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Combating the Effects of Salinity on Saffron (*Crocus sativus*.) Performance and Growth with Nano-sized Cow Manure Fertilizers

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ABSTRACT

Iran's agricultural landscape confronts significant challenges from excessive groundwater extraction, leading to escalating salinity levels that threaten saffron yield. This study investigates the effectiveness of nano-sized cattle manure fertilizers in mitigating salinity stress in saffron cultivation. Nano-sized particles (mean diameter 45 ± 5 nm, >90% particles below 100 nm) were produced using ball milling and characterized through scanning electron microscopy and particle size distribution analysis. The experiment employed a randomized complete block design with three replications (n=36, α=0.05, power=0.85), testing four irrigation water salinity levels (freshwater, 1.75, 3.5, and 5 mS cm^{-1}) and three fertilizer treatments (nano-sized cattle manure, conventional cattle manure, and control) in field conditions at Torbat Heydarieh County, Iran during 2019-2020 growing seasons. Results indicate that higher irrigation water salinity reduces saffron yield by 39% while incorporating cattle manure fertilizers results in a 27% increase, and nano-fertilizer applications enhance yield by 51.8% ($p<0.01$). Furthermore, both treatments improve electrical conductivity thresholds by 18.5% and 43%, respectively, and significantly reduce soil bulk density by 23% and 31%, respectively ($p < 0.01$). The nano-sizing process reduced fertilizer half-life from 34 to 9 weeks, enabling more efficient nutrient availability [34]. Cost-benefit analysis indicates a 2.3-fold return on investment for nano-fertilizer application compared to conventional methods, despite higher initial costs. While long-term environmental impacts require further investigation, this study advocates for adopting nano-sized cattle manure fertilizers as a sustainable and economically viable approach to address the challenges posed by salinity in saffron cultivation, particularly in regions facing increasing groundwater salinity issues.

Keywords: Bulk density, Electrical conductivity, Nano-fertilizer, Saffron yield, Soil properties

INTRODUCTION

Botanical Characteristics of Saffron

Saffron (*Crocus sativus* L.) the triploid member of the Iridaceae family exhibits distinct morphological characteristics including a compressed rounded corm (2-3 cm in diameter), grass-like leaves (25-40 cm long, 1-3 mm wide), and distinctive purple flowers bearing three crimson stigmas that constitute the commercial product. Saffron's adaptation to Iran's semi-arid conditions is evidenced by its annual growth cycle, featuring summer dormancy and autumn flowering, which aligns with the region's hot, dry summers and mild winters.

Economic Significance of Saffron in Iran

Iran's climate and geographical conditions present unique advantages for saffron (*Crocus sativus* L.) cultivation, making it the world's leading producer of this valuable spice. According to the Ministry of Jihad Agriculture's official statistical report, Iran's saffron cultivation has expanded significantly, now encompassing 124,000 hectares predominantly concentrated in the Khorasan provinces. The region's distinct geographical characteristics, including elevations between 1000-2000 meters above sea level, diurnal temperature variations of 15-20°C, and annual precipitation of 250-300 mm, create optimal conditions for saffron production [1]. This environmental suitability, combined with centuries of traditional cultivation expertise, has enabled Iran to produce approximately 400 tons of dried stigmas annually, accounting for over 90% of global production.

Salinity Challenges in Iran and Their Impact on Saffron Cultivation

Iran's agricultural landscape confronts significant challenges from excessive groundwater extraction, leading to escalating salinity levels that threaten crop productivity. Over 90% of Iran's landmass is classified as dry or semi-dry due to insufficient rainfall. This creates fundamental agricultural constraints where limited precipitation fails to leach salts from the soil profile adequately. This geographical reality results in salt accumulation through capillary rise driven by evaporation [2]. Climate change has exacerbated this natural phenomenon, with shifting precipitation patterns and rising temperatures accelerating soil salinization processes in agricultural zones.

The regional climate patterns in Iran's agricultural zones have shown significant shifts over recent decades, characterized by increasing mean annual temperatures and decreasing precipitation reliability [3,4]. These changes have intensified the natural processes of salt accumulation in agricultural soils, particularly in areas where traditional farming practices persist. The interaction between topography and climate creates distinct microclimates within saffron-growing regions, where local variations in temperature and humidity patterns significantly influence salt accumulation rates and distribution patterns within the soil profile.

The expansion of saffron cultivation, combined with decreasing rainfall, has increased dependence on groundwater resources. This increased reliance has resulted in systematic aquifer depletion, forcing farmers to drill deeper wells for irrigation. According to Dastranj and Sepaskhah, groundwater is the primary irrigation source in saffron-cultivated areas [8]. However, recent droughts have not only intensified water scarcity but have also increased salinity levels, particularly in arid and semi-arid regions where alternative water sources are limited. Historical analysis of groundwater quality in major saffron-producing regions reveals a systematic deterioration over the past four decades. The progressive decline in water table levels has been accompanied by increasing mineralization of available water resources. This trend is particularly evident in deeper aquifers, where prolonged rock-water interactions have resulted in higher dissolved solid concentrations. The chemical composition of irrigation water has shifted notably, with increased sodium, chloride, and calcium ions contributing to soil salinization processes.

The transformation in irrigation water quality has been particularly dramatic in Khorasan province. Avarseji et al. documented that farmers in this region historically relied on freshwater for irrigation [5]. However, recent drought conditions and the expansion of saffron cultivation have forced a transition to increasingly saline water sources, resulting in heightened soil salinity levels. This shift is especially concerning given saffron's sensitivity to salinity, potentially explaining recent yield declines in cultivated areas.

Traditional saffron cultivation practices in Iran have evolved over centuries, adapting to local environmental conditions and water availability patterns. These practices typically incorporated sophisticated water management techniques and crop rotation systems that helped maintain soil quality and manage salt accumulation. However, the increasing pressure on land resources and changing climatic conditions have compromised the effectiveness of these traditional approaches, necessitating new management strategies and technological interventions.

The expansion of saffron cultivation in Khorasan province reveals a striking disparity between area growth and yield performance. Between 1973 and 2017, the cultivated area increased from 2,950 to 100,408 hectares, representing a 34-fold increase. During the same period, production increased from 17 to 343 tons, a 20-fold rise. However, average yields declined from 5.76 to 3.42 kg ha^{-1} [1]. This trend indicates that production increases have been driven primarily by area expansion rather than yield improvements. While saffron demonstrates adaptability to dry and semi-dry regions, its sensitivity to water and soil salinity presents a significant limiting factor for yield optimization [6].

The economic implications of declining saffron yields are particularly significant given the crop's high value and importance to regional economies. The reduction in yield per hectare has directly impacted farmer incomes and regional economic stability. Furthermore, the increasing costs associated with deeper well drilling and water quality management create additional financial burdens for producers, potentially threatening the long-term sustainability of saffron cultivation in traditionally productive regions.

The widespread challenge of salinity has profound implications for agricultural productivity, particularly in regions where saffron cultivation is prevalent. Multiple studies have established soil salinity as one of the most significant limiting factors for crop growth [7], with salinity management remaining a critical challenge in agricultural systems [1]. Extensive research has documented the adverse impact of salinity stress on saffron yield, as demonstrated by numerous studies [8-12].

A significant study at Shiraz University examined the relationships between irrigation water salinity, cattle manure fertilizer application, cultivation methods, and saffron yield responses. The results demonstrated that at the highest irrigation water salinity level (3 decisiemens per meter), saffron yield decreased by 77% compared to control treatments [13]. Various approaches have been investigated to mitigate these negative effects, including soil washing, basin planting techniques, organic fertilizer applications, and salt-tolerant variety selection.

The effectiveness of different cultivation methods, comparing furrow and bed planting systems, indicated that while bed planting can help mitigate salinity's adverse effects on yield, this benefit stems from reduced surface soil resistance and optimized soil temperature rather than direct salinity reduction [8]. The investigation of organic amendments has shown promising results in managing salinity stress. Comprehensive studies examining irrigation water salinity levels ranging from 1 to 10 deciSiemens per meter and cattle manure application rates from 0 to 60 tons per hectare demonstrated significant effects of both factors on saffron yield, with optimal results achieved under low salinity conditions with high manure application rates [14].

Recent technological advances in nanotechnology offer new opportunities to enhance organic amendment effectiveness. The field has developed rapidly, focusing on materials with unique properties in the 1-100 nanometer range [15]. Nanoparticles, composed of tens to hundreds of atoms or molecules, exhibit distinct characteristics due to their enhanced specific surface area and unique quantum effects influencing physical and chemical properties. These properties result in accelerated microbial decomposition rates [16] and increased surface atom concentration, leading to enhanced atomic collision probability and improved material reactivity [17].

The relationship between climate change and salinity in agricultural systems has become increasingly evident through long-term monitoring and research. Rising temperatures and changing precipitation patterns have accelerated evaporation rates and altered soil moisture dynamics, leading to more rapid salt accumulation in surface soils. These climate-induced changes have particular significance for saffron cultivation, as they affect both the timing and intensity of salt stress experienced by the crop.

The unique properties of nanomaterials make them particularly promising for agricultural applications [19-20]. Their high percentage of surface-located atoms increases the collision probability between atoms, ultimately enhancing material reactivity [17]. This increased reactivity can potentially accelerate organic fertilizer decomposition in soil, providing nutrients more rapidly. Furthermore, nanoparticles' high specific surface area may aid in absorbing soluble salts in the soil. Building on these advantages, research has begun exploring nano-sized cattle manure as a strategy to enhance saffron’s resistance to salinity while mitigating potential negative effects on yield.

Research Objectives and Scope

This research aims to establish the efficacy of nano-sized cattle manure in sustainable saffron production under increasing salinity pressure through systematic investigation of particle size effects, decomposition rates, and yield responses. The findings will contribute to a theoretical understanding of nano-organic fertilizer behavior in saline conditions and practical guidance for agricultural management in regions facing mounting salinity challenges.

MATERIAL AND METHODS

Sample Size and Statistical Power

Before experiment initiation, statistical power analysis was conducted using G*Power 3.1 software to determine the appropriate sample size. Based on preliminary data and anticipated effect sizes (Cohen's d = 0.8) for yield differences between treatments, a minimum sample size of 36 experimental units was determined necessary to achieve a statistical power of 0.85 at $\alpha = 0.05$. The experimental design incorporated this requirement through three replications of twelve treatment combinations.

Production and Characterization of Nano-sized Cattle Manure

Initial Processing and Ball Milling Cattle manure was collected from a local dairy operation, air-dried at 65°C until constant weight, and processed through a 2 mm sieve to ensure uniformity of starting material. The dried manure underwent high-energy ball milling using a planetary ball mill (Retsch PM 100, Germany) operated at 60 rpm for 48 hours. The mill was equipped with stainless steel grinding jars (500 mL) and balls (10 mm diameter) at a ball-to-powder ratio of 10:1. To prevent thermal degradation; milling was conducted in 30-minute intervals with 10-minute cooling periods [21, 22]. The particle size distribution percentage of the nano-sized cattle manure fertilizer sample produced at a rotation speed of 60 rpm for 48 hours in a ball mill is shown in Fig. 2. The SEM analysis (Fig. 1) confirms the successful production of particles in the nanometer range, with clearly visible individual particles and aggregates at the 5000x magnification level.

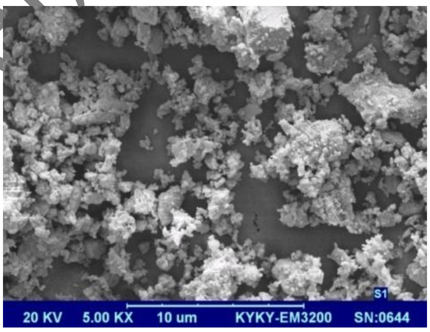

Fig. 1 SEM image of nano-sized cow manure fertilizer with a magnification of 5000 (each um is equivalent to 10-6 meters).

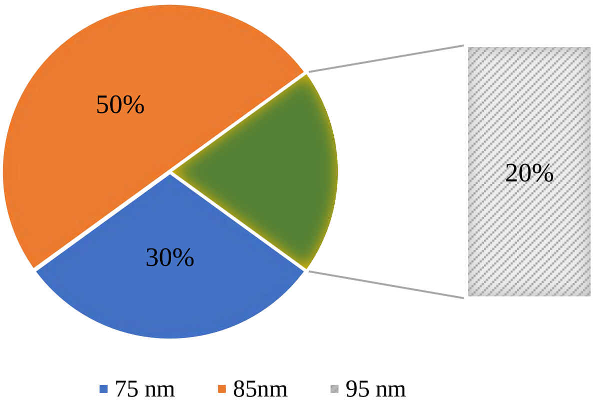

Fig. 2 Particle size distribution percentage of nano-sized cow manure fertilizer.

Particle Characterization

The resultant nano-sized particles underwent comprehensive characterization using multiple analytical techniques [16].

Morphological Analysis

Particle morphology was examined using scanning electron microscopy (SEM, JEOL JSM-7600F) at accelerating voltages of 5-15 kV. Samples were sputter-coated with gold to ensure conductivity. Transmission electron microscopy (TEM, FEI Tecnai G2 F20) provided higher-resolution imaging of particle structure and aggregation patterns.

Size Distribution Analysis

Particle size distribution was determined using dynamic light scattering (DLS, Malvern Zetasizer Nano ZS) in aqueous suspension. Measurements were conducted at 25°C with a scattering angle of 173°. Results indicated a mean particle diameter of 45 ± 5 nm, with 90% of particles below 100 nm.

Surface Area and Porosity

Brunauer-Emmett-Teller (BET) analysis using nitrogen adsorption-desorption isotherms (Micromeritics ASAP 2020) revealed a specific surface area of 68.3 m^2/g for nano-sized particles compared to 2.4 m^2/g for unprocessed manure.

Stability Assessment

Zeta potential measurements conducted in aqueous suspension across a pH range of 4-9 demonstrated colloidal stability, with values ranging from -35.2 to -42.8 mV, indicating good dispersion characteristics in soil solutions.

Chemical Composition Analysis

X-ray diffraction (XRD) and Fourier-transform infrared spectroscopy (FTIR) analyses confirmed that the nano-sizing process did not alter the fundamental chemical composition of the organic matter.

Half-life Determination

Decomposition kinetics were assessed through a systematic sampling protocol spanning 66 weeks. Soil samples were collected at 0, 11, 24, 48, 55, and 66 weeks post-application from the fertilizer incorporation depth. Organic matter content was determined using the Walkley-Black method, with initial concentrations calculated based on application rates of 20 Mg ha^{-1}. The decomposition rate constant (K) was determined using first-order kinetics [23]: $\ln[A] = \ln[A]_0 - Kt$. where [A] represents organic matter concentration at time t, $[A]_0$ is initial concentration, and K is the decomposition rate constant. Half-life ($t_{1/2}$) was calculated using: $t_{1/2} = 0.693/K$.

Field Experimental Design

The study employed a split-plot design within randomized complete blocks, with irrigation water salinity levels assigned to main plots and fertilizer treatments to subplots. Each treatment combination was replicated three times, resulting in 36 experimental units. Main Plot Treatments (Irrigation Water Salinity) are S_1: Freshwater (EC = 0.4 mS cm^{-1}), S_2: EC = 1.75 mS cm^{-1}, S_3: EC = 3.5 mS cm^{-1}, S_4: EC = 5.0 mS cm^{-1} and Subplot Treatments (Fertilizer) are C_1: Nano-sized cattle manure (20 Mg ha^{-1}), C_2: Conventional cattle manure (20 Mg ha^{-1}), C_3: Control (no fertilizer).

Plot size was established at 3 m × 4 m with 1 m buffer zones between plots to prevent treatment interference. Saline irrigation water was prepared by dissolving analytical grade NaCl and $CaCl_2$ (1:1 molar ratio) in freshwater, with electrical conductivity verified using a calibrated conductivity meter (Hanna HI98192).

Experimental Setup and Field Management

The field experiment was conducted over two growing seasons (2019 and 2020) in a Saffron farm at Torbat Heydarieh County, Iran. Before treatment application, soil samples were collected and analyzed for baseline characteristics (Table 1). The experimental design employed a randomized complete block design with three replications in crushed plots. The main factor consisted of four irrigation water salinity levels: S_1 (freshwater), S_2 (1.75 mS cm^{-1}), S_3 (3.5 mS cm^{-1}), and S_4 (5 mS cm^{-1}). The secondary factor comprised three fertilizer treatments: C_1 (nano-sized cattle manure), C_2 (conventional cattle manure), and C_3 (control without fertilizer).

Table 1 Soil characteristics before applying treatments and planting saffron bulbs.

Saturation Extract pH	ECe (mS cm^{-1})	Lime (%)	Exchangeable K	Exchangeable P	Total N	Saturation moisture	Organic matter	Clay	Silt	sand
			mg per Kg.			(%)				
7.9	0.7	12.6	315	13.8	0.06	33.5	0.66	17.5	44.3	38.2

Sand, silt, clay, and organic matter are expressed as percentage (%). Total N, exchangeable P, and exchangeable K are expressed as mg per kg soil. ECe: electrical conductivity of saturated soil extract; Saturation moisture: soil water content at saturation point.

Saffron corms with uniform diameter and weight (11-12 g) were hand-planted in September 2019 at a depth of 15 centimeters according to the predetermined density. Initial irrigation utilized freshwater to ensure consistent crop establishment across all treatments. Subsequent irrigation events employed the designated saline water treatments. Saline irrigation water was prepared by dissolving precise quantities of NaCl and $CaCl_2$ in freshwater. Total dissolved solids (TDS) were calculated using the established relationship: TDS (mg L^{-1}) = 640 × EC (mS cm^{-1}) (3)

Irrigation Management

Irrigation depth was determined based on soil moisture content, aiming to reach field capacity at a depth of 30 centimeters. The required irrigation depth was calculated using [24]: $I = \sum^{n}_{i=1} (\theta FC_i - \theta_i) \times \Delta z_i$. Where: I = irrigation depth θFC_i = volumetric soil moisture content at field capacity in layer i θ_i = soil moisture content before irrigation in layer i Δz_i = thickness of soil layer i n = a number of soil layers. To prevent salt accumulation, an additional 30% of water was applied for leaching. Irrigation was conducted 5-6 times during each growing season at 24-day intervals. All plots received uniform agricultural management practices, including hoeing and weed control throughout the growing season.

Data Collection and Analysis

Sampling for yield determination was conducted during the flowering period in late November and December, with appropriate consideration for eliminating marginal effects. Soil samples were collected for analysis of organic matter content, bulk density, and electrical conductivity of the saturated soil extract throughout the growing season.

The relationship between relative saffron yield and soil salinity was analyzed using the Maas and Hoffman (1977) model [25]: $Yr = 100 - b\,(ECe - a)$. Where: Yr = relative yield (%) b = yield reduction per unit increase in salinity a = threshold salinity tolerance (mS cm^{-1}) ECe = average soil saturation extract salinity in the root zone (mScm^{-1})

Statistical Analysis

Data analysis was performed using SAS software. Analysis of variance (ANOVA) was conducted to determine treatment effects on measured parameters. Mean comparisons were executed using the Least Significant Difference (LSD) test at $p \leq 0.05$. Given saffron's perennial nature, yield data from the second year (November-December 2020) represented treatment effects, as flowers harvested in each growing season reflect the previous year's growing conditions.

RESULTS

Fertilizer Decomposition Kinetics

Statistical analysis of variance revealed significant effects of particle size modification on cattle manure decomposition rates ($p < 0.01$). In contrast, irrigation water salinity and its interaction with particle size showed no significant influence on decomposition kinetics (Table 2). The nano-sizing process substantially altered the decomposition characteristics, reducing the fertilizer half-life from approximately 34 weeks for conventional cattle manure to 10 weeks for nano-sized material (Table 3).

Effects on Soil Physical Properties

Analysis of variance for soil bulk density demonstrated significant effects of cattle manure treatments ($p < 0.01$), while irrigation water salinity and the interaction between fertilizer and salinity showed no significant impact (Table 4). Quantitative analysis revealed that conventional cattle manure application reduced soil bulk density by 23% compared to control conditions, while nano-sized treatments achieved a 31% reduction (Table 5).

Table 2 Mean square of cow manure half-life

Source of Variance	Half Life	
	df	Mean Square
Rep	2	1.675417 ns
Cow Manure (C)	1	3589.260417 **
Salinity (S)	3	19.378194 ns
C ×S	3	7.547083 ns
CV	-	10.66647

*, ** Significant at $p \leq 0.05$ and $p \leq 0.01$ respectively; ns non-significant

Table 3 Comparison of mean half-life of cow manure at nano and conventional scales

Cattle manure treatment	Mean Half-life (week)
Common CM 20 ton ha^{-1}(C2)	35.15 a
Nano CM 20 ton ha^{-1} (C1)	10.70 b

Different letters indicate significant differences at $p \leq 0.05$ (LSD)

Table 4 Mean square of fertilizer treatments on soil bulk density

Source	DF	Mean Square
Rep	2	0.00443333 ns
Salinity (S)	3	0.00058796 ns
Fertilizer (C)	2	0.67583330 **
S × C	6	0.00057407 ns
CV (%)	-	4.762292

*, ** Significant at $p \leq 0.05$ and $p \leq 0.01$ respectively; ns non-significant

Table 5 soil bulk density mean comparison

Treatment	N	Bulk Density (g cm^{-3})
C_3 (Control)	12	1.52 a
C_2 (CM)	12	1.36 b
C_1 (Nano-CM)	12	1.05 c

Different letters indicate significant differences at $p \leq 0.05$ CM = Cattle Manure

Soil Salinity Dynamics

The effects of treatments on soil electrical conductivity were evaluated through systematic measurements during November 2019 (EC1) and October 2020 (EC2). Variance analysis demonstrated significant effects ($p < 0.01$) of both irrigation water salinity and fertilizer treatments on soil electrical conductivity during both measurement periods, though their interaction remained non-significant (Table 6). During the first year, nano-sized cattle manure treatments (C1) exhibited the highest conductivity levels, followed by conventional manure (C2), while control treatments (C3) showed the lowest values. Conventional cattle manure increased soil electrical conductivity by 5% compared to control conditions, though this increment lacked statistical significance. In contrast, nano-sized treatments generated significantly higher salinity levels, exceeding conventional treatments by 12.3% and control conditions by 16.7%. The second year of the study revealed soil electrical conductivity decreased markedly in nano-treated plots, showing a 24.3% reduction compared to first-year measurements.

Table 6 Mean square for soil electrical conductivity in stages 1 and 2.

Source of Variance	DF	Mean Square	
		EC1	EC2
R	2	0.00241944	0.00576944
)A(S	3	16. 42917037 **	14.73980370 **
)B(C	2	0.55230278 **	0.19003611 **
A ×B	6	0.00196204 ns	0.05029537 ns
Coeff Var.	-	8.515443	8.502233

*, ** Significant at $p \leq 0.05$ and $p \leq 0.01$ respectively; ns non-significant

Conventional treatments exhibited a more modest 3.1% reduction, while control plots maintained relatively stable conductivity levels. Mean comparisons of soil saturation extract electrical conductivity at different irrigation water salinity levels (Table 7) revealed distinct patterns. In the first year (EC1), soil electrical conductivity values were 0.80, 1.71, 2.60, and 3.97 mS cm⁻¹ for S1, S2, S3, and S4 treatments, respectively. The same pattern persisted in the second year (EC2), though with slightly lower values of 0.64, 1.50, 2.38, and 3.64 mS cm⁻¹.

When examining fertilizer treatments, nano-sized cattle manure (C1) initially showed the highest soil EC (2.51 mS cm⁻¹ in EC1), exceeding both conventional manure (C2: 2.20 mS cm⁻¹) and control treatments (C3: 2.09 mS cm⁻¹). However, by the second year (EC2), nano-treated plots showed the lowest EC values (1.90 mS cm⁻¹), while conventional manure and control treatments maintained higher levels (C2: 2.13 mS cm⁻¹, C3: 2.09 mS cm⁻¹).

Table 7 Comparison of mean soil saturation extract electrical conductivity in stages 1 and 2.

Factor A	N	EC1	EC2
S1	9	0.80 d	0.64 d
S2	9	1.71 c	1.50 c
S3	9	2.60 b	2.38 b
S4	9	3.97 a	3.64 a
Factor B			
C1	12	2.51 a	1.90 b
C2	12	2.20 b	2.13 a
C3	12	2.09 b	2.09 a

Four salinity levels: S1 (freshwater, EC = 0.4 mS cm⁻¹), S2 (EC = 1.75 mS cm⁻¹), S3 (EC = 3.5 mS cm⁻¹), and S4 (EC = 5.0 mS cm⁻¹). C1 (nano-Cattle manure), C2 (Cattle Manure), C3 (Control). Different letters indicate significant differences at $p \leq 0.05$

Saffron Yield Response

Analysis of variance for saffron yield demonstrated significant effects ($p < 0.01$) of both irrigation water salinity and fertilizer treatments, though their interaction did not achieve statistical significance (Table 8). Increasing irrigation water salinity to 5 mS cm⁻¹ resulted in a 39% reduction in yield compared to freshwater treatments. Treatment S4 produced the lowest yield at 4.58 kg ha⁻¹, while S1 achieved maximum productivity at 7.5 kg ha⁻¹.

Table 8 Mean square of the effect of irrigation water levels and fertilizer treatments on saffron yield.

Source of Variance	DF	Mean Square
R	2	0.4802778
)A(S	3	15.0640741 **
)B(C	2	84.9286111 **
A ×B	6	0.1949074 ns
Coeff Var	-	9.859092

*, ** Significant at $p \leq 0.05$ and $p \leq 0.01$ respectively; ns non-significant

Nano-sized cattle manure applications (C1) achieved the highest yield (9.22 kg ha⁻¹), significantly exceeding both conventional manure treatments (5.56 kg ha⁻¹) and control conditions (4.04 kg ha⁻¹). Conventional cattle manure enhanced yield by 27% under saline conditions, while nano-sized treatments achieved a 51.8% improvement compared to untreated plots (Table 9).

Table 9 Saffron yield under different treatments.

Factor A	N	Y
S1	9	7.50 a
S2	9	7.02 a
S3	9	5.99 b
S4	9	4.58 c
Factor B		
C1	12	9.22 a
C2	12	5.56 b
C3	12	4.04 c

Four salinity levels: S1 (freshwater, EC = 0.4 mS cm⁻¹), S2 (EC = 1.75 mS cm⁻¹), S3 (EC = 3.5 mS cm⁻¹), and S4 (EC = 5.0 mS cm⁻¹). C1 (nano-Cattle manure), C2 (Cattle Manure), C3 (Control). Different letters indicate significant differences at $p \leq 0.05$

Salinity Tolerance Thresholds

The relationship between soil salinity and relative yield, modeled using the Maas-Hoffman equation, revealed differences in salinity tolerance thresholds among treatments (Table 10). Threshold electrical conductivity values ranged from 0.7 to 1.24 mS cm^{-1} across treatments. Conventional cattle manure application increased the threshold electrical conductivity by 18.5% compared to control conditions, while nano-sized treatments achieved a 43% improvement. The yield reduction coefficients showed corresponding patterns, with treatment C3 exhibiting the steepest decline per unit increase in salinity (19% reduction per mS cm^{-1}), while treatments C2 and C1 showed more gradual reductions of 14.7% and 8.7% per mS cm^{-1}, respectively.

Table 10 Electrical conductivity threshold and yield reduction coefficient in fertilizer treatments.

Treatments	Threshold ECe (dS m^{-1})	Yield reduction coefficient (% ds m^{-1})
C1: Nano cattle manure	1.24	8.7
C2: Cattle manure	0.86	14.7
C3: Blank	0.7	19

Threshold ECe and yield reduction coefficient were calculated using the Maas-Hoffman model: $Yr = 100 – b (ECe - a)$, where Yr is relative yield (%), b is yield reduction per unit increase in salinity (% per dS m^{-1}), and a is threshold salinity tolerance (dS m^{-1}). Values represent model parameters derived from experimental data.

DISCUSSION

Enhanced Performance Under Saline Conditions

The nano-sized cattle manure treatments demonstrated superior yield performance under high salinity conditions (C1S4) compared to conventional ones under optimal water quality conditions (C2S1). Conversely, conventional cattle manure treatments under high salinity conditions (C2S4) showed lower productivity than untreated plots receiving freshwater irrigation (C3S1). These findings align with research by Yarami and Sepaskhah, who documented that cattle manure applications enhanced soil fertility and nutrient availability, resulting in a 23% increase in saffron yield under saline irrigation conditions [12].

The enhanced efficiency of nano-treatments can be attributed to their unique physical and chemical properties at the nanoscale level. When particles are reduced to nanometer size, quantum effects begin to dominate their behavior, fundamentally altering their interaction with the soil-plant system [35]. The increased surface-to-volume ratio of nanoparticles facilitates stronger bonding with plant exudates and accelerates decomposition by soil microorganisms [30], ensuring more consistent nutrient availability throughout the growing season.

The superior performance of nanoparticle treatments under saline conditions aligns with findings from Ould-Ahmed et al., who established the effectiveness of farm manures as soil amendments in sandy soils irrigated with saline water [31]. The improvement in soil physical properties due to nanoparticle application, as evidenced by reduced bulk density measurements (Table 5), enhances soil structure and water retention, partially mitigating the negative effects of salinity.

Mechanisms of Enhanced Salt Tolerance

The increased salt tolerance observed in nano-treated plots can be attributed to several interacting mechanisms. First, the enhanced molecular bonding between nanoparticles and plant root exudates creates a more efficient nutrient delivery system that remains effective even under salt stress. This finding supports earlier research by Borm et al. and Sasson et al. regarding the enhanced reactivity of nanoscale materials in soil systems [26, 27].

Second, improved soil physical properties—particularly reduced bulk density and enhanced aggregation observed in nano-treated plots—promote better soil aeration and water movement. These improvements are crucial for plant performance under saline conditions [32]. Third, the accelerated decomposition rates observed in nano-treatments, as evidenced by their shorter half-life (Table 3), ensure more rapid nutrient release and organic matter incorporation into the soil system. This finding aligns with research by Karimzadeh et al., who documented enhanced material reactivity at the nanoscale due to increased surface atom concentration [17].

Environmental and Economic Implications

The significant reduction in soil salinity levels during the second year of study, particularly pronounced in nano-treatments (24.3% decrease compared to 3.1% in conventional treatments), provides strong evidence for the sustainable nature of this approach. These findings complement research by Asghari et al., who documented the mitigating effects of cattle manure on salinity stress impacts on both saffron flower and corm yield [33].

The enhanced performance of nano-treatments under high salinity conditions has particular significance for regions facing increasing groundwater salinity issues [8]. Maintaining productive agriculture under such conditions addresses a critical need identified by Kafi et al. regarding the sustainability of saffron cultivation in traditionally productive regions [6].

The economic implications of these findings are substantial, considering the documented decline in saffron yields from 5.76 to 3.42 kg ha^{-1} between 1973 and 2017 [1]. The ability of nano-treatments to enhance yield by 51.8% under saline conditions, compared to the 27% improvement achieved with conventional manure, suggests a potentially viable strategy for maintaining agricultural productivity in the face of increasing salinity challenges.

Practical Implications for Saffron Cultivation

The observed improvements in soil physical properties and yield performance under nano-treatments have significant implications for sustainable saffron cultivation in saline environments. Soil salinity traditionally hinders plant growth and development through multiple mechanisms, including osmotic stress, ionic imbalances, and reduced nutrient availability [34]. The enhanced performance of nano-sized cattle manure in mitigating these effects provides a potential solution to challenges identified by Munns and Tester regarding sustainable crop production under saline conditions [35].

The reduction in fertilizer half-life from 34 to 9 weeks represents a substantial improvement in nutrient delivery efficiency. This accelerated decomposition addresses a key limitation of conventional organic amendments noted regarding the misalignment between nutrient release patterns and peak plant demands. The improved synchronization of nutrient availability with plant requirements particularly benefits saffron, given its unique growth patterns and nutrient uptake characteristics [6].

Soil Structure and Water Management

The improvements in soil physical properties observed under nano-treatments have broader implications for water management in saffron cultivation. The significant reductions in bulk density align with findings by Zamani et al. and Nazemi regarding the positive effects of organic amendments on soil structural properties [19,38]. The enhanced effectiveness of nano-sized particles in reducing bulk density (31% reduction compared to 23% with conventional manure) suggests improved soil porosity and water retention characteristics, crucial factors in saline soil management [36,37].

The enhanced soil physical properties contribute to more efficient salt leaching, as evidenced by the greater reduction in second-year soil electrical conductivity in nano-treated plots. This improvement in salt management capacity aligns with research by Yarami and Sepaskhah, who emphasized the importance of soil physical conditions in managing salinity stress in saffron cultivation [12].

Threshold Salinity Response

The increased salinity threshold tolerance observed in nano-treated plots (43% improvement compared to control conditions) represents a significant advancement in saffron cultivation under saline conditions. This improvement surpasses the effects reported by Yarami and Sepaskhah for conventional cattle manure applications, suggesting enhanced stress mitigation capabilities of nano-sized amendments [12]. The reduced yield decline per unit increase in salinity (8.7% in nano-treatments compared to 19% in control plots) further demonstrates the protective effect of these amendments under saline conditions.

The relationship between relative yield and soil salinity, as modeled using the Maas and Hoffman (1977) equation, reveals important patterns in stress response [25]. The higher threshold electrical conductivity values achieved with nano-treatments (1.24 mS cm^{-1}) compared to conventional manure (0.86 mS cm^{-1}) and control conditions (0.7 mS cm^{-1}) suggest fundamental improvements in salt tolerance mechanisms, supporting findings by Asghari et al. regarding the potential for organic amendments to enhance crop resilience under saline conditions [33].

Long-term Sustainability Considerations

The ability of nano-sized cattle manure to enhance saffron productivity under saline conditions while improving soil physical properties suggests potential long-term benefits for sustainable agriculture in regions facing salinity challenges. The observed improvements in soil structure and salt management capabilities address key concerns regarding the sustainability of saffron cultivation under increasing environmental stress [1].

These findings build upon earlier research by Alborzi Haghighi and Sepaskhah regarding the integration of organic amendments and irrigation management in saffron cultivation [13]. The enhanced performance of nano-treatments, particularly their ability to maintain productivity under high salinity conditions, provides a promising avenue for addressing the challenges documented by Avarseji et al. concerning the impact of deteriorating irrigation water quality on saffron production [5].

The observed patterns of soil improvement and yield enhancement align with fundamental principles of sustainable agriculture while addressing specific challenges faced by saffron producers in semi-arid regions. The combination of improved nutrient delivery efficiency, enhanced soil physical properties, and increased salt tolerance demonstrates the potential of nano-sized organic amendments to contribute to immediate productivity improvements and long-term agricultural sustainability.

CONCLUSION

The research demonstrates that nano-sizing cattle manure is a promising approach for improving saffron production under salinity stress conditions. The significant reduction in fertilizer half-life from 34 to 9 weeks through nano-sizing processes provides evidence of enhanced nutrient availability patterns that better align with crop requirements. This acceleration in decomposition kinetics addresses a fundamental limitation of conventional organic amendments while maintaining their beneficial effects on soil properties.

The differential response of soil physical properties to fertilizer treatments reveals important mechanisms underlying yield improvements. Nano-sized cattle manure applications achieved a 31% reduction in soil bulk density compared to a 23% reduction with conventional manure, demonstrating enhanced effectiveness in improving soil structural characteristics. These improvements in soil physical properties, documented by changes in bulk density, contribute to improved growing conditions and enhanced salt tolerance.

The impact on yield under saline conditions is particularly noteworthy, with nano-treatments achieving a 51.8% yield increase compared to control conditions, substantially exceeding the 27% improvement observed with conventional manure. This enhanced performance builds upon previous findings regarding the positive effects of organic amendments on saffron production under saline conditions. The increased threshold electrical conductivity values in nano-treated plots (from 0.7 to 1.24 mS cm^{-1}) provide quantitative evidence of improved salt tolerance mechanisms.

The temporal patterns in soil salinity, particularly the 24.3% reduction in second-year electrical conductivity under nano-treatments compared to 3.1% with conventional manure, suggest improved salt management capabilities. This enhanced salt leaching efficiency, combined with better soil physical properties, addresses key challenges regarding sustainable saffron cultivation under increasing groundwater salinity.

The successful improvement in saffron productivity under saline conditions through nano-sized amendments offers promise for addressing documented yield declines. However, several important considerations warrant attention in future research and implementation:

The mechanisms underlying enhanced salt tolerance, particularly the interaction between nano-sized particles and plant root systems, require further investigation. Long-term studies are needed to evaluate the persistence of soil improvements and the potential cumulative effects of repeated nano-fertilizer applications. Economic analyses should consider both the increased production costs of nano-sizing processes and the substantial yield benefits achieved under stress conditions.

The research contributes to both a theoretical understanding of nano-organic fertilizer behavior in saline conditions and practical guidance for agricultural management. As global agriculture faces growing pressure from climate change and resource scarcity, such innovative approaches combining traditional organic amendments with modern nanotechnology could play a crucial role in maintaining food security while preserving environmental quality.

The findings have particular relevance for regions facing increasing salinity challenges, offering a potential strategy for maintaining agricultural productivity while improving soil conditions. Future research should focus on optimizing application rates, investigating potential environmental impacts, and developing cost-effective production methods for wider implementation.

This study demonstrates that nano-sizing cattle manure represents a viable strategy for enhancing saffron production under saline conditions while improving soil properties. The significant yield improvements and enhanced salt tolerance achieved through this approach suggest promising applications for sustainable agriculture in regions facing mounting salinity challenges.

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Authors' contributions: H, K., H, A., Contributed substantially to the conception and design of the study, the acquisition of data, the analysis, and interpretation. A, R., Contributed to the data acquisition. All authors have read and approved the manuscript.

Declaration of Competing Interest

The authors have no relevant financial or non-financial interests to disclose.

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