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The covering of the bunch tail by the polymer nanocomposite mitigates date bunch drying and wilting disorders and enhances fruit quality

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Date bunch drying and wilting disorder (DBDWD) manifests in the development stage of date fruits from the Kharak to the Rutab of development, coinciding with the occurrence of hot and dry winds. This phenomenon presents a significant and detrimental challenge for producers, resulting in substantial economic losses. The present study aimed to reduce this disorder in a randomized complete block design involving 10-year-old date palms (cv. Mazafati). The bunch tails of the palms were covered by the nanocomposite formulation of g-C_3N_4/ZnO/PVA (where g-C_3N_4 denotes graphitic carbon nitride, ZnO refers to zinc oxide nanoparticles, and PVA represents polyvinyl alcohol) at two different concentrations (100 and 200 ppm) of ZnO nanoparticles at the early Kharak or Khalal stage of fruit development. The findings indicated that the covering of bunch tail with the g-C_3N_4/ZnO/PVA nanocomposite resulted in a significant reduction in DBDWD and an enhancement in both fruit quality and bunch yield. Specifically, g-C_3N_4/ZnO/PVA nanocomposite at concentrations of 100 and 200 ppm of ZnO nanoparticles led to reductions in DBDWD of 35 and 88%, respectively, along with increases in flavonoid content of 27 and 29% compared to the control group. Additionally, the covering of bunch tail with the g-C_3N_4/ZnO/PVA also resulted in a significant increase in both bunch yield and fruit phenolic content, as well as improvements in fruit weight, length, pulp weight, and the pulp-to-pit ratio relative to the control group. Consequently, the covering of bunch tail with the g-C_3N_4/ZnO/PVA effectively mitigates DBDWD while enhancing yield and fruit quality.

Keywords Percentage date bunch drying disorder, Date fruit quality, Nanotechnology, Yield

Abiotic stress significantly threatens global agricultural productivity and food security, especially under climate change. The date palm (*Phoenix dactylifera* L.), in arid and semi-arid regions, faces increasing challenges from climatic shifts, particularly in areas like Jiroft, Iran, where rising temperatures, hot and dry wind and water scarcity adversely effect on sensitive cultivar to date bunch drying disorder (DBDWD) such as 'Mazafati'[1,2]. According to the previous research[2–4] a reduction in fruit yield and quality, manifested as date palm bunch drying and wilting disorder (DBDWD), occurs due to extreme heat and low humidity levels. According to the report of Panahi and Damankshan[2], this disorder that takes place during the transition from Kharak to Rutab stages, annually results in the substantial loss of a notable proportion of the nation's date crop.

Heat stress can disrupt metabolic processes and increase oxidative stress, and finally lead to cellular damage[5,6]. Panahi et al., (2023) stated nutrient deficiencies, particularly in calcium and zinc, further exacerbate these issues, highlighting the need for improved management practices[2]. Research by Sattar et al., (2022) showed that foliar application of micronutrient applications, such as zinc, can increase plant resistance to drought stress[7]. Graphitic carbon nitride nanosheets (g-C_3N_4) have recently attracted considerable attention due to their exceptional stability, biodegradability, low cost, remarkable antibacterial properties, unique structure, and excellent catalytic properties. More importantly, g-C_3N_4 nanosheets absorb ultraviolet light and can emit blue fluorescence that overlaps with the absorption spectrum of chloroplasts. Composed solely of carbon and nitrogen, g-C_3N_4 can be easily synthesized using low-cost, nitrogen-rich compounds such as urea and melamine through thermal

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condensation[8–10]. Additionally, the incorporation of g-C_3N_4 in the polymer nanocomposite (g-C_3N_4/ZnO/PVA) plays a pivotal role in reducing drought stress and wilting disorder in date palm bunches. According to Wang et al., (2021), g-C_3N_4 enhances plant resilience by stabilizing photosynthetic mechanisms, mitigating membrane damage, and improving thermo tolerance under stress conditions. These properties contribute to preserving fruit quality and reducing water loss[11]. Polyvinyl Alcohol (PVA) hydrogels as soft contact lens material are used in the medical industry, particularly in the coating of oral drugs, including capsules[12]. PVA is chosen for its high elasticity, which allows it to form a protective and potentially controlled-release coating around drug particles, including nanoparticles. Its properties also enable it to encapsulate combined nanoparticles effectively. Given the increasing impact of climate-related stressors, it is crucial to develop sustainable agricultural practices that improve the nutritional status of the date palm. This study focuses on reduce DBDWD in Mazafati cultivar by covering of bunch tail with zinc oxide nanoparticles (ZnO NPs), as the polymer nanocomposite of graphitic carbon nitride (g-C_3N_4) embedded in polyvinyl alcohol (PVA) by covering on the bunch tail, as a sun protection coating to protect against sunburn of the bunch against damage from abiotic stresses such as intense sunlight, which is more severely observed in the form of sunburn at the onset of the visible symptoms of the drying condition on the bunch, especially on the border of the orchards.

Materials and methods

Plant material and experimental setup

This research, selected twelve healthy, 10-year-old 'Mazafati' date palms, with uniformity in size, vigor, and productivity that were irrigated using a drip irrigation system, and were grown in clay soil with a spacing of 5 × 5 m, situated in Anbar Abad, near Jiroft area, Kerman province, Iran in 2023. The orchard is located at an elevation of 600 m (GPS coordinates: 28°28'42"N, 57°50'29"E). This area faces low relative humidity, high wind speed and, with hot temperatures annually, and occasionally faces rainfall before harvesting the crop. Figure 1 shows meteorological data for the studied area including, monthly measurements of maximum temperature, relative humidity, wind speed, and rainfall which were recorded for the spring and summer of 2023.

We covered the bunch tail with a brush impregnated with the polymer nanocomposite consisting of graphitic carbon nitride (g-C_3N_4), polyvinyl alcohol (PVA), and zinc oxide nanoparticles (ZnO NPs) at concentrations of 100 and 200 ppm. The control group remained untreated. Also, emulsifying oil was used as a solvent base to increase the adhesion and durability of the composite on the bunch tail. The control group remained untreated. Before preparing this polymer nanocomposite, to find the best composite, we examined different concentrations of ZnO and PVA nanoparticles in the composite on the thick epidermis layer of the date palm bunch tail, observed it under a microscope, and selected a composite that reflects light well and whose polymer creates a uniform layer on the epidermis.

Instruments and measurements

A transmission electron microscope (TEM) model EM208S (PHILIPS) with an accelerating voltage of 100 kV, a tungsten filament electron beam source, and a digital imaging system was utilized. The crystallinity of the

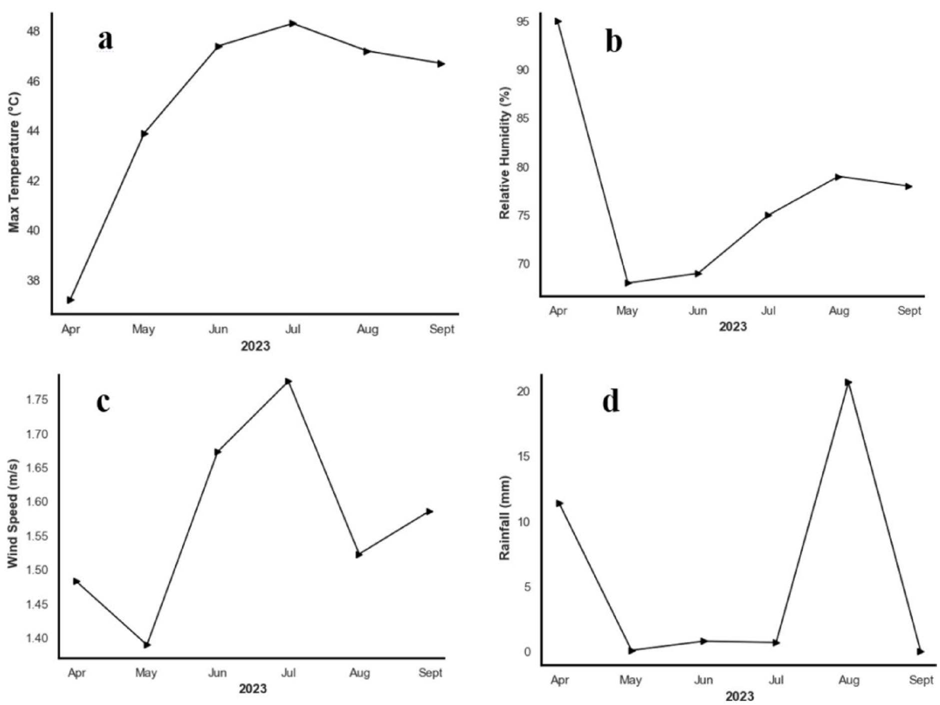

Fig. 1. Maximum temperature (**a**), relative humidity (**b**), wind speed (**c**), and monthly rainfall (**d**) from April to September 2023 at the Weather Station in Anbar Abad, Kerman province, Iran.

synthesized nanoparticles was verified using X-ray powder diffraction (XRD) analysis. The analyses were carried out on a Rigaku MiniFlex 600 XRD machine, which operates using Cu-Kα1 radiation with a wavelength of 1.54056 Å. Fourier transform infrared spectra (FT-IR) were taken with the Shimadzu model IRSpirit-TX spectrometer in the range of 4000 to 400 cm^{-1}. Melamine, Zinc acetate dihydrate (Zn (CH3CO2)2·2H2O), Polyvinyl alcohol (PVA, 75000 Da), Ethanol, and Urea CO $(NH_2)_2$ were obtained from Merck Company (Darmstadt, Germany). All the chemicals have high purity, and ultra-pure water was used during the synthesis processes.

Synthesis of layer g-C_3N_4
5.0 g of melamine was calcinated (heating rate: 5 °C/min) at 550 °C for 3 h in a tube furnace in nitrogen. Afterward, the resulting bulk g-C_3N_4 was ground into powder in a mortar.

Synthesis of g-C_3N_4/ZnO/PVA nanocomposite
Zinc oxide nanoparticles were synthesized using hydrothermal methods, with zinc acetate dihydrate as the zinc source. Lithium hydroxide and distilled water supplied the necessary oxygen, initially forming hydroxides that were later converted into zinc oxide. A polymer composite was created with a 1:1:1 ratio of polyvinyl alcohol (PVA, 75000 Da) to graphitic carbon nitride (g-C_3N_4) and zinc oxide nanoparticles, synthesized at 100 and 200 ppm concentrations. A schematic illustrating the formation of PVA functionalized with g-C_3N_4 and zinc oxide nanoparticles (g-C_3N_4/ZnO/PVA) is presented in Fig. 2.

Measurements of studied parameters
Bunch yield
For the measurement of bunch yield, the average yield of four bunches per palm tree, was recorded at the time of harvest. The average yield of four bunches per palm tree, was recorded as bunch yield.

Percentage of date bunch drying and wilting disorder
The total number of bunches on a palm tree, as well as it's dried and wilted bunches, were counted separately, and the percentage of date bunch drying and wilting disorder (DBDWD) was calculated for each palm tree.

Pomological assessments
For pomological and biochemical assessments, fifty fruits in the 'Rutab' stage of development were randomly selected from each replication. Measurements were taken for fruit and pit weight, diameter, length, pulp weight, and the pulp-to-pit ratio for twenty fruits in each replication.

Quantitative fruit parameters
Twenty fruits were utilized to prepare a uniform sample for evaluating chemical characteristics[13]. Various quantitative fruit parameters, including total soluble solids (TSS), pH, and vitamin C content, were assessed following

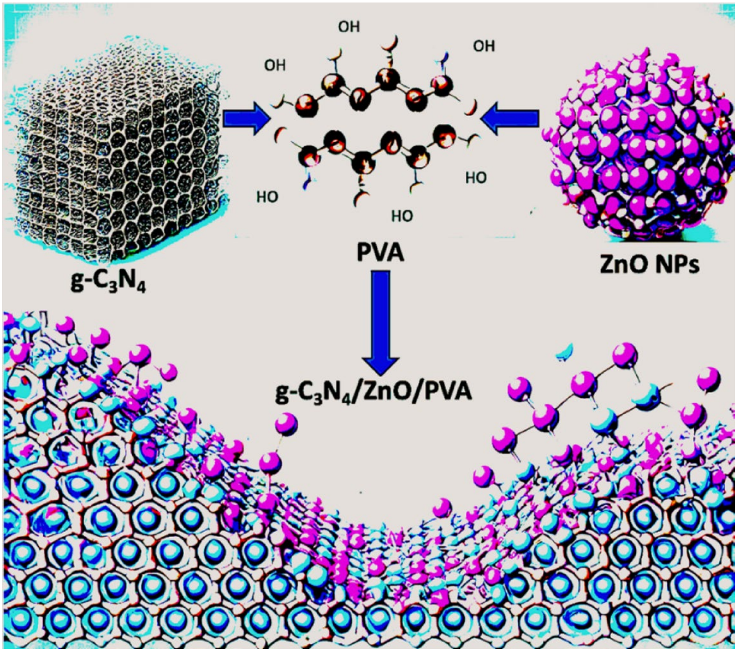

Fig. 2. Schematic illustration of the synthesis method of g-C_3N_4/ZnO/PVA nanocomposite.

Biochemical assessments
Total phenol content was determined using Waterhouse's method[15], flavonoid levels were measured via a modified method by Chang et al.[16], and anthocyanin concentration was measured according to the technique described by Lindoo and Caldwell[17].

Statistical analysis
There were three replicates in this fully randomized block design experiment. To calculate mean squares and experimental errors to identify differences between datasets, Duncan's test was run using SAS software (v. 9.4). The LSD test was utilized to determine differences between means at a significance threshold of $P<0.05$, with SAS software (v. 9.4). Data comparison graphs were drawn with Excel software and meteorological graphs were drawn with Python software.

Results and discussion
FTIR analysis
Chemical characterizations by using attenuated total reflectance Fourier transform infrared spectroscopy confirmed the successful fabrication of the g-C_3N_4/ZnO/PVA nanocomposite (Fig. 3). The FT-IR spectra of g-C_3N_4/ZnO/PVA, ZnO, and g-C_3N_4 were measured cautiously to assign their characteristic vibrational modes. In the spectrum of g-C_3N_4, strong peaks could be seen at 1337, 1454, 1587, and 1650 cm^{-1}. These peaks correspond to the stretching vibrations of the C-N heterocycles, such as C-NH-C and C-N (-C)-C bonds, and hence are in good agreement with the structure of g-C_3N_4. In composite g-C_3N_4/ZnO/PVA, a broad absorption band was observed in the region 3300–3500 cm^{-1} due to the O-H stretching vibrations of the PVA polymer. The peaks in the area of 2970–2949 cm^{-1} can be assigned to the asymmetric stretching vibrations of CH_2 groups, confirming the presence of PVA. A sharp peak at 1742 cm^{-1} indicated the presence of carbonyl (C = O) groups. The strong peak at 470 cm^{-1} was attributed to the formation of Zn-O bonds, representing the successful incorporation of ZnO into the nanocomposite structure.

XRD analysis
X-ray diffraction (XRD) analysis was performed to identify the crystallinity as well as the crystalline phases of the photocatalysts synthesized. In the case of g-C_3N_4, two distinct peaks were observed: a small peak at 13.1° and a peak with high intensity at 27.3° (Fig. 4). The peak at 13.1° is attributed to the in-plane structural packing motif of tri-*s*- triazine repeating units, and the strong peak at 27.3°, which is indexed as the (002) reflection, is attributed to interlayer stacking of conjugated aromatic systems. Such a peak is consistent with the hexagonal phase of g-C_3N_4, typical of its graphite-like layered structure. For ZnO, the diffraction pattern exhibited prominent reflections at 32.8°, 35.1°, 37.05°, 48.2°, 57.1°, 63.3°, and 68.2°, which were assigned to the (100), (002), (101), (102), (110), (103), and (112) crystallographic planes, respectively, consistent with the hexagonal wurtzite structure of ZnO (JCPDS No. 36-1451). In the XRD pattern of g-C_3N_4/ZnO/PVA nanocomposite, PVA characteristic peak at 19.8° (due to its semicrystalline d-spacing) was detected along with g-C_3N_4 characteristic peaks (13.1° and 27.3°) and ZnO. Reflections of ZnO in the composite were indexed to (010), (002), (011), (012), (110), (013), (020), (112), and (021) planes, showing its retention of the crystalline structure. Interestingly, the decreased intensity of the PVA and g-C_3N_4 peaks in the composite indicates structural incorporation, as PVA polymer chains become intercalated in the layered matrix of g-C_3N_4. On the other hand, the presence

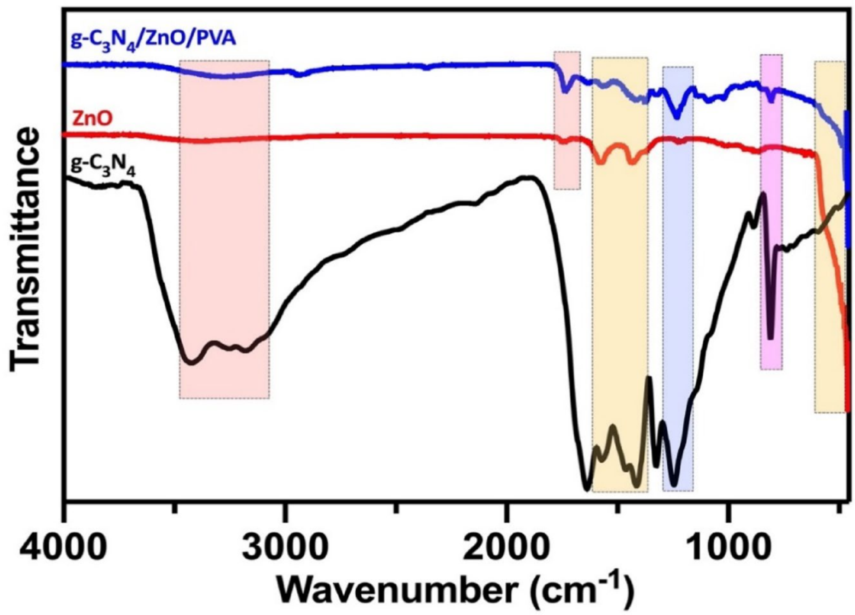

Fig. 3. FTIR spectra of synthesized g-C_3N_4 and ZnO and the nanocomposite of g-C_3N_4/ZnO/PVA.

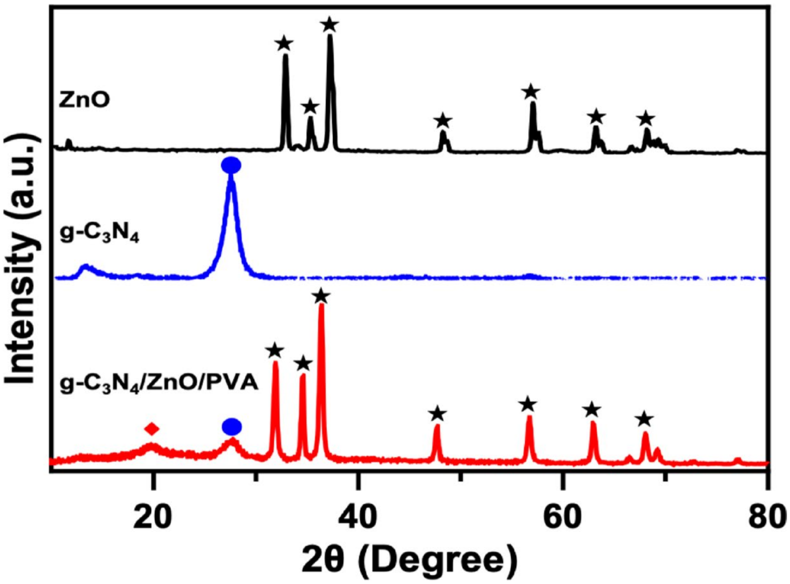

Fig. 4. XRD pattern of synthesized ZnO, g-C_3N_4, and the nanocomposite of g-C_3N_4/ZnO/PVA.

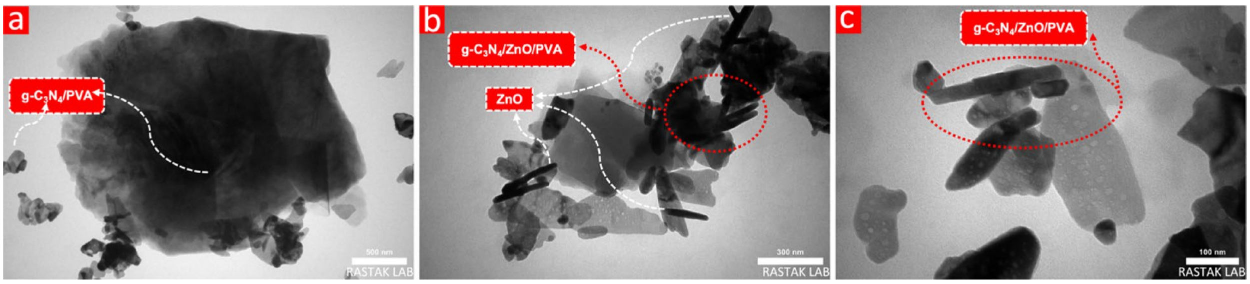

Fig. 5. Morphology characterizations of g-C_3N_4/ZnO/PVA nanocomposite, (**a**-**c**) Different magnifications of TEM images of g-C_3N_4/ZnO/PVA.

of well-resolved ZnO peaks attests to the development of ordered crystalline phases. This sort of combination of structural aspects—damped polymer crystallinity, retained ZnO crystallinity, and interlayer interactions—attests to the successful development of the g-C_3N_4/ZnO/PVA nanocomposite film.

TEM study

The morphology and particle size of the prepared catalyst were further evaluated using TEM technology. The TEM images indicate that the synthesized ZnO/PVA is loaded onto the g-C_3N_4 nanosheet surface, with the g-C_3N_4 nanosheets exhibiting a transparent surface that reflects their few-layer nature (Fig. 5a–c). The images, obtained under different magnifications (500, 300, and 100 nm), show well-defined boundaries and edges of the g-C_3N_4 nanosheet within the rod-shaped structure of the ZnO nanoparticles, indicating high crystallinity and the development of a heterogeneous structure. Notably, the highly expansive g-C_3N_4 surface acted as an effective host matrix for the ZnO/PVA nanoparticles.

Appearance symptoms

According to our observation, this disorder manifests as a brown band situated in the central arch of the fruit bunch's tail with sunburn symptom (Fig. 6A-a). It primarily appears on the upper surface, with occasional occurrence on the underside. The affected region, characterized by reduced moisture content relative to adjacent tissues, develops a slight depression. This disorder that takes place during the transition from Kharak to Rutab stages (Fig. 6A-a, and B-a). The fruits on the bunches whose tail arch is damaged are normal in the early stages, while after a short time of appearing DBDWD symptoms on the tail arch, the fruits lose water and wilt (Fig. 6A-b). Finally, completely dried bunch tail, strands, fruits, and total bunch (Fig. 6C-b) that is famous for date bunch drying and wilting disorder (DBDWD). As can be seen (Fig. 6A c-d), contrary to popular belief, this disorder was not observed in bunches where the fracture was along the axis of the bunch tail. Although all bunches on a tree experience the same environmental conditions, for unknown reasons, only some bunches develop DBDWD while others remain healthy (Fig. 6A-d).

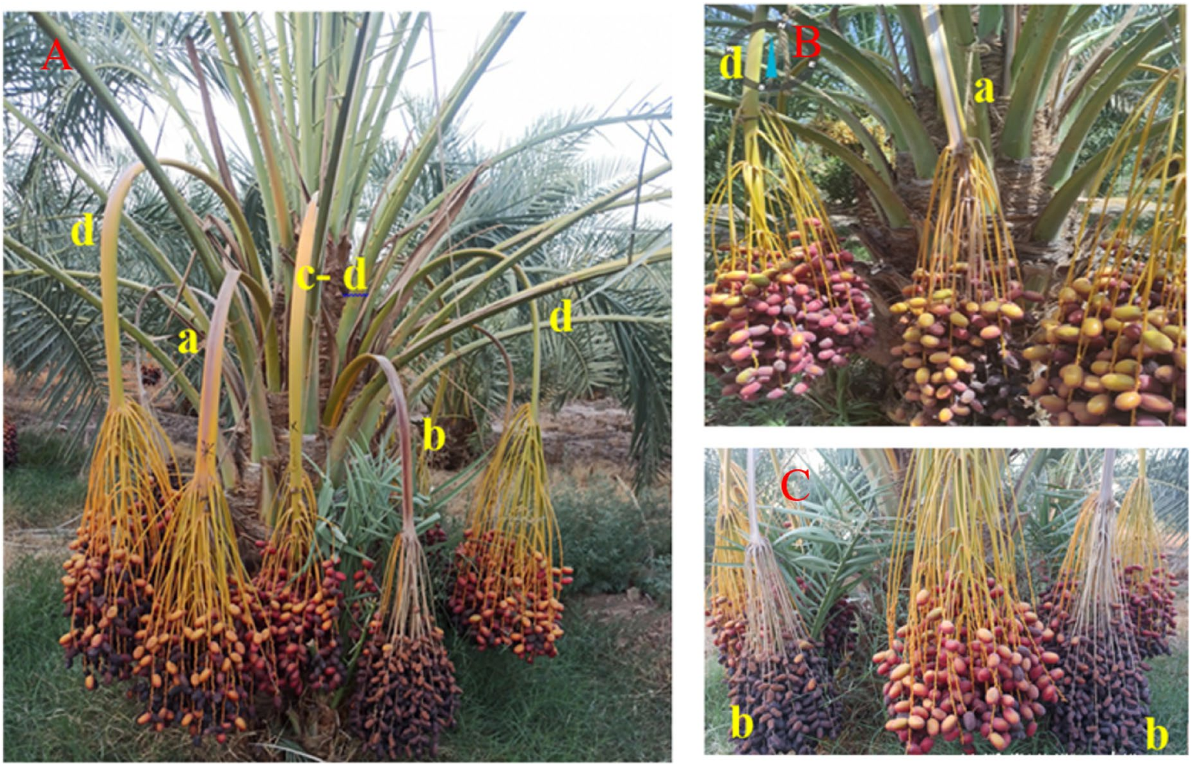

Fig. 6. Starting of date bunch drying and wilting disorder (DBDWD) in Mazafati cultivar that appears as sunburn in the central arch of the fruit bunch's tail (**a**) at ending the fruits progressively wilting and desiccate during the transition from Kharak to Rutab stages, rendering these fruits unfit for consumption (**b**), the axis of the brunch is broken but not affected by the DBDWD (**c**), the bunches with healthy fruit (**d**) (Photo of the authors).

Fruit quantitative parameters

Our findings indicated that the nanocomposite of g-C_3N_4/ZnO/PVA influenced several quantitative parameters of date fruit, including fruit weight, pulp weight, and the ratio of pulp to pit weight, and pit weight. However, it did not significantly affect pit weight, fruit diameter, or pit diameter. Specifically, the composite containing 200 ppm of ZnO nanoparticles enhanced fruit weight by 83%, pulp weight by 96%, the pulp-to-pit weight ratio by 73%, and fruit length by 20%, while simultaneously reducing pit weight by 10% in comparison to the control group. It is noteworthy that plant responses to heat stress are influenced by various factors, including temperature, duration, and plant species (Fig. 7a-d).

Bunch yield

According to Fig. 7 (e), the nanocomposite of g-C_3N_4/ZnO/PVA at a concentration of 200 ppm increased the bunch yield by 23% compared to the control group. Heat stress elevates transpiration rates, causing dehydration and a decline in the relative water content of plants. Consequently, this stress results in water loss and wilting in plants.

Date bunch drying and wilting disorder (DBDWD) percentage

According to our results (Fig. 7f), with an increase in ZnO NPs concentration in the polymer nanocomposite, the percentage of DBDWD significantly decreased compared to the control group. The highest percentage of DBDWD was observed in the control group, and the treatment of the bunch's axis with the polymer nanocomposite of g-C_3N_4/ZnO/PVA at concentrations of 100 and 200 ppm of ZnO reduced the percentage of DBDWD by 35 and 88%, respectively, compared to the control group (Fig. 7f). Therefore, it can be said that the treatment of the bunch axis with the polymer nanocomposite of g-C_3N_4/ZnO/PVA with increasing zinc oxide concentration has significantly reduced the date bunch drying disorder.

Fruit qualitative parameters

According to our result the polymer nanocomposite of g-C_3N_4/ZnO/PVA in the different concentrations of ZnO NPs hadn't significant effect on some quantitative parameters of date fruit such as pH, total soluble solid (TSS), and Vitamin C (Table 1) while effected total phenol, flavonoids and anthocyanins (Fig. 8). Covering the bunch tail with g-C_3N_4/ZnO/PVA (100 ppm of ZnO NPs) increased total phenol content by 23% (Fig. 8a). Treatments g-C_3N_4/ZnO/PVA at concentrations of 100 and 200 ppm of ZnO NPs, increased flavonoid content by 27 and

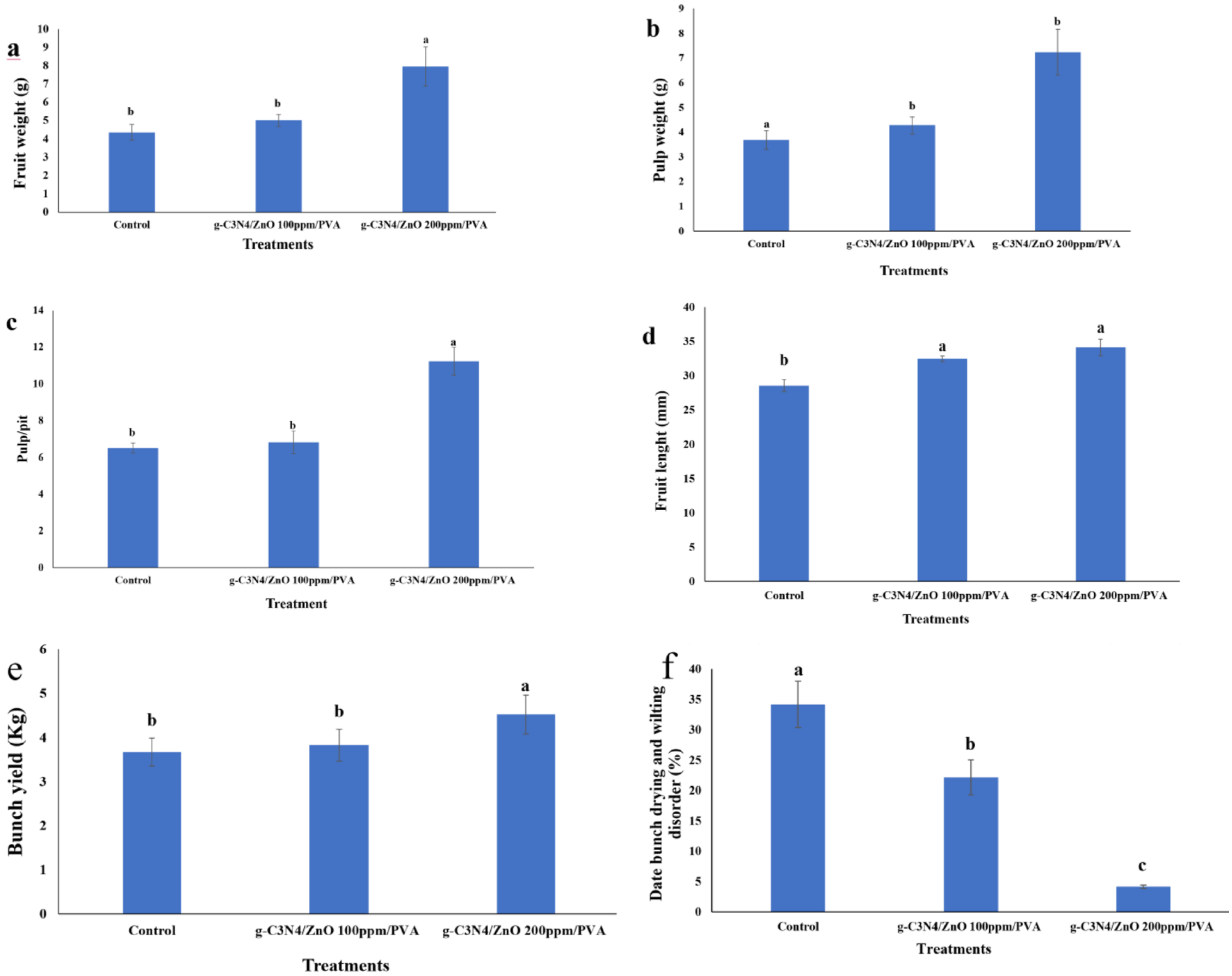

Fig. 7. Effect of the polymer nanocomposite of g-C_3N_4/ZnO/PVA on fruit weight (**a**) and pulp weight (**b**) and pulp to pit ratio (**c**) fruit length (**d**), bunch yield (**e**), and date bunch drying and wilting disorder percentage (**f**) in 'Mazafati' cultivar. Different letters on the columns indicate significant differences in means at the 5% probability level based on the LSD test. g-C_3N_4; graphitic carbon nitride, ZnO; Zinc oxide nanoparticle, PVA: polyvinyl alcohol.

Treatment	pH	TSS (°Brix)	Vitamin C (mg/100 g FW)
Control	7.12 ± 0.13a	34.00 ± 2.78a	15.02 ± 1.08a
g-C_3N_4/ZnO100 ppm/PVA	6.98 ± 0.13a	36.33 ± 4.86a	15.72 ± 1.63a
g-C_3N_4/ZnO200 ppm/PVA	6.92 ± 0.06a	35.83 ± 4.07a	18.54 ± 2.26a

Table 1. Comparison of mean value the effect of different levels of the polymer nanocomposite of g-C_3N_4/ZnO/PVA on some quantitative parameters of date fruit (Mazafati cultivar).

29% (Fig. 8b). While decreased anthocyanin content by 19 and 15%, compared to the control group, respectively (Fig. 8c).

Treatment means with same letters do not differ significantly according to LSD test (p˂0.05). Values are the mean of three replications ± StD of 4 replications. g-C_3N_4; graphitic carbon nitride, ZnO; Zinc oxide nanoparticle, PVA: polyvinyl alcohol. TSS: Total soluble solid.

In summary, this research investigated the effects of the polymer nanocomposite of g-C_3N_4/ZnO/PVA, on the Mzafati cultivar of date palm (Fig. 9). Findings demonstrated that the covering of the bunch tail with this nanocomposite substantially protect the bunch tail from sunburn and prevent water loss by the epidermal tissue, we covered the bunch tail impregnated with the polymer nanocomposite consisting of graphitic carbon nitride (g-C_3N_4), polyvinyl alcohol (PVA), and zinc oxide nanoparticles (ZnO NPs) at concentrations of 100 and 200 ppm. Which have long-lasting and highly effective sunscreen properties, to the bunch tail about one month before the plant was exposed to severe environmental stresses and the development of DBDWD, which occurred with the initial stage of fruit color change from Kharak to Rutab. Notably, the treatment with nanocomposite of

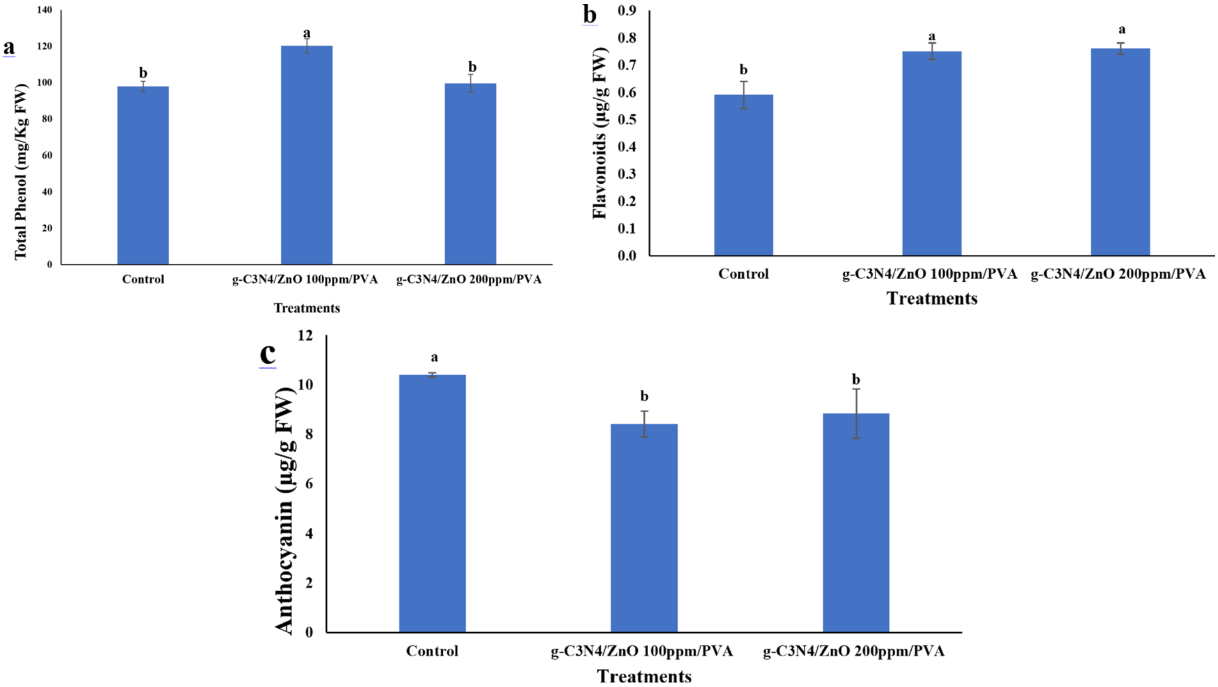

Fig. 8. Effect of the polymer nanocomposite of g-C_3N_4/ZnO/PVA on total phenol (**a**) and flavonoids (**b**) and anthocyanin (**c**) of date fruit 'Mazafati' cultivar. Different letters on the columns indicate significant differences in means at the 5% probability level based on the LSD test. g-C_3N_4; graphitic carbon nitride, ZnO; Zinc oxide nanoparticle, PVA: polyvinyl alcohol.

g-C_3N_4/ZnO/PVA (200 ppm ZnO nanoparticles) was identified as the most effective, yielding the most significant reductions in DBDWD and enhancements in fruit quality and yield. These positive results are attributed to the improved availability of ZnO, which is thought to mitigate oxidative stress and promote osmotic preservation, thereby enhancing water transfer to the fruit bunches. Consequently, this leads to healthier fruit and increased production. The study underscores the potential of the g-C_3N_4/ZnO/PVA polymer nanocomposite to bolster plant resilience against environmental stressors, suggesting its viability as a beneficial intervention for plants facing abiotic stress conditions.

Discussion

It seems that the adverse weather conditions in summer (Fig. 1) cause many abiotic stresses simultaneously during the ripening and harvesting period in the date palm. The symptom of drying and wilting of the date bunch disorder first appears as sunburn on the arch of the cluster tail, as shown in Fig. 6 (A-a). Therefore, it seems that the xylem and phloem are passive and due to non-transition of water and sap in the bunch tail, the fruits progressively shrivel and desiccate, rendering these fruits unfit for consumption (Fig. 6A-b). The covering of bunch tails with nanomaterials in agriculture has gained momentum owing to their unique properties that enhance plant growth and resilience against abiotic stressors. This study investigates the effects of g-C_3N_4/ZnO/PVA nanocomposites on various quantitative and qualitative parameters of date fruit. Notably, the findings indicate that the covering of tha bunch tail with this composite, particularly at a concentration of 200 ppm ZnO nanoparticles (NPs), resulted in significant increases in fruit weight (83%) and pulp weight (96%). The ability of g-C3N4/ZnO/PVA composites to enhance water retention is indicative of their potential role in improving physiological resilience in plants facing heat stress. Heat stress poses significant challenges to plant health, often leading to increased transpiration rates and a decline in relative water content[18]. By mitigating the adverse effects of heat stress, these composites could serve as valuable tools in developing sustainable agricultural practices, particularly in regions where high temperatures prevail. The physiological mechanisms underlying the observed enhancements are multifaceted. Heat stress disrupts photosynthesis by affecting the plant's water potential, impairing metabolic processes essential for growth and productivity[6]. The role of zinc in alleviating the adverse effects of temperature fluctuations and salinity is well-documented[6]. The covering of bunch tails with g-C_3N_4/ZnO/PVA composites can support overall plant health and resilience, enabling them to withstand abiotic stresses more effectively. Therefore, it seems that this polymer nanocomposite, by providing a coating layer containing UV-absorbing nanosheets (g-C_3N_4) and sunlight-reflecting nanoparticles (ZnO), on the epidermis of the date palm bunch tail protects it from sunburn, and reduces damage to underlying tissues such as the parenchyma and vascular system in the stem, thereby ensuring that the fruits in the stem receive sufficient water and increasing the weight of the fruit and fruit flesh.

The use of g-C_3N_4/ZnO/PVA composites has shown a substantial impact on key growth metrics of date fruit. The enhancement of the pulp-to-pit weight ratio by 73% is particularly noteworthy, indicating a

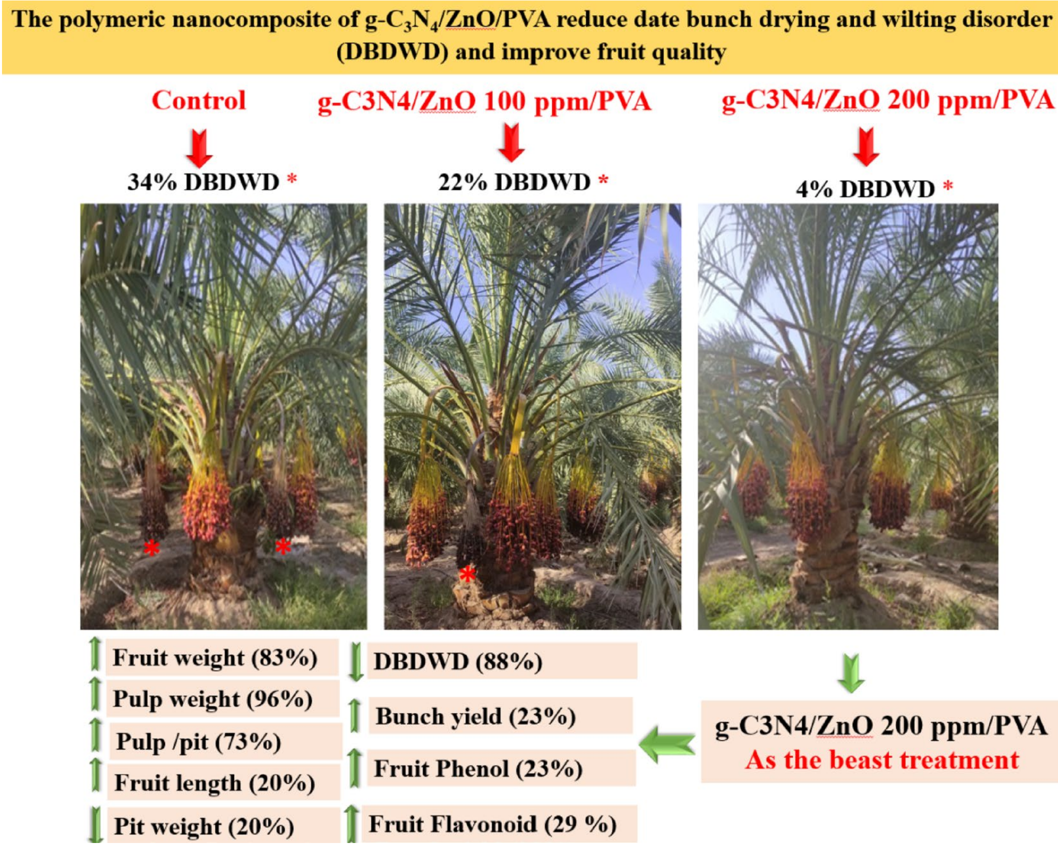

Fig. 9. The summary of the polymer nanocomposite of g-C_3N_4/ZnO/PVA on date bunch drying and wilting disorder (DBDWD) percentage, bunch yield, and quantitative and qualitative parameters of date fruit 'Mazafati' cultivar. g-C_3N_4; graphitic carbon nitride, ZnO; Zinc oxide nanoparticle, PVA: polyvinyl alcohol.

favorable allocation of resources towards commercially valuable pulp. This finding aligns with previous studies demonstrating that ZnO nanoparticles can stimulate metabolic processes that promote fruit development[17]. The enhancement of fruit weight and pulp weight indicates that ZnO NPs may improve nutrient uptake and photosynthetic efficiency, as suggested by Hanif et al.[19]. Zinc oxide nanoparticles have been recognized for their role in mitigating abiotic stresses, particularly high temperatures. Heat stress can disrupt plant physiology, leading to reduced yield and quality[20,21]. The unique properties of ZnO NPs, including their enhanced bioavailability compared to traditional fertilizers, position them as valuable tools for improving plant resilience. Research indicates that foliar applications of Zn NPs can enhance yield and product quality, as evidenced by improved fruit dimensions and weight[20].

Interestingly, while the composite demonstrated significant effects on fruit weight and pulp weight, it did not markedly influence pit weight, fruit diameter, or pit diameter. This selective response indicates that although ZnO NPs enhance certain aspects of fruit development, their impact may not be universally applicable to all morphological traits. The unchanged pit weight may reflect a threshold effect, where the composite's influence is more pronounced in actively growing tissues such as pulp. The complex interactions between nanomaterials and plant physiology underscore the need for further research to understand the mechanisms through which these composites influence growth and development. The intricate responses of plants to abiotic stressors, particularly heat stress, are influenced by various factors, including temperature and plant species. The interaction between heat stress and covering of the bunch tail with nanocomposite deserves careful consideration, as elevated temperatures may exacerbate physiological stress, potentially counteracting the beneficial effects of ZnO nanoparticles.

In addition to improving growth metrics, the findings from this study indicate a clear inverse relationship between the concentration of ZnO nanoparticles in the polymer nanocomposite of g-C_3N_4/ZnO/PVA and the occurrence of date bunch drying disorder (DBDWD). The covering of the bunch tail with g-C_3N_4/ZnO/PVA nanocomposites led to significant reductions in DBDWD, particularly at concentrations of 100 and 200 ppm, which resulted in decreases of 35 and 88%, respectively, compared to the control group. The relationship between ZnO NPs and DBDWD can be understood through the stress response mechanisms in plants. DBDWD is exacerbated by environmental stressors such as elevated temperatures and low humidity[2]. Under stress conditions, plants typically respond by synthesizing various stress indicators, including ethylene, abscisic acid (ABA), and reactive oxygen species (ROS)[23,24]. The presence of ZnO NPs may modulate these stress responses, enhancing plant resilience.

Research demonstrates that ZnO NPs can enhance the resilience of plants to osmotic and heat stress by lowering ABA levels and promoting the expression of defense-related genes[25,26]. This is particularly relevant for date palms, which are susceptible to similar stressors. The ability of ZnO NPs to regulate hormonal responses and enhance gene expression related to stress tolerance underscores their multifaceted role in protecting plants from DBDWD. According to Wang et al.[11], graphitic carbon nitride (g-C_3N_4) enhances plant resilience by stabilizing photosynthetic processes, mitigating membrane damage, and augmenting thermotolerance during stress conditions. These attributes collectively facilitate the maintenance of fruit quality and decrease water loss.

An examination of qualitative parameters revealed interesting variations in phytochemicals in date fruits treated with g-C_3N_4/ZnO/PVA nanocomposites. While certain quantitative attributes such as pH and total soluble solids (TSS) remained largely unaffected, significant increases were observed in the total phenolic content (23% increase at 100 ppm ZnO NPs), flavonoids (27 and 29% increases at 100 ppm and 200 ppm, respectively), and a decrease in anthocyanin content (19 and 15% decreases at 100 ppm and 200 ppm, respectively). The increase in total phenol content suggests that ZnO NPs may enhance the biosynthesis of phenolic compounds, which are essential for plant defense mechanisms and contribute to the antioxidant properties of fruits[27]. Flavonoids, known for their role in reducing oxidative stress and inflammation, enhance the overall health benefits of date fruits[28]. However, the observed decrease in anthocyanin content raises questions regarding the interaction of ZnO NPs with the biosynthetic pathways of these pigments. The findings of this study underscore the potential of g-C_3N_4/ZnO/PVA composites by covering the bunch tail in enhancing fruit quality and yield, providing a compelling case for the integration of nanotechnology into agricultural practices. The observed enhancements in fruit quality, particularly in terms of phenolic compounds and flavonoids, suggest that these nanocomposites can optimize fruit quality without adversely affecting critical nutritional parameters. These results suggest a promising avenue for the integration of nanotechnology in agricultural practices, particularly in enhancing fruit production and quality.

Conclusion

The covering of bunch tail with g-C_3N_4/ZnO/PVA nanocomposites has demonstrated significant potential in bolstering the resilience of the 'Mazafati' date palm cultivar against environmental stresses, particularly with hot and dry wind conditions. The observed reductions in date bunch drying and wilting disorder (DBDWD), alongside improvements in fruit quality, underscore the efficacy of zinc nanoparticles in enhancing plant health and productivity. As climate change continues to exert pressure on agricultural systems, the integration of such innovative nanomaterials into sustainable farming practices emerges as a critical strategy for improving the nutritional status and overall resilience of crops. The findings of this research reinforce the valuable role of nanotechnology in modern agriculture. Future studies should aim to elucidate the mechanisms underlying the observed benefits and assess the environmental implications of sustained nanomaterial use. By addressing these knowledge gaps, we can better inform agricultural policies and practices that promote sustainable development in the face of ever-increasing climate-related challenges.

Data availability

The raw data and analyzed data used during the current study are available from the corresponding author upon reasonable request.

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References

1. Alwahshi, K. J. et al. Molecular identification and disease management of date palm sudden decline syndrome in the united Arab Emirates. *Int. J. Molecul Scie*. **20** (4), 923. https://doi.org/10.3390/ijms20040923 (2019).
2. Panahi, B., Damankeshan, B. & Asaadi, M. Evaluation of amino chelate applications that reduce symptoms of date palm bunch drying disorder. *Int. J. Horti Sci. Technol.* **10** (1), 69–76. https://doi.org/10.22059/ijhst.2022.319862.446 (2023).
3. Kardavani, P., Ezetian, V. & Amandadi, N. An investigation of the effects of Climatological factors, UV radiation and Ozon on the bunch of mozafatidate dryness based on neural artificial networks and main component regression (Case Study- Jiroft). *J. Landsc. Geogr.* **10** (1), 1–14 (2013).
4. Saleh, J. An investigation of the effect of the optimum use of nutrient elements on intensity of date palm ear drought disorder. In *Annual Research Report of Soil and Water Research Department, Hormozgan Agricultural and Natural Research Center* (Bandar Abbas, 2005).
5. Haque, M. S. et al. Heat stress at early reproductive stage differentially alters several physiological and biochemical traits of three tomato cultivars. *Horticulturae* **7** (10), 330. https://doi.org/10.3390/horticulturae7100330 (2021).
6. Hassan, M. U. et al. Heat stress in cultivated plants: nature, impact, mechanisms, and mitigation strategies—A review. *Plant. Biosystems-An Int. J. Dealing all Aspects Plant. Biol.* **155** (2), 211–234. https://doi.org/10.1080/11263504.2020.1727987 (2021).
7. Sattar, A. et al. Foliar application of zinc improves morpho-physiological and antioxidant defense mechanisms, and agronomic grain biofortification of wheat (*Triticum aestivum* L.) under water stress. *Saudi J. Biol. Sci* **29**(3), 1699–1706. https://doi.org/10.1016/j.sjbs.2021.10.061(2022).
8. Cao, S. W. et al. Artificial photosynthetic hydrogen evolution over g-C3N4 nanosheets coupled with Cobaloxime. *Phys. Chem. Chem. Phys.* **15**, 18363–18366. https://doi.org/10.1039/C3CP53350F (2013).
9. Zhao, Y. et al. Dual-mode luminescent nanopaper based on ultrathin g-C3N4 nanosheets grafted with rare-earth upconversion nanoparticles. *ACS Appl. Mater. Interfaces*. **8**, 21555–21562 (2016).
10. Song, S. et al. Gold-cluster-based dual-emission nanocomposite film as ratiometric fluorescent sensing paper for specific metal ion. *Part. Part. Syst. Charact.* **35**, 1700471 (2018).
11. Wang, C. et al. Fluorescent g-C3N4 nanosheets enhanced photosynthetic efficiency in maize. *Nano Impact*. **24**, 100363. https://doi.org/10.1016/j.impact.2021.100363 (2021).
12. Hyon, S. H. et al. Poly (vinyl alcohol) hydrogels as soft contact lens material. *J. Biomaterials Sci. Polym. Ed.* **5** (5), 397–406 (1994).
13. Ranganna, S. *Manual of Analysis of Fruit and Vegetable Products* second edn 634 (Tata McGraw-Hill, 1979).

14. *Official Methods of Analysis* 17th edn. (AOAC, 2000).
15. Waterhouse, A. L. Determination of total phenolic. *Curr. Protocols Food Anal. Chem.* **6** (1), 1–1 (2002).
16. Chang, C. C., Yang, M. H., Wen, H. M. & Chern, J. C. Estimation of total flavonoid content in propolis by two complementary colorimetric methods. *J. Food Drug Anal.* **10** (3), 211–221 (2002).
17. Lindoo, S. J. & Caldwell, M. M. Ultraviolet-B radiation-induced Inhibition of leaf expansion and promotion of anthocyanin production: lack of involvement of the low irradiance phytochrome system. *Plant. Physiol.* **61**, 278–282 (1978).
18. Abdel-Sattar, M., Makhasha, E. & Al-Obeed, R. S. Conventional and nano-zinc foliar spray strategies to improve the physico-chemical properties and nutritional and antioxidant compounds of Timor Mango fruits under abiotic stress. *Horticulturae* **10** (10), 1096. https://doi.org/10.3390/horticulturae10101096 (2024).
19. Hanif, S. et al. Harnessing the potential of zinc oxide nanoparticles and their derivatives as nanofertilizers: trends and perspectives. *Plant. Nano Biol.* 100110. https://doi.org/10.1016/j.plana.2024.100110 (2024).
20. Kumar, V. et al. Mitigation of heat stress responses in crops using nitrate primed seeds. *South. Afr. J. Bot.* **140**, 25–36. https://doi.org/10.1016/j.sajb.2021.03.024 (2021).
21. Ul Hassan, M. et al. Linking plants functioning to adaptive responses under heat stress conditions: a mechanistic review. *J. Plant. Growth Regul.* 1–18. https://doi.org/10.1007/s00344-021-10493-1 (2021).
22. Tavallali, V., Rahemi, M., Eshghi, S., Kholdebarin, B. & Ramezanian, A. Zinc alleviates salt stress and increases antioxidant enzyme activity in the leaves of pistachio (*Pistacia Vera* L.'Badami') pitlings. *Turkish J. Agric. Forestry*. **34** (4), 349–359. https://doi.org/10.3906/tar-0905-10 (2010).
23. Huang, J., Zhao, X., Bürger, M., Chory, J. & &Wang, X. The role of ethylene in plant temperature stress response. *Trends Plant. Sci.* **28** (7), 808–824 (2023).
24. Pospíšil, P. Production of reactive oxygen species by photosystem II as a response to light and temperature stress. *Front. Plant. Sci.* **7**, 1950. https://doi.org/10.3389/fpls.2016.01950 (2016).
25. Qiu, J. et al. The application of zinc oxide nanoparticles: an effective strategy to protect rice from rice blast and abiotic stresses. *Environ. Pollution*. **331**, 121925 (2023).
26. Ahmad, J. et al. Enhancing plant resilience to biotic and abiotic stresses through exogenously applied nanoparticles: a comprehensive review of effects and mechanism. *Phyton (0031-9457)*. **94** (2). https://doi.org/10.32604/phyton.2025.061534 (2025).
27. Khan, M. A., Raza, A., Yousaf, R., Ali, H. & Darwish, H. Impact of zinc oxide nanoparticles on biosynthesis of thymoquinone in cell cultures of *Nigella sativa*. *Plant. Nano Biol.* **10**, 100109. https://doi.org/10.1016/j.plana.2024.100109 (2024).
28. Maqsood, S., Adiamo, O., Ahmad, M. & Mudgil, P. Bioactive compounds from date fruit and seed as potential nutraceutical and functional food ingredients. *Food Chem.* **308**, 125522. https://doi.org/10.1016/j.foodchem.2019.125522 (2020).

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M. A.: Data curation, Visualization, Methodology, A. S.: Project administration, Supervision, Formal analysis, Conceptualization, Writing - review & editing, Investigation, and MJ. J. Methodology and Writing. All authors reviewed the manuscript.

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Declarations

Competing interests
The authors declare no competing interests.

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