Applications of nanomaterials in agriculture system seem to be a promising technology, promoting development in the sustainable production systems and modernize agricultural practices with a clear emphasis on the agricultural growth and environmentally friendly approaches (Duhan et al., 2017; Lowry et al., 2019). The use of nanomaterials for fertilizers could be a crucial development in the sustainable crops production as well as safe keeping of the environment compared to conventional chemical fertilizers (Adisa et al., 2019), hence reducing leaching and emission of pollution to the atmospheric environment (Verma et al., 2022).

The unique properties of nanomaterials give progressive applications in the agriculture sector, in order to ensure sustainability in the crops production for global food security (Heydari et al., 2018). Applications of nanotechnology in the agricultural sectors have been carried out by many researchers and several reports emphasised nanotechnology-based research have been published globally (Hassanisaadi et al., 2022). In addition, nanotechnology have been applied in agriculture system for the managing and monitoring of pest-control agents, checking of soil quality, and provision of nutrients to the plants (Zhao et al., 2021). Nanofertilizers have the ability to retain sufficient nutrients because of their large specific surface area and slowly release the nutrient ions in exact amount require by the plants (Hassanisaadi et al., 2022). Nanofertilizers has a high specific surface area and small size which make its reactivity to increase in solubility, diffusion and availability of nutrients to the crops as to boost productivity (Heydari et al., 2021). Nanofertilizers can explore its nanostructured materials as resources to increase the performance of nutrient usage by the plants and minimize environmental degradation (Sharma et al., 2022).

Some researchers have proven some beneficial effects of nanofertilizers such as effective usage of nutrients, growth promotion in annuum plants good yield and reduction in soil pollution. (Nadeci and Danesh et al., 2013; Mishra et al., 2014; Liu and Lal, 2015; Elmer and White, 2016; Dimkpa et al., 2018; Balogun et al., 2020; Yuan et al., 2020; Singh et al., 2021; Xiaorong et al., 2021). These potential benefactions of nanofertilizers to improve growth of crops attributed to its ability for greater absorbance and high reactivity. It is simple for the nanofertilizer components to enter the plant cells directly through the sieve-like cell wall structures if the particle sizes are smaller than the sizes of cell wall pores. However, since the production and implementation of these nanofertilizers are still at an early stage, their commercialization and widespread adoption are hampered by several analytical issues such as concerns over their safety, environmental impact, regulatory framework, cost-effectiveness and long-term effect. Therefore, the development and application of new and innovative fertilizers that have a very high efficiency and minimal disadvantages are urgently needed for sustainable crops productivity. The main objective of this present work is to study the rate of release of nutrients of a developed hydroxyapatite-based fertilizer loaded with carbon nanotube and compare its effects on the tested crops productivity response with the conventional chemical fertilizers.

2 MATERIALS AND METHODS

2.1 MATERIALS

All chemicals and equipment used throughout this study were bought from the Chemiz (M) Company, Malaysia, of analytical grade and used without any further form of purification. soil pH meter, moisture meter, soil texture test kits, spectrophotometer.

2.2 METHODS

Synthesis of the developed nanofertilizers was achieved in three stages as described below:

2.2.1 Green production of urea and urea-hydroxyapatite nanohybrid composites

Firstly, the synthesis of green urea and production of urea-hydroxyapatite nanohybrid composites were carried out using our previously reported method (Mohammed et al., 2024).

2.2.2 Production of carbon nanotubes and nanofertilizer

The second stage is production of carbon nanotube (CNT). The synthesis of CNT was carried out employing our previously reported method with little modification (Adewumi et al., 2021).

Urea-hydroxyapatite nanohybrid composites sample incorporated with CNTs production is the last stage of preparing the newly developed nanofertilizer. The dispersion of urea-hydroxyapatite nanohybrid composites prepared was loaded with CNTs dispersion at the ratio of 1:2 under ultrasonic mixing at 25 kHz for 40 min in order to achieve uniform dispersion. The obtained uniform dispersion of urea-hydroxyapatite fertilizer loaded with CNTs was dried inside an oven at 70 °C for 10 hrs and keep for further usage.

The electron microscopy images of the developed of urea-hydroxyapatite fertilizer loaded with CNTs were examined by making use of JOEL JSM 6330 emission scanning electron microscope. Fourier transform Infrared analysis was also studied with aid of Perkin Elmer 100 FTIR spectrometer.

2.2.3 Potency of the developed nanofertilizer

In the first place, the characteristics of soil sample collected at the farm of Faculty of Agriculture, LAUTECH Ogbomoso Nigeria were studied and analysed in the laboratory before the experiment and after the harvesting of the plants. This is to have the knowledge of initial nutrient contents level in the soil sample and to study the impact of developed nanofertilizer on the soil after an interval of time. An in-vitro incubation setup for the soil samples involving controlled environmental conditions by installation of sensors for monitoring temperature, moisture, gas concentrations and other relevant parameters. This is to study soil microbial activity and the release behaviour of the components of the developed fertilizer into the soil. For the proper collection, handling, and preparation of samples to minimize contamination and maintain representativeness of the field conditions, the soil samples collected using augers, the soils passed through a sieve to remove large debris and create homogenous sample, the moisture of the sample was adjusted to a desired water-filled pore space using distilled water and equal-sozed subsamples were prepared for the incubation and analysis. The period of incubation considered during the investigation are 0, 20 and 40 days. The similar procedure was followed as described in (Chowdhury et al., 2020).

Under green-house environmental conditions, two pot experiments were conducted on a soil sample between May and September, 2023. The plastic pots of dimension 50cm in height and 40cm in diameter were filled by the soil sample and leaving 10cm from the top of the pot to ensure the stagnation of water during the experiment. A number of three holes were made at the bottom of each plastic pot.

Three treatments in four replicates to ensure statistical power and reduce variability were designed as follows:

- Application of developed urea-hydroxyapatite fertilizer incorporated with CNTs to the soil sample for pepper plants
- Application of conventional chemical fertilizer (NPK) to the soil sample for Habanero pepper plants
- Control experiment (soil sample without any treatment of fertilizer) for Habanero pepper plants

All the data acquired were analysed statistically using Microsoft Excel packages. To carry out the statistical analysis, the Least Significant Difference test (LSD) at a 5 % level of probability was used to test the significance differences among the means.

3 RESULTS AND DISCUSSION

3.1 CHARACTERIZATION OF CARBON NANOTUBE

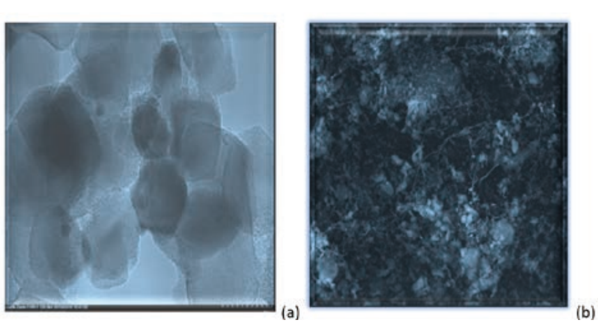

Figure 1: Electron microscopy images of (a) urea-hydroxyapatite fertilizer loaded with CNTs (b) Without CNTs.

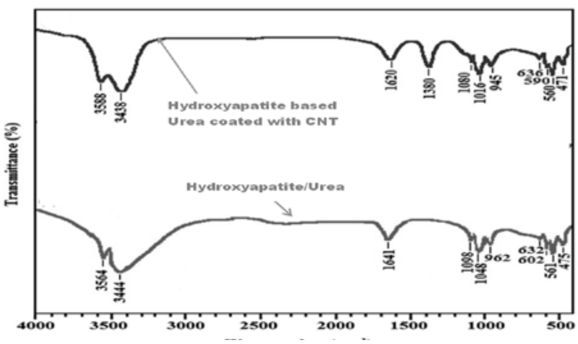

Figure 2: FTIR spectra of urea-hydroxyapatite fertilizer loaded with and without CNTs.

3.1.1 Morphological properties of the developed nanofertilizer

The electron microscopy images of the developed of urea-hydroxyapatite fertilizer loaded with CNTs samples presented in Figure 1. It could be observed from the figure that the nanohybrid of urea-hydroxyapatites composites had twisted and clustered the particles of with a rough morphology as shown in Figure 1a (Fatemeh and Shahoo, 2022). The sizes of opening in the nanohybrid composites of urea-hydroxyapatites structures reduced with the present of CNTs compared to composites of urea-hydroxyapatites without CNTs particles (figure 1b), this could be due to the fact that CNTs particles entering into the composites of urea-hydroxyapatites pore structure. Furthermore, it is revealed that most of the tubular wall structure of CNTs have been ruptured due to chemical interactions between carbon nanotubes and the composites of urea-hydroxyapatites.

Figure 2 presents the Fourier transform infrared analysis spectra of urea-hydroxyapatites structures with CNTs. The composites of urea-hydroxyapatites with CNTs displayed the same peaks to those of composites of urea-hydroxyapatites nanohybrid without CNTs, except for the peak at 1360 cm^{-1} which occured in urea-hydroxyapatites with CNTs spectrum as shown in Figure 2. The absorption peaks characteristic for phosphate group of nanohybrids of urea-hydroxyapatites are observed at 558 and 590 cm^{-1}, 1017 and 1081 cm^{-1} and 948 cm^{-1}, which are allotted to P–O bending, asymmetric P–O stretching and symmetric P–O stretching vibrations, respectively. Furthermore, The NH_2 groups from the nanohybrids of urea-hydroxyapatites may react with the carboxyl groups on the surface of CNTs to give amide groups hence, the outcomes from the Fourier transform infrared analysis spectra indicate that chemical functionalization has taken place within the particles of urea-hydroxyapatites and CNTs.

3.2 CHARACTERISTICS OF SOILS

3.2.1 Features of soil sample

The soil sample used for the experiment was mouldable but not sticky a such in texture and acidic of pH 4.80. The sample soil composed of 0.90 % of organic carbon, 1.65 % of organic matter, 0.004 % of nitrogen, 0.002 % of phosphorous, 0.20 % meq of potassium, 0.0009 % of sulphur and 5.68 % meq of cation exchange capacity (CEC). The moisture content of the soil sample was 23.65 %.

3.2.2 The pH of soil sample

The initial pH of the soil sample treated with conventional fertilizer and developed nanofertilizer was higher than the soil sample without any treatment (control soil of the experiment). The pH of all the three soil samples regardless of their treatments decreased on the following days. Although, the decrease was gentle towards the end of the assessment as presented in the figure 3. Close to 20 days of incubation till final stage of the experiment, the pH of the treated soil with developed nanofertilizer was always lower than the control soil. A higher initial pH of the soil sample treated with developed nanofertilizer was due to the alkaline nature of hydroxyapatites. However, the reduction in pH of the soil sample treated with developed nanofertilizer on the following days was attributed to ability to preserve moist condition for long period. This indicates that the developed nanofertilizer has slight positive effect on soil pH.

3.2.3 Moisture of the soil sample

From determination of percentages of moisture contents in the different soil samples treatment after each incubation period, it is noted that despite the same volume of water was put in to each soil sample for the purpose of moistening, the soil sample treated with developed nanofertilizer however, retained more volume of

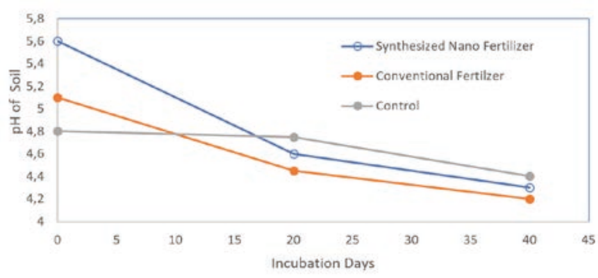

Figure 3: The pH of soil samples at various incubation days

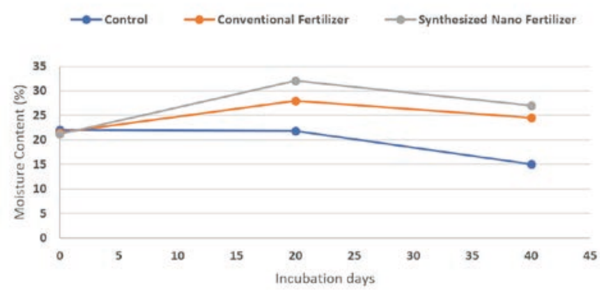

Figure 4: Moisture content of the soil at various incubation days

water compared to the sample treated with conventional fertilizer and control (Figure 4). This is an indication that developed nanofertilizer can also improve the water use efficiency. Hydroxyapatites can serve as high water absorber of their weight (Verma et al., 2022), this confirms that application of the developed nanofertilizer could improve water-holding capacity of the soil. Therefore, the nanofertilizer has a positive effect on soil moisture.

3.2.4 Nitrogen content of soil sample

The impacts of developed nanofertilizer on available nitrogen content of the soil at different incubation days are presented in Figure 5. The availability of nitrogen content was eminent for the soil sample treated with the developed nanofertilizer at the initial stage of the experiment till final stage compared to the other soil samples. Thought all the soil samples displayed similar manner of nitrogen content available but at different levels (Figure5). Nevertheless, the soil sample without any treatment contained less nitrogen than the other samples treated with the fertilizers.

Figure 6 shows percentage of nitrogen content release at different incubation days by the treated soil samples only. The percentage release of nitrogen content of conventional fertilizer treated soil sample was initially lower as compared to the developed nano-fertilizer soil sample treatment. The soil sample treated with conventional fertilizer revealed an increase till day 20 of incubation followed by decrease at long last. While with the developed nano-fertilizer treated soil sample showed an initial higher rate of percentage release of nitrogen content, subsequently a decreasing trend was recorded and followed by an increase towards the 40 days of incubation (Figure 6). The progressive high release of nitrogen content by the soil treated with developed nano-fertilizer was attributed to a very strong bond within the ammonium ions in the hydroxyapatites-carbon nanotubes composites. The increase in nitrogen release after 40 days confirmed that the bonding might have been better and therefore, the developed nanofertilizer has the prospect of releasing nutrients moderately.

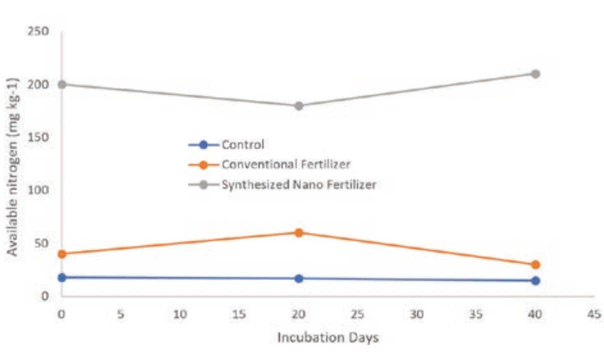

Figure 5: Nitrogen of the soil at various incubation days

3.3 VISUAL SYMPTOMS OF TREATED PLANTS

By monitoring and observing the growth of the Habanero pepper plants, it was visually appeared that the peppers were doing better in term of growth performance in both soil samples treated with fertilizers than the control soil sample. However, the plant growth performance was better with the developed nanofertilizers treatment soil compared to the soil sample treated with convectional fertilizer. The soil treated with the developed nanofertilizer demonstrated improved absorption of water, no subsidence, firm consistency and no insect or pest infestations were detected on the leaves of pepper plants. However, control and conventional fertilizer treated soils showed considerable subsidence.

3.4 EFFECTS OF NANOFERTILIZER ON THE FRESH AND DRY PRODUCTION OF PEPPER

The growths of 'Habanero' pepper as affected by the different soil samples on the mass of fresh and dry productions are presented in Table 1. It was observed and recorded that the mass of fresh production of pepper was higher in the soil treated with developed nanofertilizer compared to the other soil samples. The significant difference recorded in the fresh production of 'Habanero' pepper was attributed to appropriate water balance received by the plants from the soil as a result of better water retention potentiality of developed nanofertilizer application (Sharma et al., 2022). This showed that there is a significant positive effect of the developed nanofertilizer treatments on the fresh mass and dry mass of 'Habanero' pepper.

Table 1: Mass of fresh and dry production of 'Habanero' pepper plant.

Treatment	Fresh Mass (g/100 plants)	Dry Mass (g/100 plants)
Control	66.65	4.3
Conventional Fertilizer	75.67	5.1
Developed Nanofertilizer	76.00	5.33

3.5 PHYTO-AVAILABILITY OF NITROGEN

The phyto-availability of nitrogen in the pepper plant was assessed by measuring and recording the concentration and uptake of nitrogen at different treatments of the soil sample (Table 2). It is observed from the table that concentration of nitrogen was in the minimum level (1.61%) for pepper plant from the control soil sample whereas nitrogen concentration was the same in magnitude for the pepper plants from soil samples treated with conventional fertilizer and developed nanofertilizer. The intake of nitrogen by the pepper plants was estimated by multiplying the nitrogen concentration in the plant with their corresponding dry matter production. It is seen from the investigation that intake of nitrogen by the pepper plants was better in both conventional fertilizer and developed nanofertilizer over control soil sample though, plant from developed nanofertilizer treatments soil recorded highest uptake of nitrogen.

A report was devised to appraise the estimation of nitrogen contents in the experimental set up (presented in Table 3). From the table, initially all the treated soil pots held 70 mg pot^{-1} of nitrogen while the control sample held 20 mg pot^{-1}. At the period of plant growth, an amount of this nitrogen has been absorbed by the pepper plants while some amount of nitrogen is expected to be left over in the soil after the plants have been harvested. Based on the estimate presented in the Table 3, the total nitrogen could not retrieve because certain amount was lost at the period of plant growth. The considerably lower percentage of nitrogen lost (2.03 %) for the developed nanofertilizer treated soil compared to the higher percentage recorded for the both conventional fertilizer treatment (28.9 %) and control soil (39.55 %). This implies that the nitrogen content of the developed nanofertilizer was efficiently utilized for the both plant and the soil development.

3.6 IMPACTS OF NANO FERTILIZER AFTER HARVESTING

After harvesting of 'Habanero' pepper, the soil sam-

Table 2: Nitrogen concentration and intake in 'Habanero' pepper plant.

	Nitrogen	
Treatment	Concentration (%)	Intake (mg/100 plants)
Control	1.62	69.77
Conventional Fertilizer	1.74	88.74
Developed Nanofertilizer	1.74	92.80

Table 3: The evaluation of nitrogen content in the various soil samples

Nitrogen (mg/pot)	Experimental Pot		
	Control	Conventional fertilizer	Synthesized nano fertilizer
Initial nitrogen content in the soil	20	20	20
Nitrogen content from different fertilizer source	0.00	40	40
Total nitrogen content in the soil (m)	20	60	60
Intake through plant (n)	2.09	2.66	2.78
Left over in soil after harvest (p)	10	40	56
n + p = q	12.09	42.66	58.78
Nitrogen content lost (m - q)	7.91	17.34	1.22
Percent of content not accounted for (%)	39.55	28.9	2.03

(Only inorganic fraction is considered)

Table 4: Initial and after harvesting properties of soil samples.

Treatment	pH	Moisture (%)	Organic Carbon (%)	CEC (meq %)	Available N (mg kg^{-1})
Control	5.7 (5.9)	2.8 (4.6)	1.5 (0.92)	6.14 (5.79)	10 (20)
Conventional fertilizer	5.6 (5.9)	2.7 (4.6)	1.7 (0.92)	5.93 (5.79)	40 (20)
Synthesized nano fertilizer	4.7 (5.9)	3.0 (4.6)	0.7 (0.92)	6.79 (5.79)	56 (20)

(The figures in the parentheses are the initial values.)

ples characteristics were studied in order to compare the initial properties of the soil samples before harvesting and its properties after harvesting (presented in Table 4). It was noted that for all the soil samples, the values of their pH decreased slightly after harvesting. The decreasing in pH generally was attributed to the root exudates of plants which was more prominent in the case of developed nanofertilizer soil treatment (though still in a good range for agricultural production) (Junxi et al., 2013)

Generally, the moisture content of all the soil decreased after harvesting compared to their initial soil moisture content. This decrease was caused by moisture uptake by the plants as well as evapotranspiration loss which was a bit minimal for the developed nanofertilizer soil treatment. This was due to ability of the developed nanofertilizer to improve water-holding capacity of a soil. Hence, this indicates that the developed nanofertilizer has a non-significant positive effect on soil moisture.

The organic carbon of the soil sample after harvesting increased for the conventional fertilizer treatment and control soil sample whereas it is decreased for the developed nanofertilizer soil treatment. The increase of the organic carbon (for the conventional fertilizer treatment and control soil) may be attributed to release of root exudates while the reduction in organic carbon (for the developed nanofertilizer) was caused by the higher amount of available nitrogen content in developed nanofertilizer. According (Junxi et al., 2013), the growth and abundance of organisms to release carbon dioxide as a result of decomposition of organic matter highly depend on availability of nitrogen. This indicates that the developed nanofertilizer has a significant negative impact on organic carbon.

Generally, the cation exchange capacity of soil sample after harvesting was increased compared with the initial soil sample for all the cases. However, the increase of the soil treated with the developed nanofertilizer is higher than the other because hydroxyapatites do often used as inexpensive cation exchanger due to its high cation exchange capacity (Millar et al., 2008). The nanofertilizer has positive significant effect on cation exchange capacity.

It could be observed in the Table 4 that with the exception of control soil sample, the available nitrogen content in the soil samples treatment after the harvesting are much higher than their respective initial soil sample. A very higher available nitrogen content in the developed nanofertilizer soil treatment than the others was due to the leftover fertilizer in soil and moreso, nanofertilizer holds higher amount of inorganic nitrogen than the conventional fertilizer. This confirms that the developed nanofertilizer has significant positive effect on available nitrogen.

3.7 EFFECTS OF DIFFERENT TREATMENTS OF THE SOIL SAMPLE ON THE NITROGEN INTAKE AND MASS OF FRESH HABANERO PEPPER PLANT

On the Table 5, the data are displayed as means ± standard deviation (n = 3), least significant difference (LSD) test at $p \leq 0.05$. The nitrogen contents intake by the pepper plant from the soil samples treated with the developed and conventional fertilizers were significantly increased ($p \leq 0.05$) relatively compared with the control sample. More so, the fresh pepper plants from the soil samples treated with the both fertilizers achieved higher mass compared with the control one. This significant difference effect was due to the positive interaction between the components content of the fertilizers and that of the soils. However, the plant from the soil sample treated with the developed fertilizers recorded the highest nitrogen intake and fresh mass significantly compared with the one treated with conventional fertilizers. This achievement is attributed to regulation in the slow and steady release of nutrient contents and minimized losses leading to the increased uptake of nitrogen from the soil treated with the developed fertilizers. Moreover, the developed fertilizers have large surface area compared to the conventional one, which contributed to the increased in the plant's metabolic efficiency. The results agreed with (Millar et al., 2008) that nanofertilizers have potential of

Table 5: Effects of different treatments of the soil sample on the nitrogen intake and weight of fresh 'Habanero' pepper plant.

Treatment	Nitrogen intake (mg/100 plants)	Fresh mass (g/100 plants)
Control	69.77 ± 0.18	66.65 ± 0.052
Conventional Fertilizer	88.74 ± 0.13	75.67 ± 0.070
Developed Nanofertilizer	92.80 ± 0.12	76.00 ± 0,078

promoting the uptake of water and nutrients which is reflected in the plant's mass.

4 CONCLUSION

The extraordinary physical and chemical properties of nanomaterials are being explored to resolve significant challenges associated with global food demand, environmental implications, and sustainable crops productivity. Nanomaterial increases fertilizer utilization efficiency by targeted release of nutrient contents in adequate proportion without any harmful effect on the soil, plant as well as environment. Hence, the growth process of Habanero pepper plant, its uptake and concentration of nitrogen was better in the developed nanofertilizer application than in the conventional chemical fertilizer indicating the fact that there is a scope of the developed nanofertilizer in sustainable crops agriculture practice. The study therefore indicates a bright possibility of using the developed nanofertilizer in the agriculture sector given the cost effectiveness is assessed. However, further research is needed to understand the long-term effects of nanomaterials on soil health, plant physiology, and the overall ecosystem.

Conflicts of interest

The authors declare that there is no conflict of interest.

Acknowledgments

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