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Eco-Friendly Carbon Nanodots from Mango Peel Waste Combined with NPK Fertilizer: A Novel Growth Enhancer for Chili (*Capsicum frutescens* L.) Plants

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Abstract

Purpose: This study aimed to develop an eco-fertilizer by integrating carbon nanodots (C-dots) as a growth enhancer with NPK fertilizer for chili plants, evaluated through controlled pot experiments.

Methods: The C-dots, synthesized from mango peel waste via the two-step low heating (TSLH) method yielded a dark brown solution. The C-dots were combined with NPK fertilizer to produce NPK/C-dots composites. The materials were characterized using UV–Vis spectrophotometer, PL spectrometer, FTIR spectrometer, TEM, and SEM. The evaluation was conducted on 25 chili plants under five treatments: well water, pure NPK, pure C-dots, and NPK/C-dots at 100% and 50% concentrations.

Results: UV-Vis analysis revealed absorption peaks at 264 nm and 215 nm for pure C-dots and NPK/C-dots, respectively, with a maximum PL emission at 527 nm. FTIR analysis confirmed the presence of C=C functional groups as the C-dots core. The surface morphology of the C-dots appeared as a continuous wrinkled sheet-like structure. The TEM analysis indicated that the C-dots had an average particle size of 2.6 ± 0.7 nm. Experimental results demonstrated that the 100% NPK/C-dots composite yielded the highest chili productivity of 174.9 g.
Conclusion: These findings highlighted the potential of C-dots as an innovative supplement for enhancing crop yield while supporting sustainable organic waste treatment.

Keywords: C-dots, NPK fertilizer, mango peel waste, chili plant

1 Introduction

Chili (*Capsicum frutescens* L.) is a high-demand agricultural commodity with significant economic and dietary importance. In Indonesia, chili is cultivated in substantial quantities. According to the Central Bureau of Statistics of Indonesia, national production of chili reached approximately 1.57 million metric tons in 2024 [1]. Consequently, optimizing chili cultivation is essential to achieve both high-quality yields and sufficient production volumes. Such optimization requires adequate and balanced nutrient supplementation, particularly nitrogen (N), phosphorus (P), and potassium (K), which are critical for vegetative and reproductive plant development [2]. While conventional NPK fertilizers play a vital role in maintaining the availability of these essential elements [3], they present several drawbacks for both plants and soil ecosystems. Due to their high-water solubility, these conventional fertilizers release nutrients rapidly. Yet, plants typically absorb only 50–60% of applied N and K, and a mere 10–25% of P [4, 5]. This sharp discrepancy between nutrient release rates and plant uptake capacity leads to severe nutrient loss through leaching, runoff, and volatilization, ultimately resulting in low nutrient use efficiency [4].

To address these limitations, the development of advanced growth enhancers is required, encompassing improved photosynthetic efficiency, controlled (slow-release) nutrient delivery, and reduced nutrient loss in soil systems, thereby enhancing nutrient uptake efficiency. One of the most promising candidates as a growth enhancer is carbon nanodots (C-dots), a class of nanomaterials with sizes in the range of 1–10 nm, exhibiting unique physicochemical properties and broad application potential [6]. Notably, C-dots synthesized via green synthesis approaches offer advantages such as low toxicity, tunable surface functionality, and environmental friendliness [7]. Due to these properties, C-dots have been widely applied in various fields, including bioelectronics [8], drug delivery systems [9], and agriculture [10]. In the agricultural sector, C-dots have demonstrated significant potential as photosynthetic enhancers [11], nanofertilizers [12], and nanocarriers [13]. Furthermore, C-dots synthesized from organic precursors provide an environmentally sustainable approach, as their production can simultaneously serve as an effective method for organic waste management.

According to the Ministry of Environment and Forestry of Indonesia [14], organic waste has dominated the national waste composition from 2020 to 2024, largely due to limited public awareness of proper waste management practices. One significant source of organic waste is mango peel, which is often discarded without further utilization. Mango is widely consumed due to its sweet taste and high content of vitamins A, B, and C, and is commonly processed into products such as juices, chips, puddings, and candied fruits [15]. However, only the edible pulp is typically utilized, leaving substantial amounts of peels and seeds as waste. The accumulation of such residues can lead to unpleasant odors, pest attraction, and environmental pollution [16]. Therefore, converting mango peel waste into C-dots represents a promising strategy to support net-zero emission and circular economy principles by minimizing carbon emissions while transforming low-value waste into economically valuable materials.

This study presents a novel approach to synthesizing biomass waste-derived C-dots by combining oven heating and microwave methods to produce a zero-waste NPK/C-dots hybrid fertilizer that synergistically enhances nutrient uptake efficiency and significantly stimulates chili plant growth. Based on these considerations, this study aims to develop a hybrid eco-fertilizer by integrating C-dots with conventional NPK fertilizer (NPK/C-dots composites) as a growth enhancer for chili plants, evaluated through laboratory-scale field experiments. The synthesized C-dots derived from mango peel waste were characterized in terms of their optical properties, functional groups, morphological structure, and elemental distribution using ultraviolet–visible (UV–Vis) spectrophotometry, photoluminescence (PL) spectroscopy, Fourier transform infrared (FTIR) spectroscopy, transmission electron microscope (TEM), and scanning electron microscopy coupled with energy-dispersive X-ray spectroscopy mapping (SEM–EDS mapping).

2 Materials and Methods

The materials utilized in this research consisted of synthesis precursors and agricultural inputs for plant cultivation. The primary carbon precursor for C-dots synthesis was mango peel waste as much as 500 g, specifically using a blended mixture of the *Arumanis* and *Manalagi* cultivars. The biological target for the growth enhancer application consisted of 25 local chili seedlings of *Cakra Putih* cultivar. The cultivation substrate consisted of agricultural soil matrices filled into polybags, which served as the growth medium. As the chili plants progressed through their growth stages, the soil substrate was replaced, and the plants were transplanted into larger pots. For experimental treatment and comparative analysis, liquid NPK fertilizer (*Indofertil* brand) as much as 500 mL was employed both as a positive control and a component in the NPK/C-dots composite formulation. Finally, distilled water (5 L) and well water were utilized as the solvent for C-dots preparation and negative control during routine experimental treatment, respectively.

Fig. 1 illustrates the synthesis process of carbon dots (C-dots) via a two-step low-heating (TSLH) method using mango peel waste as the precursor. First, a total of 800 g of mango peel waste was sun-dried for three days. Following the drying process, the waste was oven-heated at 150 °C for 45 min and subsequently ground

into a fine powder. A 10 g portion of the resulting powder was mixed with 300 mL of distilled water and sonicated for 60 min, after which the mixture was allowed to stand undisturbed for 24 h. Finally, the mixture was filtered, and the obtained filtrate was microwaved until dryness to yield the C-dots powder.

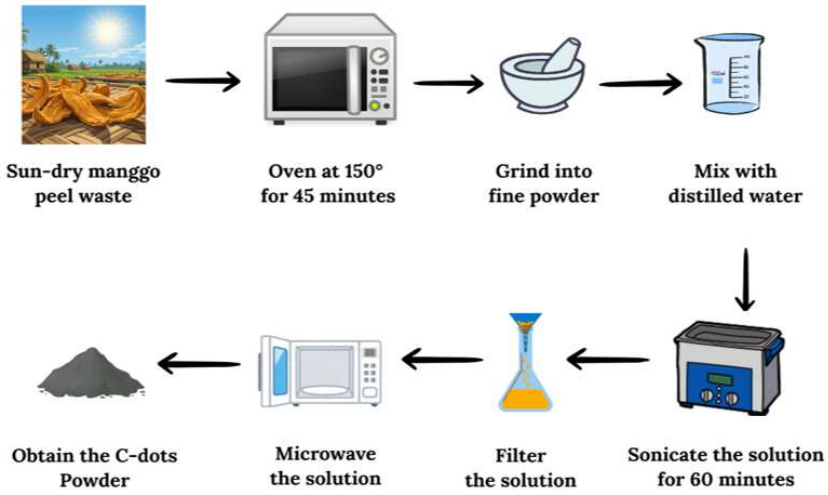
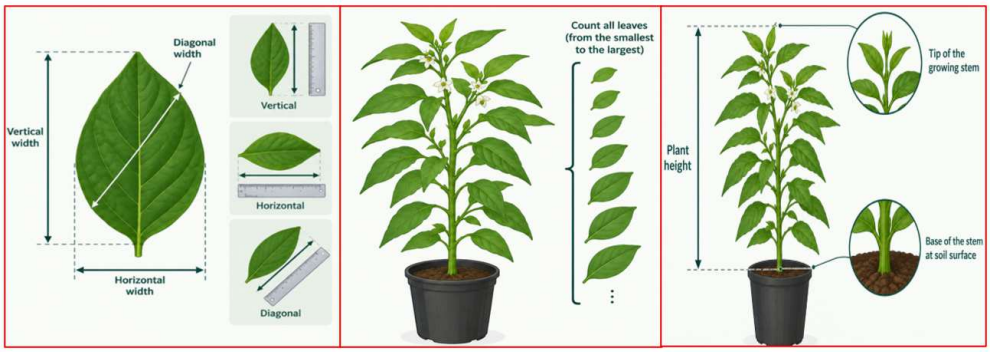


Fig. 1 C-dots preparation using the TSLH method.

The NPK/C-dots composites were prepared as follows. A total of 0.25 g of C-dots powder was dissolved in 50 mL of distilled water to prepare the C-dots based solution, while 10 mL of NPK fertilizer solution was diluted in 1 L of distilled water to prepare the NPK-based solution. The C-dots sample was prepared by diluting the C-dots based solution with 5 L of groundwater. Meanwhile, the NPK fertilizer sample was prepared by diluting 50 mL of the NPK-based solution with 5 L of groundwater. The NPK/C-dots 100% sample was prepared by mixing the C-dots based solution and the NPK-based solution in 5 L of groundwater. The C-dots based solution was then diluted in 50 mL of distilled water to reduce its concentration to 50%, which was subsequently mixed with the NPK-based solution and 5 L of groundwater to obtain the NPK/C-dots 50% sample.

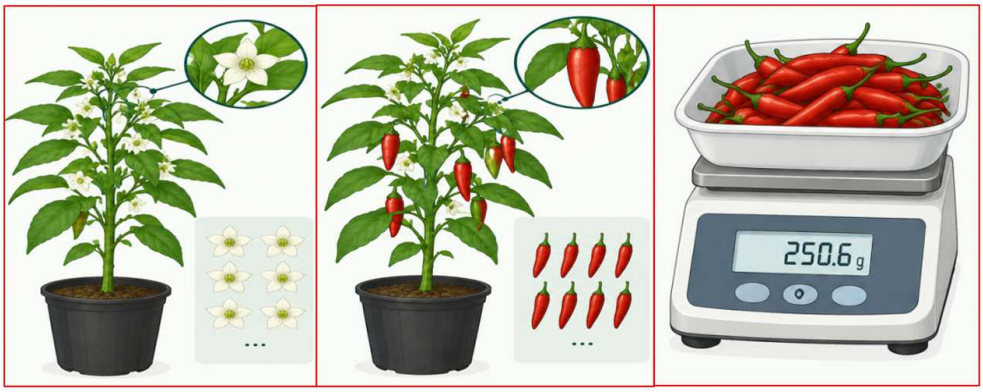
Various characterizations were conducted upon the prepared materials, i.e.: C-dots and NPK/C-dots. The absorption spectra of C-dots and NPK/C-dots were determined via UV-Vis spectrophotometer. The functional groups of C-dots were determined from the transmission spectrum using a FTIR spectrometer. The luminescence of C-dots was determined using PL spectrometer. The surface morphology and particle sizes of C-dots were determined using SEM and TEM, respectively.

Five treatments of plant watering were applied to 25 chili plants (five plants per treatment) using i.e., groundwater, NPK fertilizer, C-dots, NPK/C-dots 100%, and NPK/C-dots 50% samples. Each chili plant was irrigated with 200 mL of the respective sample every two days a week for 12 weeks.



(a) (b) (c)

Fig. 2 Measurements of leaf width (a); number of leaves (b); and plant height (c).



(a) (b) (c)

Fig. 3 Number of flowers (a); number of fruits (b); and weight of fruits (c).

Leaf width, number of leaves, and plant height were measure as indicators of plant growth. Whilst number of flowers, number of fruits, and weight of fruits were measure as harvest yield. Leaf width was measure using a ruler in vertical, horizontal, and diagonal directions [Fig. 2(a)]. The average value of the three datasets was calculated to obtain a single leaf width value. The number of leaves measured includes all leaves that have grown ranging from the smallest to the largest [Fig. 2(b)]. Plant height was measured from the base of the stem at the soil surface to the tip of the growing stem [Fig. 2(c)]. Figures 3(a) and 3(b) show that the number of flowers and fruits was determined by counting all flowers produced and fruits harvested from each chili plant. The total harvested fruit biomass was subsequently measured using a balance to determine the fresh weight of the harvested chili fruits [Fig. 3(c)].

3 Results

The C-dots sample synthesized using the TSLH method exhibited a dark brown, caramel-like appearance [Fig. 4(a)] and could be readily dissolved in distilled water to form a transparent brownish solution [Fig. 4(b)]. Qualitative analysis reveals that the C-dots solution emits green fluorescence when exposed to UV light [Fig. 4(c)]. Quantitatively, this emission is confirmed by photoluminescence (PL) measurements, which show a peak at a wavelength of 527 nm [Fig. 4(d)]. This PL peak corresponds to a bluish-green emission consistent with previous studies confirming the luminescent properties of C-dots [17, 18]. The observed fluorescence emission is attributed to surface defects, which introduce specific energy states within the band gap associated with absorption and emission processes [19]. In the context of C-dots as a growth enhancer, these surface defects can indirectly improve photosynthetic efficiency by enhancing energy transfer processes during photosynthesis [20].

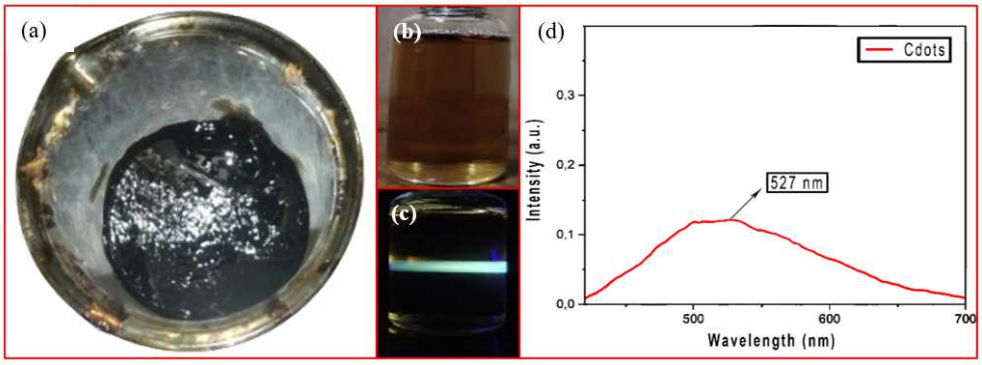


Fig. 4 C-dots caramel (a); C-dots solution (b), luminescence of C-dots (c), and PL spectrum of C-dots (d).

Furthermore, the UV–Vis spectrum of the C-dots exhibits a prominent peak at 264 nm [Fig. 5(a)]. This peak is associated with $\pi \rightarrow \pi^*$ electronic transitions, indicating the presence of C=C functional groups, in agreement with previous reports [21]. Figure 5(b) shows that the band gap energy of the C-dots is approximately 2.8 eV. This light absorption scheme facilitates the ability of C-dots to extend the range of light utilization in plants and promote photosynthesis through energy transfer processes induced by excitation under UV irradiation [3, 22]. On the other hand, the incorporation of C-dots into NPK fertilizer (NPK/C-dots composites) alter their optical properties (compared to pure NPK), as evidenced by a shift toward shorter wavelengths (blueshift) observed in Figs. 5(c) and 5(d) (231 nm to 215 nm). This shift can be attributed to chemical interactions among surface functional groups, which modify the optical characteristics of the NPK/C-dots composites system [23].

Fig. 6 confirms the presence of C=C functional groups in the FTIR spectrum, representing the core structure of the C-dots, along with other functional groups such as

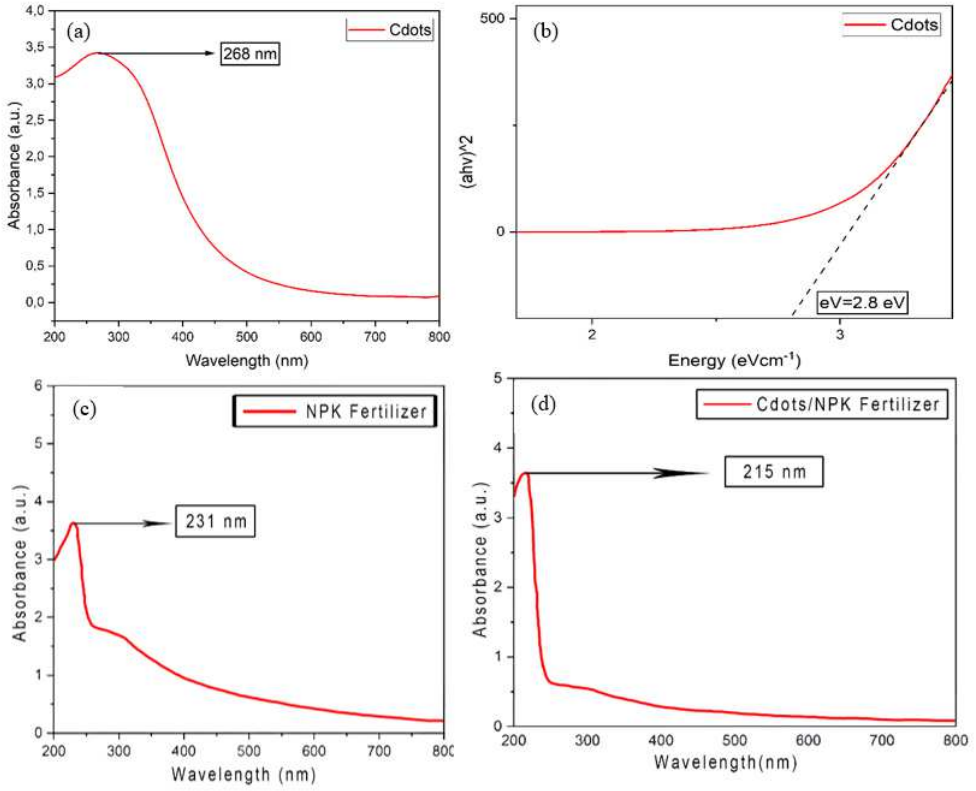


Fig. 5 Absorption spectrum of C-dots (a); band gap energy of C-dots (b); absorption spectrum of NPK fertilizer (c); and absorption spectrum of NPK/C-dots composites (d).

C–O and O–H, which indicate the surface states of the C-dots [24]. The presence of these functional groups suggests that C-dots possess a surface rich in active sites, which is highly relevant to their application as a growth enhancer. Oxygen-containing functional groups play a crucial role as active sites for binding, adsorbing, and gradually releasing nutrients (slow-release mechanism), thereby enhancing fertilization efficiency and reducing nutrient loss due to leaching or volatilization [3, 25].

Fig. 7(a) shows the surface morphology of the C-dots, which appears as a continuous wrinkled sheet-like structure. Furthermore, TEM analysis reveals that the C-dots are spherical dots or spots [Fig. 7(b)] with an average particle diameter of 2.6 $\pm$ 0.7 nm [Fig. 7(c)]. This discrepancy between SEM and TEM images arises from differences in sample conditions during measurement and resolution limitations. In the SEM characterization, the use of dried samples causes ultra-small particles to undergo agglomeration and self-assembly due to interactions among surface functional groups (such as –OH and –COOH). Consequently, with relatively lower resolution, the observed morphology appears as continuous wrinkled sheets [26]. Moreover, biomass-based synthesis involving partial carbonization can lead to the formation

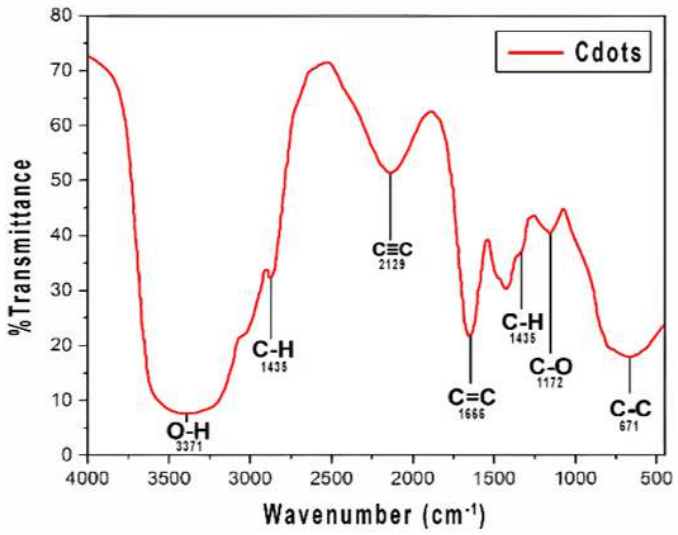


Fig. 6 IR spectrum of C-dots.

of intermediate phases, such as amorphous carbon networks or polymer-like carbon structures that are not fully carbonized, which further contribute to the sheet-like morphology observed in the SEM image [27]. Originating from organic precursors, the inherently spherical structure and ultra-small particle size of the C-dots facilitate more effective and efficient nutrient delivery in plants when functioning as nanocarriers [3, 28–30]. Therefore, these characteristics strongly support the role of C-dots as a growth enhancer in chili plants by maximizing the effectiveness of NPK fertilizers.

The comparative evaluation across Figs. 8(a), 8(b), and 8(c) indicates that different fertilizer treatments exhibit distinct levels of chili plants growth depending on the observed growth parameters. In term of plant height in Fig. 8(a), the NPK/C-dots 100% growth enhancer produces the highest plant height, followed closely by C-dots, both outperforming conventional NPK. For leaf width in Fig. 8(b), C-dots emerges as the most effective treatment, with NPK/C-dots 100% showing comparable performance, while NPK exhibits the lowest leaf width, even below well water treatment. Meanwhile, the analysis of leaf number in Fig. 8(c) reveals that NPK initially promotes a rapid increase in leaf number up to week 8 but then significantly declines toward the harvest period. In contrast, C-dots and NPK/C-dots treatments show more stable and consistent number of leaves, indicating better long-term plant growth.

The superior performance of C-dots and NPK/C-dots treatments can be attributed to their ability to enhance nutrient use efficiency, regulate plant physiological processes, and improve soil plant interactions. Carbon-based nanomaterials, particularly C-dots, have been widely reported to enhance photosynthetic activity, chlorophyll content, and nutrient uptake, thereby promoting plant growth and biomass accumulation [3, 31]. These nanomaterials can also regulate phytohormonal signaling and improve plant stress tolerance, which contributes to enhanced cell division and elongation associated with increased plant height and leaf expansion [25, 32]. In addition,

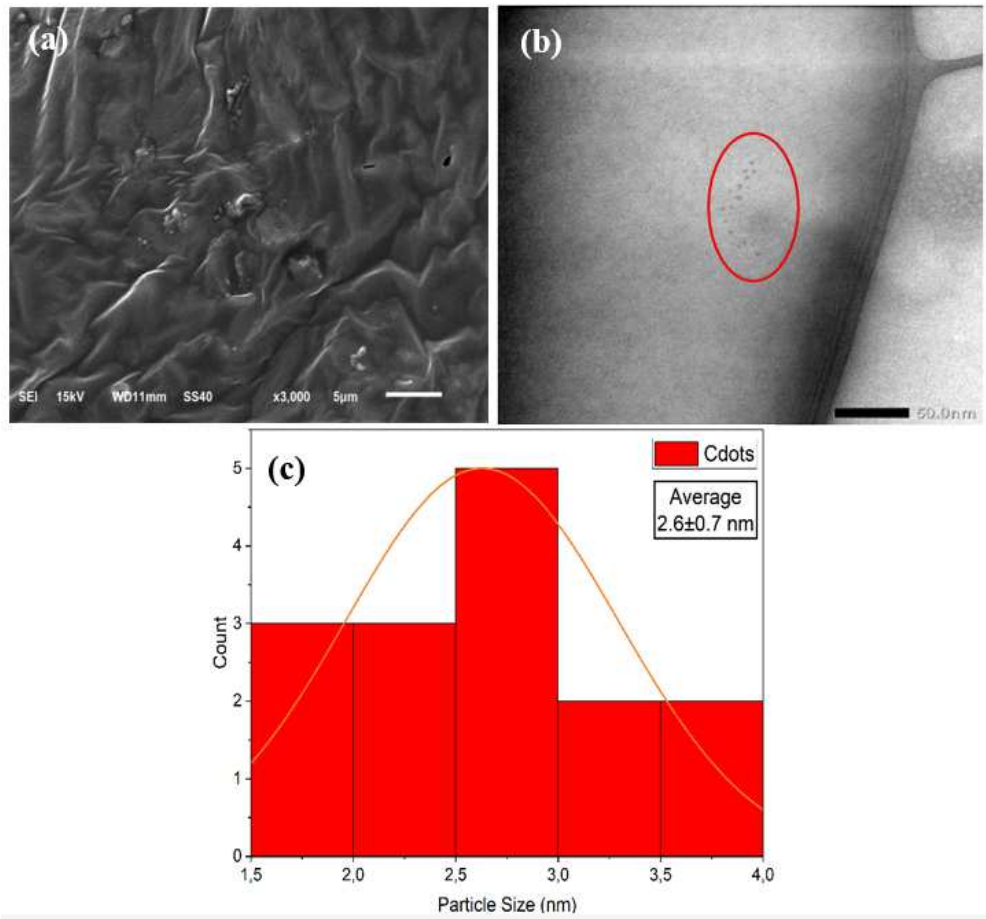


Fig. 7 SEM image of C-dots (a); TEM image of C-dots (b); and particle size distribution of C-dots (c).

C-dots have been shown to improve soil health and plant resilience under environmental stress, supporting more stable plant development [33]. In contrast, the reduced effectiveness of NPK over time is associated with low nutrient use efficiency and losses due to leaching, particularly N and P, which are highly mobile in soil systems and easily lost under irrigation or rainfall conditions [3]. The absence of organic or nanostructured supplements further exacerbates nutrient loss and limits long-term soil fertility, ultimately reducing sustainable plant growth.

Fig. 9(a) shows that the NPK/C-dots 50% treatment achieves the highest total number of flowers, followed by NPK/C-dots 100%, while NPK performs better than pure C-dots. In Fig. 9(b), which illustrates the number of fruits during the harvest period (weeks 7 to 11), the NPK/C-dots 100% treatment yields the highest fruit count, followed by NPK/C-dots 50%, NPK, and C-dots, respectively. These

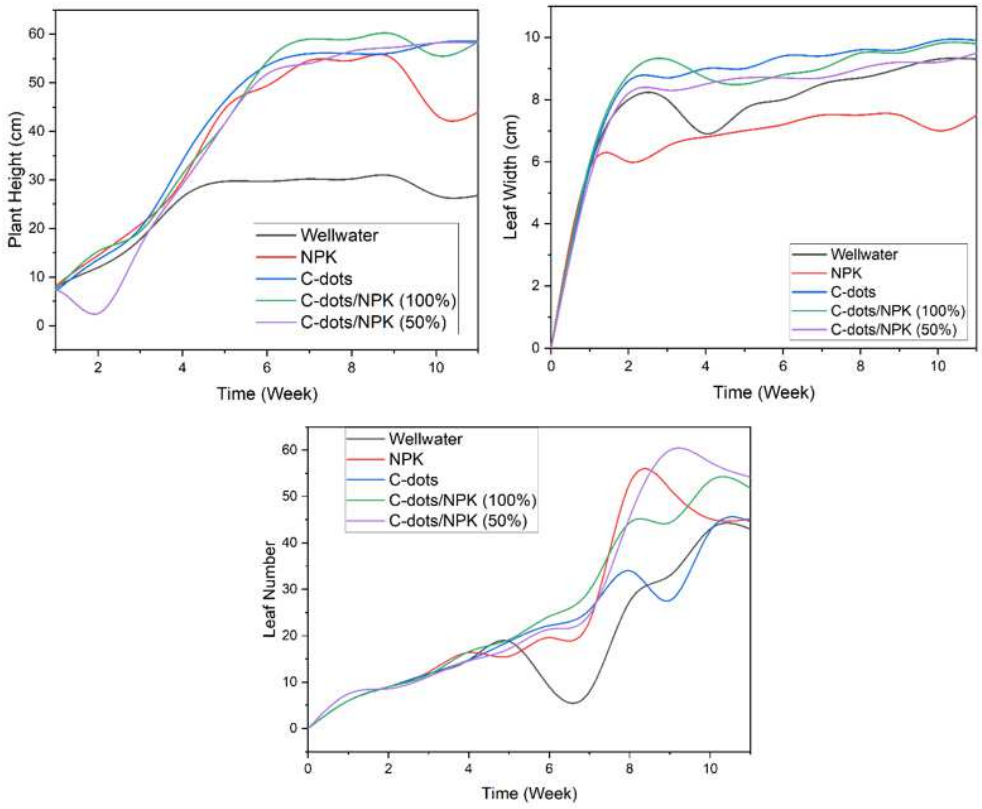


Fig. 8 Comparison of plant height (a); leaf width(b); and number of leaf (c) of chili plant samples.

results indicate that the NPK/C-dots fertilizers provide a significant enhancement in reproductive performance compared to the pure C-dots and NPK. The superior performance of NPK/C-dots treatments during the flowering and fruiting stages can be explained by the synergistic interaction between nanomaterials and conventional nutrients, which enhances nutrient availability and plant physiological efficiency during the reproductive phase. Nanomaterials have been reported to improve nutrient uptake efficiency, stimulate photosynthetic activity, and regulate phytohormonal signalling such as auxin and gibberellin, which are essential for flower initiation and fruit development [34, 35]. Furthermore, nanomaterials can function as nano-carriers that enable controlled nutrient release, thereby maintaining nutrient availability during critical stages such as flowering and fruiting [36]. In contrast, conventional fertilization systems often exhibit lower nutrient use efficiency due to nutrient losses, limiting reproductive performance [37]. Therefore, the integration of C-dots into NPK enhances both nutrient efficiency and physiological regulation, resulting in improved flower formation and fruit yield.

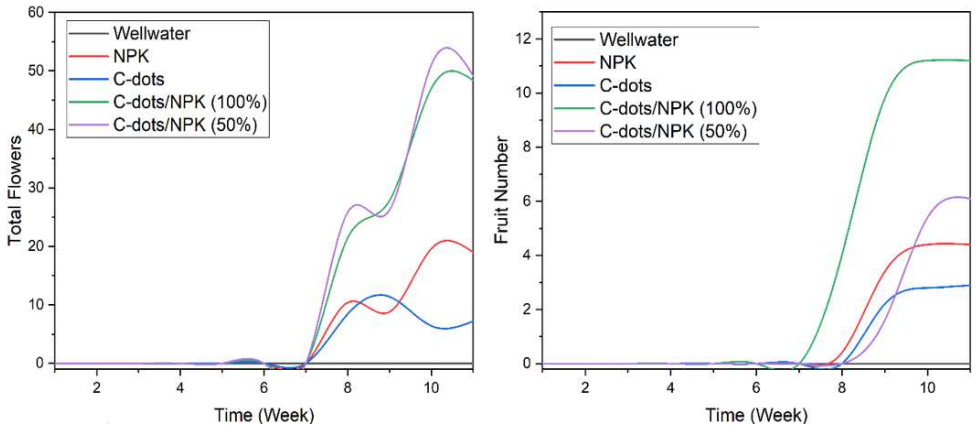


Fig. 9 Comparison of total flowers (a) and chilies (b).

Fig. 10 presents the harvest yield of the chili plants. It may be observed that the NPK/C-dots 100% produces the highest chili plant yield, followed by the NPK/C-dots 50%. This demonstrates that the NPK/C-dots composites give a much greater effect in enhancing chili plant productivity compared to pure C-dots and NPK. Moreover, it may also be observed that the pure C-dots gives a slightly better yield than the NPK fertilizer. C-dots are capable of enhancing the uptake of essential nutrients such as Fe, Ca, Mg, and K by binding these ions and facilitating their translocation into plant tissues, while also improving photosynthetic efficiency through increased stomatal conductance, chlorophyll content, and photosystem II (PSII) activity. This combination of enhanced nutrient uptake and improved photosynthesis promotes biomass accumulation and accelerates vegetative growth [29, 38]. In addition, C-dots can improve fertilization efficiency and nutrient uptake due to their extremely small size and large surface area, enabling them to function as nanocarriers. As nanocarriers, C-dots are able to adsorb nutrient ions (e.g., N and P) and release them gradually (slow-release), thereby reducing leaching (nutrient loss from soil due to chemical fertilizer application) and prolonging nutrient availability in the soil [39, 40]. C-dots also reduce plant stress caused by environmental conditions (such as drought, salinity, heat, and nutrient deficiency) by enhancing antioxidant enzyme activity and strengthening physiological defense mechanisms as well as water retention capacity [28, 41]. This allows photosynthesis, nutrient uptake, and plant metabolism to remain optimal, thereby increasing plant productivity even under less favorable environmental conditions.

C-dots have demonstrated their potential through superior and stable growth performance, contributing to enhanced photosynthesis and improved tolerance to environmental stress [42]. Moreover, their role as nanocarriers in mitigating the leaching effect associated with chemical NPK fertilizers further highlights their advantage in preventing soil contamination and reducing the greenhouse effects typically associated with conventional NPK fertilizers. Hence, C-dots show strong potential to reduce

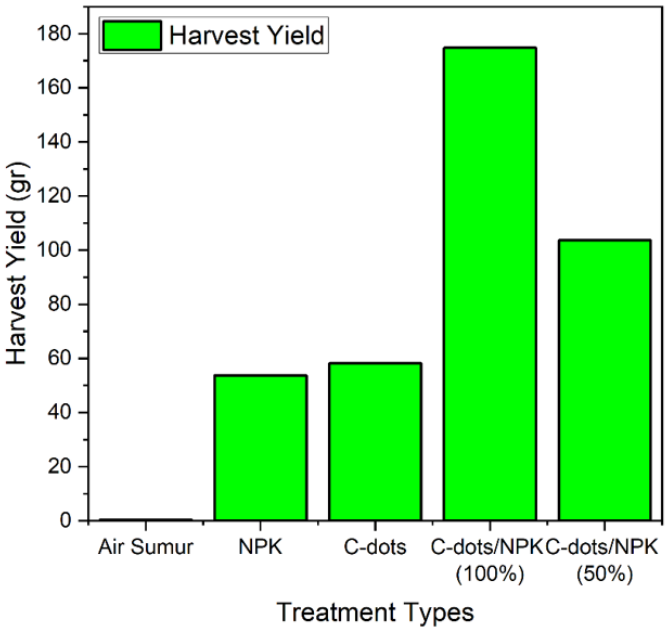


Fig. 10 Harvest yield of chili plants.

the negative impacts of NPK fertilizers, such as leaching effects, soil contamination, greenhouse effects, and poor tolerance to adverse environmental conditions.

4 Conclusion

This study successfully demonstrates the synthesis of C-dots from mango peel waste using the TSLH method and their application as a growth enhancer in a hybrid eco-fertilizer system with conventional NPK. The synthesized C-dots exhibit desirable optical, structural, and surface characteristics, including strong PL, the presence of active functional groups (C=C, C–O, and O–H), and nanoscale size, which collectively support their role as nanocarriers and photosynthetic enhancers. The integration of C-dots with NPK fertilizer significantly improves nutrient use efficiency and plant physiological performances, where the NPK/C-dots composites particularly at 100% concentration produce the highest chili yield, outperforming both pure NPK and C-dots treatments. This enhancement is attributed to synergistic effects, including improved light absorption, enhanced photosynthetic activity, controlled nutrient release, and reduced nutrient loss through leaching and volatilization. Furthermore, C-dots contribute to more stable reproductive growth, as reflected in consistent plant height, leaf width, number of flowers, and number of fruit production. Their abilities to enhance nutrient uptake, regulate physiological processes, and improve plant resilience under environmental stress highlight their potential as a multifunctional agricultural nanomaterial. Overall, these findings confirm that mango peel-derived C-dots combined with NPK represent an effective and sustainable supplement, enhancing chili

productivity while supporting environmentally friendly agricultural practices through waste valorization and reduced negative impacts of chemical fertilization.

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Declarations

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- **Conflict of interest**
  The authors have no relevant financial or non-financial interests to disclose.
- **Ethics approval and consent to participate**
  Not applicable.
- **Consent for publication**
  Not applicable.
- **Data availability**
  All data supporting the findings of this study are available upon request to the corresponding author.
- **Author contribution**
  W.S.B.D. started the conception, design of the work, and supervising the project. M.W. and A.A conducted the data acquisition and data analysis (methodology). L.E.I. and H.P.P. conducted the data interpretation. M.W. and A.A drafted the manuscript. L.E.I, H.P.P., and W.S.B.D revised the manuscript. All authors approved the final draft to be submitted.

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