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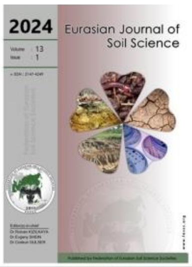

Efficacy of nano-zinc oxide and iron oxide formulations on shelf life of strawberry

Lakhwinder Singh [a,*], Ramesh Kumar Sadawarti [a], Shailesh Kumar Singh [a], Vishnu D. Rajput [b], Tatiana Minkina [b], Svetlana Sushkova [b]

[a] Department of Horticulture, School of Agriculture, Lovely Professional University, Phagwara, 144-411, Punjab, India
[b] Academy of Biology and Biotechnology, Southern Federal University, Rostov-on-Don, Russia

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Author(s)
L.Singh *
R.K.Sadawarti
S.K.Singh
V.D.Rajput
T.Minkina
S.Sushkova

* Corresponding author

Abstract

The research investigates the transformative impact of nano-zinc oxide and iron oxide formulations on prolonging the shelf life of strawberries. A total of 16 distinct treatments were applied through foliar application, and a nano-zinc oxide (ZnO) and iron oxide (FeO) formulations were administered. Each square meter received 42 ml of the solution in triplicate, ensuring a comprehensive exploration of the formulations' impact on shelf-life enhancement. Notably, the combined application of ZnO and FeO NPs at 150 mg/l, specifically T_{15} (Z_3F_3), exhibited superior effectiveness in preserving the crop. T_{11} (Z_2F_2), featuring 100 mg/l ZnO and 100 mg/l FeO, closely trailed T_{15}, showcasing significant improvements in parameters such as ascorbic acid content (49.66 mg/100g), and anthocyanin content (39.82 mg/l), etc. at nine days after harvesting. Besides this, TSS (7.25 ^{o}brix) in T_{14} and acidity (0.65%) in T_5 and T_9 at nine days intervals. These findings advancing the strawberry preservation methods in the agriculture and food industries and establishes the superiority of simultaneous applications of nano-formulations in T_{15} (150 mg/l ZnO + 150 mg/l FeO) and T_{11} (100 mg/l ZnO + 100 mg/l FeO). These formulations emerge as optimal solutions for extending the shelf life of strawberry fruits, particularly the Cv. Winter Dawn under Punjab Region, India, and could implement in similar climatic condition around world.

Keywords: Strawberry, winter dawn, nano-fertilizers, ZnO, FeO, shelf life, anthocyanin content.

Introduction

Strawberry fruits are vibrant, with significant minerals and vitamins, plants can reach a height of 20–22 cm (8-10 inches) and have 2-4 years of economic life before replacing plants (Menzel, 2023). China dominates global strawberry production in every aspect with production of 3.336.690 tons during the 2021-22 period, whereas the USA follows with a production of 1.055.963 tons of strawberries (FAO, 2023). Strawberry is an aggregate accessory fruit formed through the enlargement of the receptacle. Typically, the fruit's external surface is adorned with diminutive seeds referred to as achenes, which protrude slightly from its flesh (Barakhov et al., 2023). Strawberries are preferably grown in soil having a pH range of 4.6-6.5 (Cankurt and İpek, 2023).

The soil beneath the strawberry plants provides the foundation for their growth, bearing the responsibility of supplying essential nutrients, maintaining proper pH levels, and ensuring adequate drainage (Al-Mamun et al., 2021). As such, soil nutrition is central to the success of strawberry production. It not only influences the plant's growth, vigor, and disease resistance but also plays a pivotal role in determining the fruit's quality, flavor, and shelf life (Duralija et al., 2021). Among the various essential nutrients strawberries require for optimal growth, two micronutrients, zinc (Zn) and iron (Fe), have emerged as critical players in shaping fruit quality and shelf life.

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The shelf life of strawberries is significantly influenced by the presence of zinc oxide and iron oxide in the soil. These minerals play crucial roles in various physiological processes within the strawberry plant, ultimately impacting the quality and longevity of the fruit (Jatav et al., 2021) Zinc oxide and iron oxide are essential micronutrients required for the proper growth and development of strawberry plants. ZnO-NPs improve biochemical indices of strawberry plants (Singh et al., 2024a,b,c). Adequate levels of zinc and iron in the soil promote optimal nutrient absorption and act as cofactors for antioxidant enzymes such as superoxide dismutase (SOD) and catalase, which play critical roles in scavenging reactive oxygen species (ROS) and protecting plant cells from oxidative damage (Singh et al., 2022a,b). Iron is involved in the synthesis of phytoalexins, which are compounds produced by plants in response to microbial attack, while zinc enhances the activity of defense-related enzymes and strengthens cell walls (Panigrahi et al., 2019). By bolstering the plant's immune system, zinc oxide and iron oxide help reduce the incidence of diseases that could otherwise compromise fruit quality and shelf life (Mohapatra et al., 2022). This research delves into the intricate relationship between soil nutrition, particularly the impact of zinc oxide and iron oxide on shelf life of strawberries under Punjab region of India.

Nano-fertilizers are more sensitive and can penetrate the epidermis, empowering them to promote nutrient consumption efficiency while reducing nutrient overabundance (Al Tawaha et al., 2024). NPs also stimulate root hair development, increasing nutrient absorption capacity. Furthermore, ZnO-NPs influence ion transporters and channels (Singh et al., 2024a,b,c) Advances in nanotechnology research could improve fundamental aspects of food security, including agricultural productivity, soil progress, use of safe water, food dispersal in stores, and food quality (Singh et al., 2024a,b,c). These micronutrients, although required in small quantities, have a disproportionate impact on the overall health and productivity of the strawberry crop. Their influence on synthesizing vital biomolecules, enzyme activities, and redox processes makes them indispensable contributors to the various stages of strawberries from blossom to harvest (Bayat et al., 2019). Zinc, an essential micronutrient, participates in numerous enzymatic reactions within the plant, including those related to hormone regulation, protein synthesis, and nucleic acid metabolism (Meyer et al., 2021). Understanding the specific role of zinc in strawberries is critical for farmers and horticulturists seeking to maximize the visual appeal and nutritional value (Bandeira et al., 2020). Iron, another micronutrient, plays an equally pivotal role in the life cycle of strawberry plants. Iron is a fundamental component of chlorophyll, the pigment responsible for photosynthesis, and is essential for electron transfer reactions within the plant (Warang et al., 2023). In strawberries, adequate iron availability is closely linked to healthy foliage, efficient photosynthesis, and the synthesis of vital compounds like phenolic compounds and anthocyanins, contributing to fruit color and antioxidant content. As such, unraveling the specific role of iron in strawberries is paramount for those aiming to enhance fruit quality and health benefits (Duralija et al., 2021).

By focusing on the specific roles of zinc and iron, present study aimed to intricate interplay of soil nutrition and shelf life of strawberry fruits. The mechanisms underlying the effects of zinc and iron on strawberries, strategies to optimize the availability of these nutrients in the soil and to cultivate strawberries that exhibit not only visual appeal but also enhanced nutritional richness and prolonged shelf life.

Material and Methods

Description of the location and plants

The present research was conducted at Lovely Professional University, School of Agriculture, Horticulture Research Farm, Punjab, India (2022-2023). Experimental site which is nearly 237m (768 ft.) above mean sea level. It is located in the Punjab state at 31.2232°N latitude and 75.7670°E longitudes, with an average annual rainfall of 816 mm. The runners of strawberry cv. Winter Dawn (one month old) were transplanted by the 7th and 8th of November 2022 under protected and open field conditions with three replications. A summary of materials and methodology are mentioned below,

Field preparation

Before the transplanting of strawberry runners, urea was applied in two splits at a concentration of 23.9 g per square meter, while DAP was applied at 21.7 g and MOP at 20 g per square meter as per the recommendation of package practice provided by state agriculture university (Punjab). Phosphorus and potash were applied prior to planting and drip irrigation method was used for irrigation at discharge rate of 2 liters/hour, total 6 irrigation were applied to the field for both conditions from transplanting to harvesting stage.

Characterization of ZnO and FeO

Nano zinc oxide can enhance nutrient uptake, induce systemic acquired resistance, and act as an antioxidant in strawberry plants, promoting growth and stress tolerance Similarly, iron oxide nanoparticles can improve photosynthesis efficiency, bolster plant defense mechanisms, and potentially increase disease resistance in strawberries. Zinc and iron enhance the shelf life of strawberries by promoting enzymatic activity, which aids in maintaining fruit freshness and delaying decay processes. Additionally, these minerals contribute to the stabilization of cellular structures, extending the longevity of the fruit during storage (Chaplygin et al., 2020).

Preparation of ZnO and FeO doses

Nanoform of ZnO and FeO were prepared at a concentration of 50, 100 and 150 mg/l. Zinc oxide and iron oxide using digital weighing scale in micrograms and place it in a weighing dish. The 0.05 g of ZnO and FeO separately were used in order to make a 50 mg/l solution then dissolve the weigh calculated ZnO and FeO in 10ml ethanol after that mix the 10 ml of prepared stock solution to 90 ml distilled water to make 100 ml solution and same for the 100 mg/l and 150 mg/l concentration. Commercial grade nano zinc oxide and iron oxide fertilizers were used in foliar applications (1000 ml) on leaves of each strawberry plant. These NPs were obtained from ad-nano Technologies Pvt. Ltd., and prepared by the chemical precipitation method, and had a purity rate of 99.9%, average particle size of 30–80 nm, and bulk density of 0.58 g/cm^3.

Observations, Analysis and Treatment details

Procedure for determination of biochemical constituents

Spoilage

Shelf-life parameters was monitored at 0-, 3-, 6- and 9-days interval and fruits were stored at ambient room temperature conditions. The spoilage was calculated by as the total number of spoiled units, divided by the total units produced, and multiplied by hundred.

Total soluble solids (TSS)

Total soluble solids (TSS) were calculated with a digital refractometer, and ascorbic acid content was estimated using a modified procedure from A.O.A.C. Titratable acidity was determined by titration with 0.1N NaOH and phenolphthalein as an indicator.

Physiological Loss in eight (PLW)

The physiological loss in weight was calculated by subtracting the final weight of the fruit from the initial weight of the fruit and determine in percentage.

Anthocyanin

Differential method of pH has been used to determine the anthocyanin content and the absorbance was measured using UV- spectrophotometer and absorbance was read at 520 nm.

Total sugars and reducing sugars

Lane and Eynon method were used to estimate the total sugars and reducing sugars.

Data analysis

Statistical analysis was conducted on shelf-life parameters and treatments were computed using SPSS software for randomized block design (RBD).

Soil analysis

Total nitrogen was determined through the micro-kjeldahl (Jackson, 1973), while total phosphorus was estimated by the Vandomolybdophospheric yellow color method (Jackson, 1973), and total potash was estimated on Flame photometer (Jackson, 1973). The available nitrogen in the soil is 225.8 kg/ha, phosphorous levels ranging between 12-22 kg/ha with an average of 16.5 kg/ha, mean available potassium is about 158.32 kg/ha-221.04 kg/ha with an average of 179.20 kg/ha respectively.

Experimental setup

The experiment consists of sixteen various treatments: T_0 (100 % RDF), T_1 (500 mg/l ZnO NPs), T_2 (100 mg/l ZnO NPs), T_3 (150 mg/l ZnO NPs), T_4 (50 mg/l FeO NPs), T_5 (100 mg/l FeO NPs), T_6 (150 mg/l FeO NPs), T_7 (50 mg/l ZnO NPs + 50 mg/l FeO NPs), T_8 (50 mg/l ZnO NPs + 100 mg/l FeO NPs), T_9 (50 mg/l ZnO NPs + 150 mg/l FeO NPs), T_{10} (100 mg/l ZnO NPs + 50 mg/l FeO NPs), T_{11} (100 mg/l ZnO NPs+ 100 mg/l FeO NPs), T_{12} (100 mg/l ZnO NPs + 150 mg/l FeO NPs), T_{13} (150 mg/l ZnO NPs + 50 mg/l FeO NPs), T_{14} (150 mg/l ZnO NPs + 100 mg/l FeO NPs), T_{15} (150 mg/l ZnO NPs + 150 mg/l FeO NPs) and conducted in Randomized block design.

Results and Discussion

Spoilage

Spoilage (%) of strawberry was affected by the different doses of Nano-ZnO and FeO, as presented in Table 1 respectively. Minimum Spoilage (0.73%) was observed in T_{15} significantly at 3 days interval and maximum spoilage (2.79%) was recorded in T_0 after six days interval minimum spoilage (1.51%) was observed in T_{15} and maximum (5.85%) was recorded in T_0 and at 9 days interval spoilage was observed minimum in T_{15} and maximum was observed in T_0 (8.39%). Spoilage percent of strawberry was observed from 0.73% - 8.39% respectively as shown in Figure 1 and Table 1. Numerous studies observed that applying Zn and Fe significantly influences crops' plant growth, shelf life, quality, and productivity of strawberry crop. For instance, de la Rosa et al. (2013) observed, increased shelf life and minimum spoilage and decay percentage in strawberry fruits are due to the application of $ZnSO_4$ in tomato, which might impute the availability of the appropriate quantity of Zn within the system of plants as the element elevates ribosome and ribonucleic acid (de la Rosa et al., 2013). Iron's influence on the spoilage percentage by the foliar application may be related to its availability and involvement in photosynthesis, which boosts the photosynthetic rate in the plant and produces more quality fruit for guava crop (Yogeesha et al., 2005). A study by Raliya and Tarafdar (2013) observed that various concentrations of NPs were applied to cucumber, alfalfa, and tomato to decrease the mass decay percentage of the fruits (Raliya and Tarafdar, 2013). Based on a study, it was noted that the simultaneous application of Zn and Fe nanoparticles at different concentrations led to an enhanced life span of strawberry fruits at various concentrations in comparison with the control (Kumar et al., 2017). Sing et al. (2005) discovered that $ZnSO_4$ by foliar application method in papaya plants, accelerated blooming in the papaya and more fruit having more life span compared with the control (Singh et al., 2005).

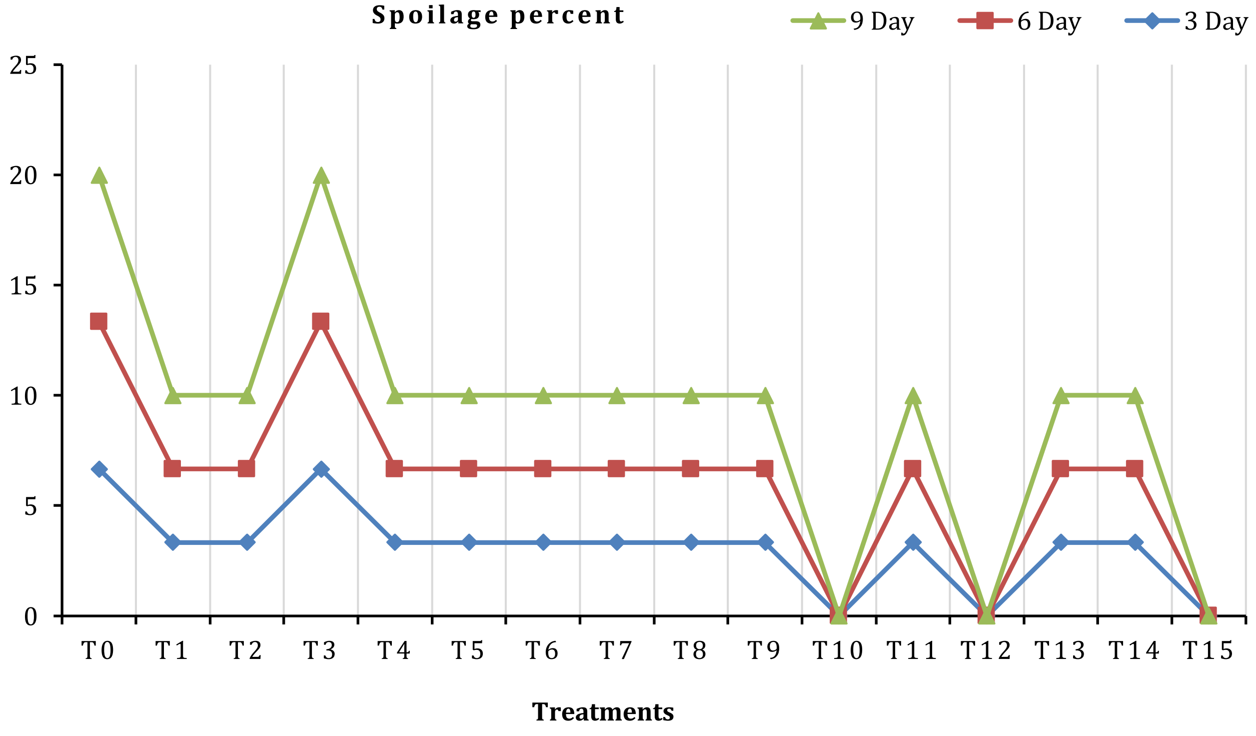

Figure 1. Effect of zinc oxide and iron oxide on spoilage percentage of strawberry

Total Soluble solids

In comparison, the minimum TSS was recorded at 3 days interval in T_0 having a value of (5.53 °brix) and maximum was recorded in T_7 (6.99 °brix) after 6 days interval the maximum value for TSS in °brix was observed in 7.15 and minimum was observed in T_0 (6.25 °brix) and at 9 days interval the value for TSS is 7.25 °brix in T_{14} and minimum in T_{12} (7.10 °brix) as shown in Table 1. TSS °brix of strawberry was observed from 5.53 °brix-7.25 °bix respectively. Same finding was observed by Chaturvedi et al. (2005) that maximum 9.42^0 Brix was recorded with a lower concentration of ferrous sulfate (0.2%), closely trailed by 0.4% zinc sulfate (9.32^0 Brix). Zinc and iron sprays demonstrated significant support for photosynthesis, thereby enhancing fruit quality. Additionally, zinc plays a pivotal role in regulating enzymatic activity, facilitating the conversion of carbon compounds into glucose (Chaturvedi et al., 2005).

Table 1. Effect of zinc oxide and iron oxide on spoilage, tss, acidity and ascorbic acid of strawberry

Treatments	Spoilage % (Days Interval)			TSS °Brix (Days Interval)			Acidity % (Days Interval)			Ascorbic acid mg/100g (Days Interval)		
	3 Day	6 Day	9 Day	3 Day	6 Day	9 Day	3 Day	6 Day	9 Day	3 Day	6 Day	9 Day
T_0	2.79^{b}	5.85^{d}	8.39^{d}	5.53^{a}	6.25^{ab}	7.28^{a}	0.53^{abc}	0.50^{abc}	0.47^{ab}	49.35^{ab}	47.93^{a}	46.63^{a}
T_1	1.22^{ab}	2.68^{abc}	3.99^{bc}	5.58^{a}	5.98^{a}	7.22^{a}	0.49^{a}	0.47^{a}	0.45^{a}	49.14^{a}	48.65^{ab}	46.81^{a}
T_2	1.08^{ab}	2.27^{ab}	3.40^{ab}	5.69^{ab}	6.13^{a}	7.18^{a}	0.60^{cde}	0.58^{cd}	0.56^{cd}	50.18^{abcde}	49.10^{abc}	47.20^{a}
T_3	1.22^{ab}	2.76^{abc}	3.83^{bc}	6.05^{bc}	6.20^{ab}	7.23^{a}	0.61^{cde}	0.59^{cde}	0.58^{cd}	50.98^{bcde}	49.93^{bcd}	48.61^{a}
T_4	1.97^{ab}	2.58^{ab}	3.37^{ab}	6.23^{cde}	6.74^{cd}	7.24^{a}	0.65^{def}	0.63^{def}	0.61^{cd}	51.36^{de}	50.44^{cd}	47.59^{a}
T_5	1.09^{ab}	2.23^{ab}	3.04^{ab}	6.09^{bcd}	6.38^{abc}	7.18^{a}	0.70^{f}	0.68^{ef}	0.65^{d}	51.61^{e}	50.38^{cd}	48.13^{ab}
T_6	1.54^{ab}	2.26^{ab}	3.12^{ab}	5.75^{ab}	6.17^{a}	7.12^{a}	0.62^{def}	0.60^{ab}	0.57^{d}	51.07^{cde}	49.69^{bcd}	48.00^{ab}
T_7	1.35^{ab}	2.74^{abc}	4.21^{bc}	6.99^{f}	7.15^{d}	7.15^{a}	0.50^{a}	0.49^{def}	0.47^{ab}	49.52^{abc}	48.37^{ab}	46.59^{ab}
T_8	1.91^{ab}	3.53^{abc}	4.31^{bc}	5.60^{a}	5.95^{a}	7.16^{a}	0.62^{def}	0.60^{def}	0.57^{cd}	50.48^{abcde}	49.19^{abc}	47.00^{ab}
T_9	2.19^{ab}	4.65^{cd}	5.63^{c}	6.81^{fg}	6.95^{d}	7.22^{a}	0.70^{f}	0.68^{f}	0.65^{d}	51.82^{e}	50.69^{cd}	47.12^{a}
T_{10}	1.92^{ab}	3.03^{abc}	4.89^{bc}	6.40^{cdef}	6.67^{bcd}	7.15^{a}	0.58^{bcd}	0.56^{bcd}	0.54^{bc}	49.85^{abcd}	49.15^{abc}	47.18^{a}
T_{11}	1.61^{ab}	0.11^{bc}	3.98^{bc}	6.41^{cdef}	6.77^{cd}	7.23^{a}	0.63^{def}	0.61^{def}	0.59^{cd}	51.18^{cde}	49.96^{bcd}	47.89^{a}
T_{12}	1.81^{ab}	3.00^{abc}	3.66^{ab}	6.50^{def}	6.84^{cd}	7.10^{a}	0.61^{cde}	0.60^{def}	0.57^{cd}	51.71^{e}	50.68^{cd}	48.75^{a}
T_{13}	1.29^{ab}	2.93^{abc}	3.95^{bc}	6.78^{fg}	7.00^{d}	7.24^{a}	0.67^{def}	0.64^{def}	0.61^{cd}	50.99^{bcde}	49.52^{abcd}	48.15^{a}
T_{14}	1.17^{ab}	3.44^{abc}	4.45^{bc}	6.61^{efg}	6.78^{cd}	7.25^{a}	0.61^{cde}	0.58^{cd}	0.56^{c}	50.36^{abcde}	49.13^{abc}	46.90^{ab}
T_{15}	0.73^{ab}	1.51^{a}	1.91^{a}	6.28^{cde}	6.39^{abc}	7.17^{a}	0.68^{ef}	0.65^{def}	0.63^{cd}	51.59^{e}	50.99^{d}	49.66^{b}

T_0 (Control 100% RDF), T_1 (50mg/l ZnO NPs), T_2 (100 mg/l ZnO NPs), T_3 (150 mg/l ZnO NPs),T_4 (50 mg/l FeO NPs), T_5(100 mg/l FeO NPs), T_6 (150 mg/l FeO NPs), T_7 (50mg/l ZnO NPs + 50mg/l FeO NPs), T_8 (50pm ZnO NPs + 100mg/l FeO NPs), T_9 (50mg/l ZnO NPs+ 150mg/l FeO NPs), T_{10} (100mg/l ZnO NPs + 50mg/l FeO NPs), T_{11} (100mg/l ZnO NPs+ 100mg/l FeO NPs), T_{12} (100mg/l ZnO NPs + 150mg/l FeO NPs), T_{13} (150mg/l ZnO NPs + 50mg/l FeO NPs), T_{14} (150mg/l ZnO NPs + 100mg/l FeO NPs), T_{15} (150mg/l ZnO NPs + 150mg/l FeO NPs)

Acidity

Readings on acidity percentage of strawberry fruits Cv. Winter Dawn significant variations were found between different treatments. The data showed that maximum acidity (0.70%) was observed in T_5 and T_9, and minimum (0.49%) was recorded in T_0 at 3 days interval after 6 days interval maximum acidity was observed in T_9 (0.68%) and minimum in T_1 (0.47%). At 9 days interval maximum acidity percentage was noted in T_5 and T_9 (0.65%) respectively and minimum was recorded T_1 (0.45%) as shown in Table 1. Acidity (%) of strawberry fruits was observed from 0.45%-0.70% respectively shown in Figure 1 and Table 1. The maximum contents of acidity (0.968%) was observed with 0.4 per cent zinc sulphate, closely followed by 0.2 per cent ferrous sulphate (65.94 mg and 0.967%). This increase might be due to the fact that zinc works as stimulant of amino acids and appears to be helpful in the process of photo synthesis and accumulation of carbohydrates (Kumar et al., 2022).

Ascorbic Acid

Significant variations were found among all the treatments on the 3, 6 and 9 days interval after harvesting regarding ascorbic acid of fruits; maximum ascorbic acid content at 3 days interval was observed in T_{12} (51.71 mg/100g) and minimum was recorded in T_1 (49.14 mg/100 g) after 6 days interval maximum ascorbic acid was noted in T_{15} (50.99 mg/100g) and minimum was noted in T_0 (47.93 mg/100g). At 9 days interval maximum content of ascorbic acid was observed in T_{15} (49.66 mg/100g) and minimum was recorded in T_0 (46.63 mg/100g) as shown in Table 1 and Figure 2. Ascorbic acid (mg/100g) of strawberry fruits was observed from 46.63 mg/100g-51.71 mg/100g respectively. Highest levels of ascorbic acid (66.10 mg) were observed with 0.4% zinc sulfate, closely followed by 0.2% ferrous sulfate (65.94 mg and 0.967%, respectively). This augmentation could be attributed to the role of zinc as a stimulant for amino acids, contributing to the process of photosynthesis and carbohydrate accumulation. In guava, the highest levels of ascorbic acid was recorded with 0.4% zinc sulfate (Sharma et al., 1991). Furthermore, the shelf life of berries increased with 0.6% zinc sulfate when stored at ambient temperature (Jurgens, 1990). By the Foliar application of micronutrient mixture (1%) (Ca, Fe and Zn) on banana cv. Grand Naine recorded maximum amount of ascorbic acid (0.70 mg/100 g) (Yadlod and Kadam, 2003).

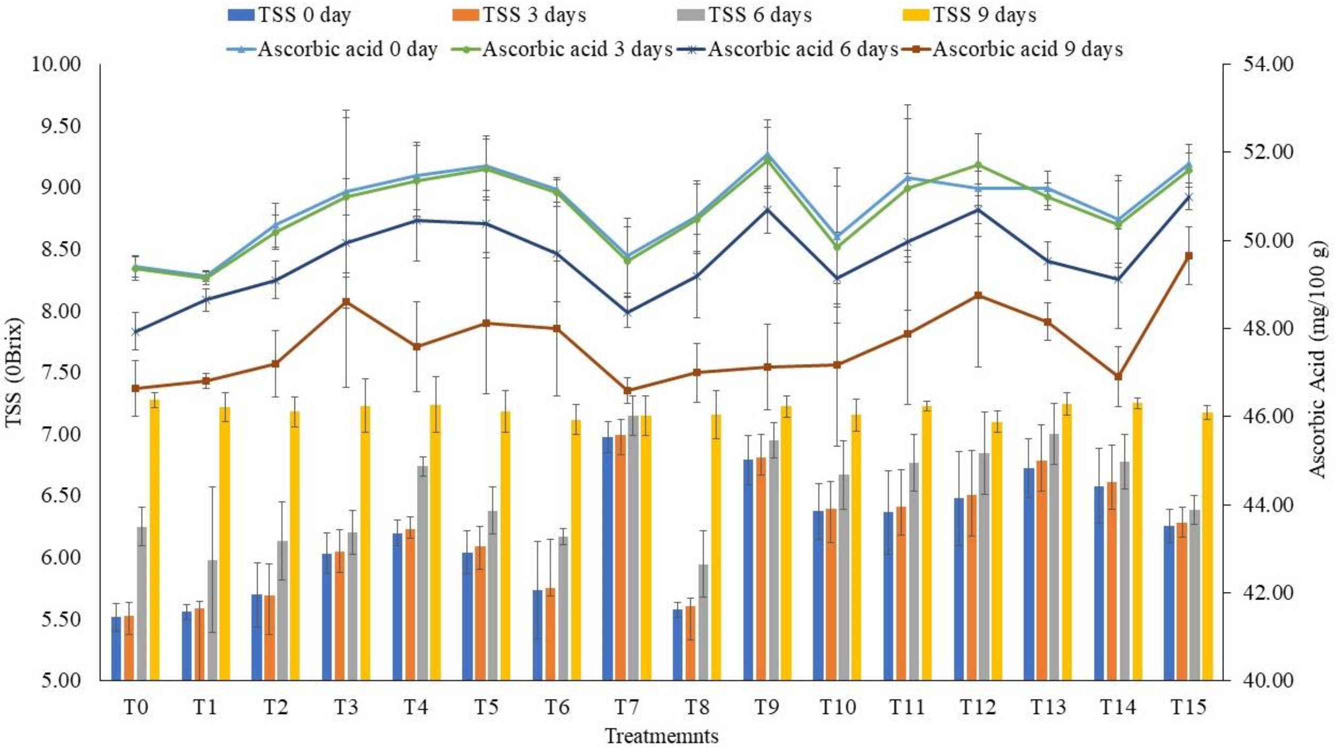

Figure 2. Effect of Zinc oxide and Iron oxide on TSS ºBrix and Ascorbic acid content (mg/100g) of strawberry

Anthocyanin Content

Concerning the anthocyanin content (mg/l), variations were found amongst all the treatments. Maximum anthocyanin content at 3 days interval was observed in T_{15} (41.12 mg/l) and minimum in T_0 (32.28 mg/l) after 6 days interval maximum ascorbic acid was noted down in T_{15} (41.56 mg/l) and minimum in T_0 (32.56 mg/l) after 9 days interval same findings was observed maximum anthocyanin content was observed in T_{15} (39.82 mg/l) and minimum in T_0 (31.44 mg/l). The value of anthocyanin content was varying from 31.44 mg/l-41.56 mg/l as shown in Figure 3. and Table 2. In 2019 Panigrahi observed that with the foliar application of ferrous sulphate at 0.2-0.6 per cent alone in plants promote the development of vibrant colors and desirable anthocyanin content. Fruits with well-developed color and flavor appeal more to consumers and have a longer shelf life. Iron is involved in synthesizing pigments, such as anthocyanins and flavonoids, which contribute to the color and flavor of fruits (Panigrahi et al., 2019).

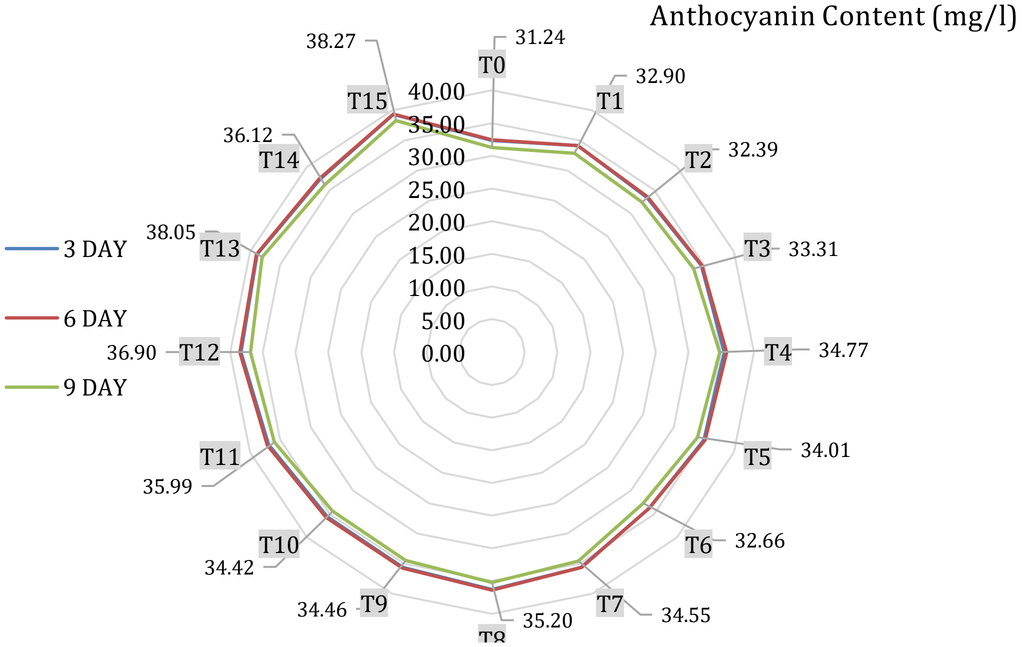

Figure 3. Effect of ZnO and FeO on Anthocyanin content (mg/100g) of strawberry

Table 2. Effect of zinc oxide and iron oxide on anthocyanin content, total sugars, and reducing sugars of strawberry at different days interval

Treatments	Anthocyanin Content (mg/l) (Days Interval)			Total Sugars (%) (Days Interval)			Reducing Sugars (%) (Days Interval)		
	3 Day	6 Day	9 Day	3 Day	6 Day	9 Day	3 Day	6 Day	9 Day
T_0	32.28^{a}	32.56^{a}	31.44^{a}	7.15^{bc}	7.53^{bcde}	8.40^{e}	4.48^{bcd}	4.54^{bcd}	4.77^{bcde}
T_1	33.59^{ab}	33.76^{ab}	32.91^{ab}	7.19^{bc}	7.42^{bcd}	7.71^{bc}	4.21^{bc}	4.31^{bc}	4.39^{abc}
T_2	33.43^{ab}	33.65^{ab}	32.72^{ab}	6.54^{a}	6.75^{bcde}	7.08^{a}	3.56^{a}	3.61^{a}	3.83^{a}
T_3	34.57^{abcd}	34.82^{abc}	33.94^{abcd}	7.21^{bc}	7.46^{bcd}	7.82^{bc}	4.52^{bc}	4.55^{bcd}	4.76^{bcde}
T_4	34.64^{abcd}	34.85^{abc}	33.82^{abcd}	7.34^{bcd}	7.56^{a}	7.82^{a}	4.33^{bcd}	4.40^{a}	4.52^{bcd}
T_5	37.77^{cdef}	38.11^{cde}	37.26^{cdef}	7.66^{bcde}	7.82^{bcd}	8.03^{bcd}	4.62^{bcd}	4.68^{bcd}	4.83^{bcde}
T_6	33.97^{abc}	34.15^{ab}	33.41^{abc}	7.17^{bc}	7.32^{bcde}	7.54^{ab}	4.13^{ab}	4.20^{b}	4.38^{abc}
T_7	36.73^{bcde}	36.95^{bcd}	36.18^{bcdef}	7.98^{de}	8.10^{bcde}	8.34^{de}	4.95^{bcd}	4.99^{cd}	5.16^{e}
T_8	34.56^{abcd}	34.82^{abc}	33.90^{abcd}	7.38^{bcd}	7.57^{bc}	7.80^{bc}	4.34^{bcd}	4.41^{bcd}	4.54^{bcde}
T_9	36.16^{abcde}	36.46^{abcd}	35.34^{abcde}	7.88^{de}	8.01^{e}	8.17^{cde}	4.83^{d}	4.88^{cd}	5.03^{cde}
T_{10}	38.61^{ef}	38.83^{de}	37.93^{ef}	7.78^{cde}	7.90^{cde}	8.08^{bcd}	4.76^{bcd}	4.82^{bcd}	4.98^{cde}
T_{11}	38.25^{def}	38.50^{cde}	37.52^{def}	7.55^{bcde}	7.75^{de}	8.04^{cde}	4.50^{bcd}	4.58^{bcd}	4.76^{bcde}
T_{12}	35.73^{abcde}	35.97^{abcd}	35.25^{abcde}	7.10^{bc}	7.27^{cde}	7.63^{bc}	4.13^{ab}	4.22^{bc}	4.33^{ab}
T_{13}	40.61^{f}	40.94^{e}	39.36^{f}	7.64^{bcde}	7.74^{bcde}	8.05^{bcde}	4.52^{bcd}	4.58^{bcd}	4.73^{bcde}
T_{14}	37.90de^{f}	38.36^{cde}	37.48^{def}	7.21^{bc}	7.33^{ab}	7.71^{bc}	4.22^{bc}	4.28^{bc}	4.39^{abc}
T_{15}	41.12^{f}	41.56^{e}	39.82^{f}	7.56^{bcde}	7.66^{bcde}	7.84^{bcd}	4.50^{bcd}	4.60^{bcd}	4.71^{bcde}

T_0 (Control 100% RDF), T_1 (50mg/l ZnO NPs), T_2 (100 mg/l ZnO NPs), T_3 (150 mg/l ZnO NPs),T_4 (50 mg/l FeO NPs), T_5(100 mg/l FeO NPs), T_6 (150 mg/l FeO NPs), T_7 (50mg/l ZnO NPs + 50mg/l FeO NPs), T_8 (50pm ZnO NPs + 100mg/l FeO NPs), T_9 (50mg/l ZnO NPs+ 150mg/l FeO NPs), T_{10} (100mg/l ZnO NPs + 50mg/l FeO NPs), T_{11} (100mg/l ZnO NPs+ 100mg/l FeO NPs), T_{12} (100mg/l ZnO NPs + 150mg/l FeO NPs), T_{13} (150mg/l ZnO NPs + 50mg/l FeO NPs), T_{14} (150mg/l ZnO NPs + 100mg/l FeO NPs), T_{15} (150mg/l ZnO NPs + 150mg/l FeO NPs

Total Sugars and Reducing Sugars

At 3 days interval the maximum value for total sugars was observed in T_7 (7.98%) and maximum reducing sugars was also noted in T_7 (4.95%) while minimum total sugars and reducing sugars was observed in T_2 (6.54%, 3.56%) and after 6 days interval the maximum total sugars was recorded in T_7 (8.10%) and reducing sugars (4.99%) and minimum in T_2 (6.75% and 3.61%). At 9 days interval the maximum value for total suagrs and reducing sugars was recorded maximum in T_7 (8.34% and 5.16%) and T_2 having minimum values (7.08% and 3.83%). Total sugars (%) of strawberry fruits was observed from 6.54%-8.34% and reducing sugars was noted from 3.16%-4.99% respectively as shown in Table 2. In 1983, Singh and Chhonkar conducted research and observed that total soluble solids and total sugars were recorded maximum in guava by foliar spray of 0.2% $ZnSO_4$ (Singh and Chhonkar 1983). With the application of 0.4% $ZnSO_4$ (T_4) recorded highest total sugar (5.42%) and reducing sugar (4.19%). As a component of proteins, zinc acts as a functional, structural, or regulatory cofactor of a large number of enzymes and involved in carbohydrate metabolism (Mousavi et al., 2013).

Conclusion

Present research showed the efficacy of various treatments on the shelf life of strawberry fruits with the application of nano-form of ZnO and FeO, with a specific focus on cv. Winter Dawn. Notably, treatments T_{15} Z_3F_3 (150mg/l ZnO NPs + 150mg/l FeO NPs) and T_{11} Z_2 F_2 (100mg/l ZnO NPs + 100mg/l FeO NPs) have emerged as particularly promising avenues. The concurrent application of ZnO and FeO NPs has demonstrated notable benefits, as evidenced by microbial analysis highlighting the antimicrobial properties of ZnO NPs, thereby contributing significantly to the prolonged shelf life of the fruits. When combined with ZnO, FeO substantially enhances the shelf life of fruits. Zinc oxide at a concentration of 150mg/l fulfills essential functions such as chlorophyll production, thylakoid synthesis, and chloroplast maintenance, while iron oxide at the same concentration complements these processes, further enhancing the fruits' longevity. It can be recommended that the combining ZnO and FeO (150 mg/l) could enhance the shelf life of strawberry.

List of Abbreviations

ZnO-Zinc oxide, FeO- Iron oxide, NPs- Nanoparticles, DAT- Days after transplanting, g- Gram, $ZnSO_4$- Zinc sulphate, mg/l- Milligram per litre, Cv.- Cultivar, DAP-Diammonium phosphate, MOP-Muriate of Potassium, g/cm^{3}- Gram per centimeter cube, nm-Nanometer.

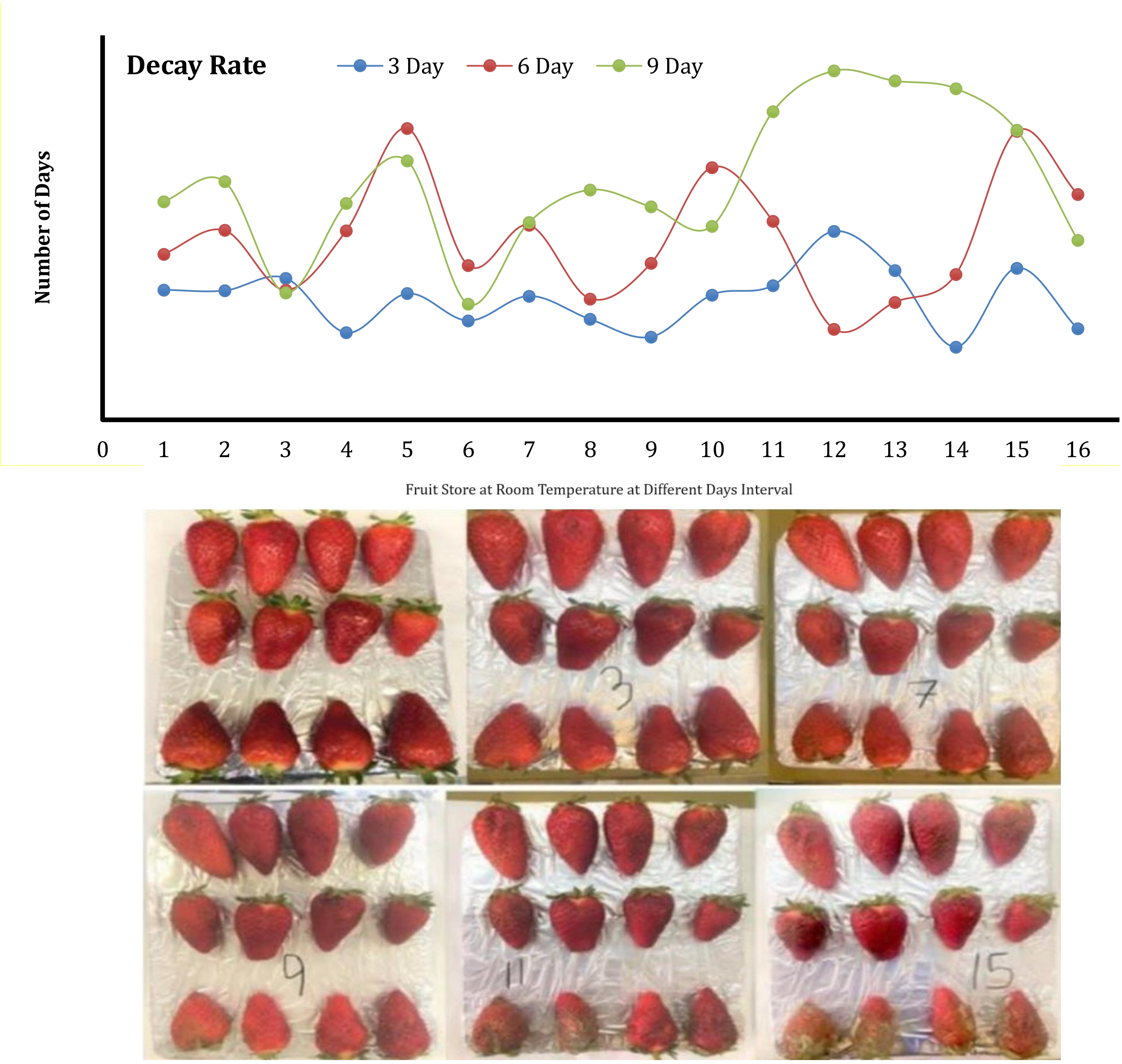

Figure 4. Effect of ZnO and FeO on decay rate with storage time in days (0-15) of

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