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Potential Impact of Silica and/or Alumina Combined with Potassium and/or Manganese on Potato Growth and Productivity

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WITH THE growing demand for the potato crop to fill the food gap in the world, in conjunction with the challenges facing potato cultivation due to climate change, the work in improving its productivity and tuber quality has become a critical aim. So, a field trial was carried out aiming to investigate the influence of spraying nano silica and/or nano alumina combined with potassium acetate and/or Mn-EDETA on potato growth, yield and tuber quality during the 2024/2025 growing season under the split plot experimental design. The main plots included the Nano silica and alumina treatments [Control (tap water), nano alumina (at rate of 10 ppm), nano silica (at rate of 10 ppm) Nano alumina (at rate of 5.0 ppm) + nano silica (at rate of 5.0 ppm)], while the sub main plots included the potassium acetate and Mn-EDETA treatments [Control (tap water, K (at rate of 2.5 cm^3L^{-1}), Mn (at rate of 1.0 g L^{-1}), K (at rate of 2.5 cm^3L^{-1}) + Mn (at rate of 1.0 gL^{-1})]. Concerning the individual effect of nano-silica and alumina, the highest values of all studied parameters such as plant height (cm), fresh and dry weights ($gplant^{-1}$) after 70 days from planting, as well as tuber traits, including average tuber weight (g), No. of tuber plant-1 and yield (ton fed^{-1}), vitamin C (VC, mg $100g^{-1}$), total carbohydrates (%), dry matter (%) and total sugars (%) in tubers were realized with the combined application of both nanoparticles, followed by the nano-silica alone, then nano-alumina alone and lately the control treatment. Regarding the individual effect of potassium and manganese, the highest values of aforementioned traits were realized with the combined treatment of potassium and manganese, followed by manganese alone and then potassium alone, and lastly the control treatment. Notably, The interaction between nano silica and/or nano alumina combined with potassium and/or manganese treatments further emphasized the synergistic role of the studied treatments, as the combined treatment of nano silica and nano alumina + potassium and manganese resulted in the highest values of all studied growth, yield and quality traits. Therefore, this study recommends the incorporation of this approach into potato fertilization programs. Also, it can be said that this study represents a preliminary trial and forms the basis for longer trials in the future.

Keywords: Sustainability, Tuber quality, Nano-scale form, Plant nutrient.

1. Introduction

Potato (*Solanum tuberosum* L.) is one of the most critical strategic crops in Egypt and the world due to its economic and nutritional importance. It is rich in carbohydrates, protein, fiber and vitamin C. **(Abdelhalem, 2022)**. With the increasing demand for potato crops to fill the food gap, in addition to the challenges facing potato cultivation due to climate change, it has become imperative to improve both its productivity and tuber quality **(Abd El-Hady & Mosaad, 2023).** Therefore, all those working in the field of plant nutrition must work to improve potato fertilizer programs by introducing modern approaches that contribute to increasing absorption efficiency, improving plant physiological performance, and increasing yield and quality. Among these promising approaches is the incorporation of elements such as silica (silicon dioxide) and alumina (aluminum oxide) into potato fertilizer programs. Silica is one of the most important compounds, which has an important role in the physiological processes in higher plants (**Wadas, 2021; Awad-Allah, 2023).** It improves higher plant resistance to environmental stress as well as it enhances growth criteria and improves cellular structure *via* its vital role in regulating transpiration and strengthening cell walls (**De-Sousa et** ***al.*** **2019; Puppe** ***et al.*** **2024)**. Alumina also plays an essential role in the physiological processes in higher plants *via* stimulating enzyme activities **(Liu** ***et***

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***al.* 2020; Dağlıoğlu *et al.* 2022),** regulating the absorption of micronutrients and improving the higher plant's ability to adapt to stressful circumstances (**Riahi *et al.* 2012; Belhamel *et al.* 2020).**

In other words, silica and alumina play a potentially important role in enhancing the uniformity of the tuber size through their direct influence on vegetative growth criteria and potato plant physiological activity. Silica contributes to enhance the plant's ability to withstand environmental stresses *e.g.,* drought and salinity, which positively impacts the efficiency of water and nutrient absorption, hence improving the balanced distribution of stored substances within the tubers. Silica also plays a vital role in strengthening cell walls, contributing to the regularity of cell division and growth within the tuber. Furthermore, alumina is a potential source of aluminum in small quantities, which may indirectly influence the regulation of enzymatic activity within the plant, contributing to the stability of the biological processes responsible for tuber formation (**De-Sousa et *al.* 2019; Wadas, 2021; Puppe *et al.* 2024)**. Both silica and alumina may be more effective when they are applied in nano scale form, which lead to enhance fertilization efficiency in comparison with the conventional form. The nano scale approach reduces the amount of industrial chemical fertilizers used while preserving the environment (**Riahi *et al.* 2012; De-Sousa et *al.* 2019).**

Potassium element (K) is one of the major essential nutrients for potato plant, as K plays a critical role in transporting both carbohydrate and sugars from the leaves of potato to their tubers, hence it can be said than K positively affects tuber size and improves their dry matter content **(Abdelhalem, 2022)**. Potassium also helps regulate the opening and closing of stomata **(El-Metwally *et al.* 2025).** Furthermore, its presence in its organic form, such as potassium acetate, shows a greater capacity for rapid absorption and effective results in a short period (**Hussein, 2023)**. Manganese is an essential microelement, plying a vital role in chlorophyll formation and the activation of several enzymes (**Makhlouf, 2023)**. Additionally, Its effectiveness is enhanced when it presented in a chelated form (Mn-EDETA), which facilitates Mn absorption and maximizes plant benefits (**Sheta *et al.* 2025)**.

Therefore, the major aim of the current research work is to investigate the effect of Nano silica and/or Nano alumina combined with potassium acetate and /or Mn-EDETA on potato growth, yield and tuber quality. To our knowledge, this is the first study to examine the interaction impact of nano silica, nano alumina, potassium and manganese on potato under Egyptian field circumstances. Understanding these interactions may help design more efficient nutrient management strategies to improve tuber quality and crop uniformity. In this research, it is hypothesize that the combination among silica and alumina with potassium and manganese will have a synergistic impact on potato tuber size uniformity *via* enhancing the nutrient uptake efficiency and higher plant physiological responses. This hypothesis can be tested *via* field trail and statistical analysis of the treatment interactions.

2. Materials and Methods

A field trail was implemented during the season 2024 at a private farm located in Serewa village, Bilaa district, Kafr El-Sheikh Governorate, Egypt, aiming to investigate the influence of spraying Nano silica and/or Nano alumina combined with potassium acetate and/or Mn-EDETA on potato growth, yield and tuber quality during the 2024/2025 growing season. The split plot experimental design was used under this investigation, as the main plots included the nano silica and alumina treatments [Control (tap water), nano alumina (at rate of 10 ppm), nano silica (at rate of 10 ppm) nano alumina (at rate of 5.0 ppm) + nano silica (at rate of 5.0 ppm)], while the sub main plots included the potassium acetate and Mn-EDETA treatments [Control (tap water, K (at rate of 2.5 cm^3L^{-1}), Mn (at rate of 1.0 g L^{-1}), K (at rate of 2.5 cm^3L^{-1}) + Mn (at rate of 1.0 gL^{-1})]. Each plot measured 12 m² (4.0 m width × 3.0 m length), containing 30 potato plants, arranged in 5 ridges, with 6 plants ridge-1, as the spacing between plants within the row was 30 cm, which corresponds to a plant density of approximately 19,000 plants per feddan. Potatoes were planted at a depth of 10–12 cm. Figure 1 shows the flowchart of the trial.

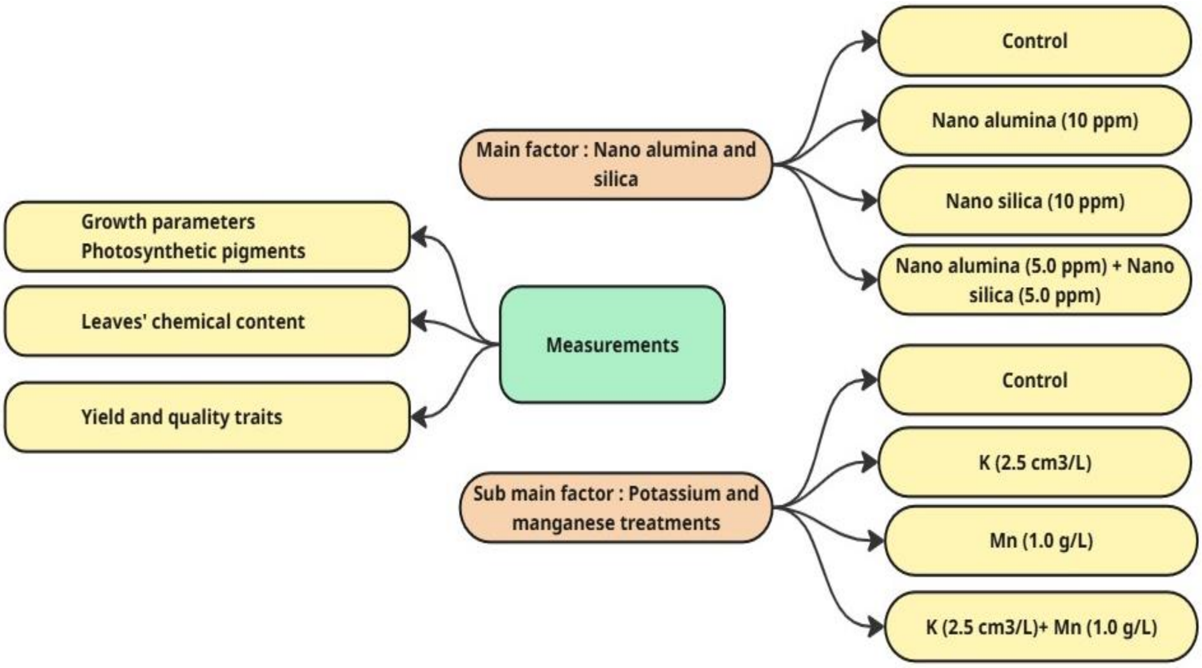

Fig. 1. The flowchart of the experiment.

The experiment was carried out in clayey soil having 49, 31 and 20% clay, silt and sand, respectively. It possesses available N, P, K, Mn and Si with values of 20.2, 7.3, 210, 1.5 and15.0 $mgkg^{-1}$, respectively, while Al in soil was not detected. Additionally, the studied soil has EC and pH values of 3.25 dSm^{-1} and 7.99, respectively. The standard methods, which used in the initial soil analysis, are shown in Table1.

Table 1. Soil analysis methods.

Parameters	Methods	References
Particle size distribution (clay, silt and sand)	*Via* using pipette method	**[1]**
Available N, P, K	*Via* Kjeldahl method, spectrophotometric method, flame photometer	**[2]**
Soil EC (1:5, soil extract) Soil pH (1:2.5, soil suspension)	EC-meter pH-meter	**[3]**

List of refs: [1] Gee and Baudet (1986), [2] Sparks *et al.* (2020), [3] Dewis and Freitas, (1970)

Silica and alumina were purchased and then turnt into Nanoparticles *via* a biological method, specifically biosynthesis using active algae, which was used to produce algae-based nanoparticles. Algae of the species *Sargassum latifolium* were used in turning silica and alumina into Nano-Silica and Nano-alumina. This method involves leveraging the natural characteristics of algae to encapsulate and transform salt particles into a nano-sized form suitable for higher plant absorption. This process was implemented by Bio-Nano Apparatus in the Agri. Chemistry Dept., Faculty of Agri, Mansoura Univ (**El-Ghamry and El-Khateeb (2021)**. Table 2 shows some information of silica and alumina products, while Figures 2 and 3 display the results of Transmission Electron Microscope (TEM) for both Nano-silica and Nano-alumina. On the other hand, Table 3shows the property of potassium and manganese used in this investigation.

Table 2. Silica and alumina information.

Product name	Silicon dioxide	Aluminum oxide
Molecular formula	SiO_2	Al_2O_3
Molecular weight	60.08 g/mol	101.96 g/mol
Purity	99%	99%
Density	2.65 g/cm^3	3.95 g/cm^3

Table 3. Characteristics of the potassium and manganese salts studied.

Trace element	Potassium (K)	Manganese (Mn)
Salt	Potassium acetate	Chelated manganese
Chemical Formula	CH_3 COOK (50%K)	Mn-EDTA (13%Mn)
Purity	99%	99%
Density	1.57 g/cm³	0.9 g/cm³

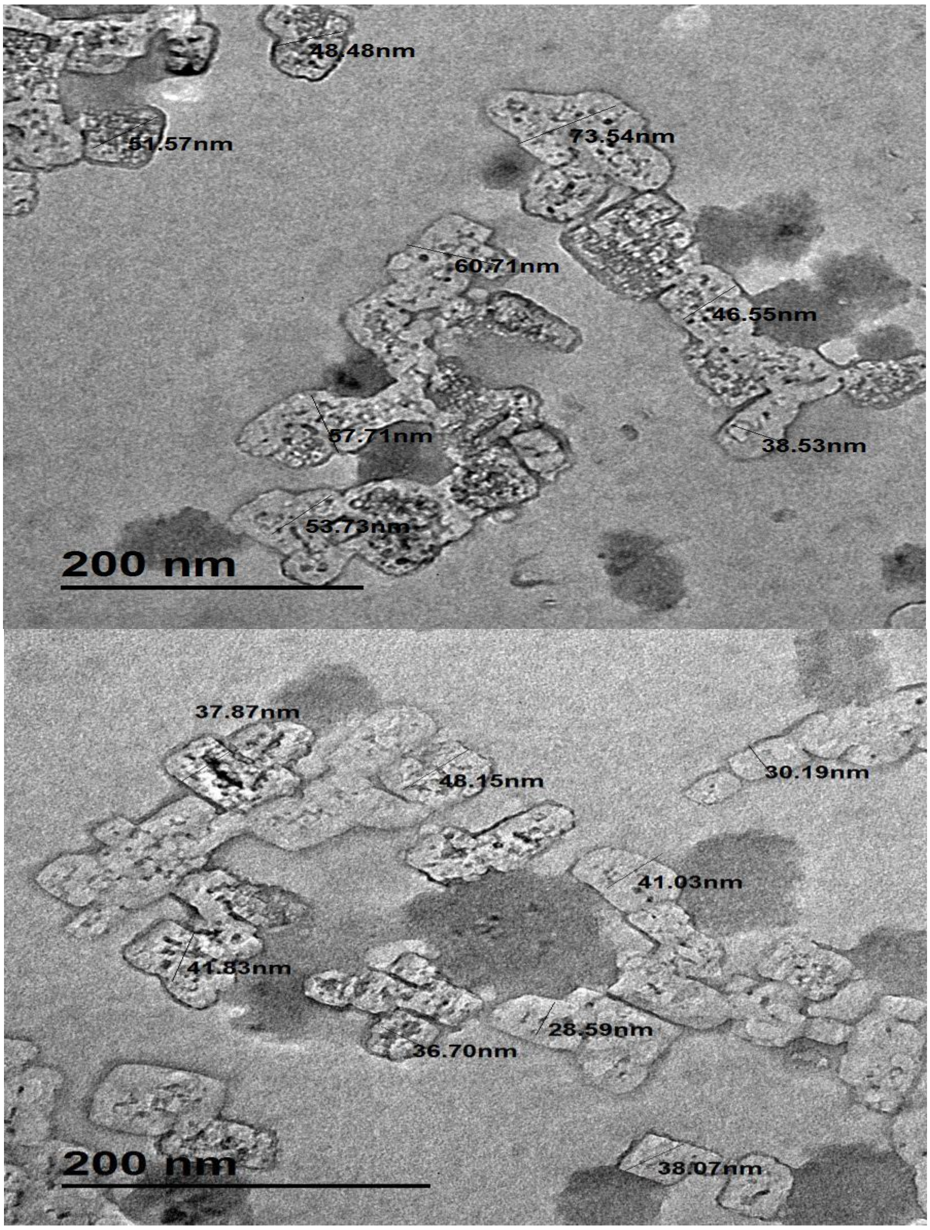

Fig. 2. TEM for silica.

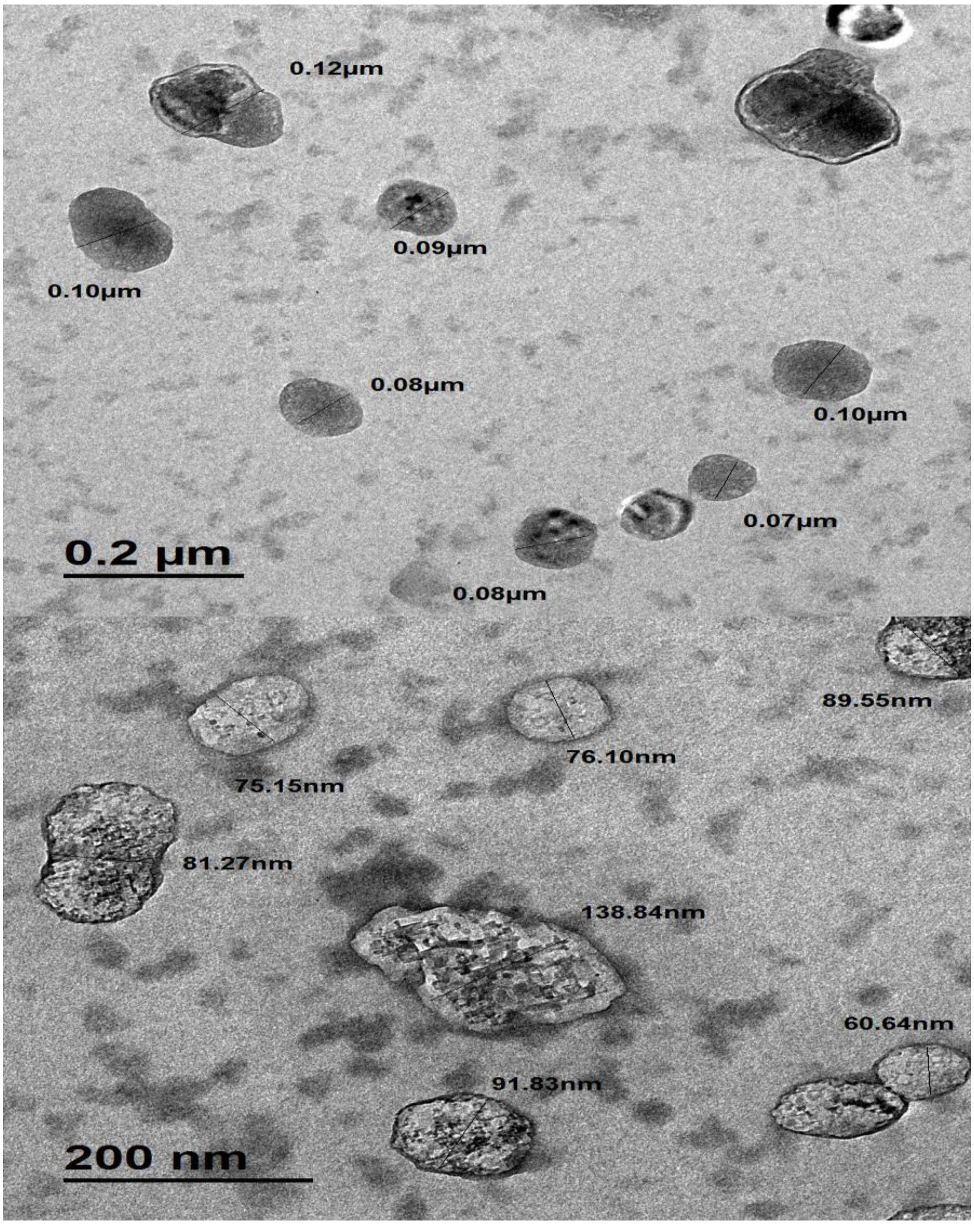

Fig. 3. TEM for alumina.

The solutions of nano silica and nano alumina were prepared according to the studied treatments, as they were applied 3 times, starting from 45 days after planting, with an interval of 14 days. Tubers were obtained from MASR (Ministry of Agriculture and Soil Reclamation).To maximize the number of planting units from available seed, tubers (Sponta Varity) were cut into smaller pieces prior to planting. Each piece weighed approximately 40.0 g on average and contained at least one to two healthy and well-developed sprouting eye buds. The scientific rationale for cutting seed potatoes is based on agronomic practices that aim to balance plant vigor and resource use efficiency. Cutting allows for more plants per unit of seed weight, reduces costs, and promotes uniform sprouting when done correctly. Tubers were cut using a sterilized sharp knife under hygienic conditions to minimize the risk of disease transmission. After cutting, pieces were left to heal and suberize at room temperature (typically for 2–3 days) in a shaded, well-ventilated area. This healing process forms a protective layer over the cut surface, which helps prevent infections after planting. Potato tubers pieces were sown on 15 January. Compost was added at rate of 7 ton fed^{-1} at 30 days before planting as well as calcium superphosphate was added at the same time at a rate of 150 kg fed^{-1}. Ammonium nitrate was added in two equal doses at a rate of

70 unit N fed^{-1} with the 1st and 2nd irrigation events after planting. Potassium sulphate was added at a rate of 50 kg fed^{-1} with the 3^{rs} irrigation event after planting. The guidelines of MASR for potato production were followed. The harvest process was done on 13 May. Implemented measurements to evaluate the studied treatments are shown in Table 4. The obtained data were statistically analyzed as described by **Gomez and Gomez (1984)** by CoStat software **(Version 6.303, CoHort, USA, 1998-2004)** and Duncan's Multiple Range Test at a significance level of 0.05. The data were analyzed using split-plot ANOVA, which accounts for the hierarchical structure of the design and the appropriate error terms for main plots and sub-plots.

Table 4. Measurements during the studied stages.

Parameters	Methods	References
Plant height (cm), fresh weight and dry weight (gplant^{-1}), No. of leaves plant^{-1}	Manually	--------------
Leaf area, (cm^2 plant^{-1})	leaf area was calculated using the following formula Leaf area (cm^2) = Length × Width × correction factor (0.65)	**[1]**
Chlorophyll a & b and carotene pigments (mg g^{-1})	Spectrophotometrically, using acetone	**[2]**
Digestion of potato leaves for leaf chemical NPK	Using a mixture of $HClO_4$ + H_2SO_4 *via* Kjeldahl, spectrophotometr and flame photometer apparatus for NPK, respectively	**[3,4]**
a. At harvest (at 115 days from planting)		
Average tuber weight (g), No. of tuber plant^{-1} and yield (ton fed^{-1})	Manually	--------------
Tuber chemical constituents (NPK)	The same method used in leaf analysis	**[3,4]**
Vitamin C (VC, mg 100g^{-1}), total carbohydrates (%), dry matter (%), total sugars (%), total dissolved solids (TDS, %)	According to the standard methods mentioned in association of official analytical chemists	**[5]**

List of refs: [1] Gordon *et al*. (1997), [2] Wellburn (1994), [3] Peterburgski (1968),[4] Walinga *et al.* (2013),[5] AOAC (2000)

3. Results

3.1. Vegetative growth parameters

Table 5 displays the effect of nano-silica and/or nano-alumina combined with potassium and/or manganese on potato growth parameters, *i.e.*, plant height (cm), fresh and dry weights (g plant^{-1}), No. of leaves plant^{-1} and leaf area (cm^2 plant^{-1}) at 70 days from planting during the growing season of 2023/2024. As for the individual effect of nano-silica and nano-alumina, the highest values of plant height (cm), fresh and dry weights (gplant^{-1}), No. of leaves plant^{-1} and leaf area (cm^2 plant^{-1}) were realized with the combined treatment of nano-silica and Nano-alumina followed by the treatment of nano-silica alone, then nano-alumina alone, while the lowest values were achieved with untreated plants (control treatment without Nano-silica or nano-alumina). In other words, applying nano silica and alumina as a combined treatment led to an increase in dry weight by 15.77% compared to the control (without nano silica or alumina). When using nano alumina alone and nano silica alone, the increasing rates were 5.76% and 9.98%, respectively, compared to the control (without nano silica or alumina).

Table 5. Effect of nano silica and/or nano alumina combined with potassium and/or manganese on potato growth performance after 70 days from planting during 2023/2024 season.

Treatments		Plant height, cm	Fresh weight, g plant^{-1}	Dry weight, g plant^{-1}	No. of leaves plant^{-1}	Leaf area, cm^2 plant^{-1}
Main factor : Nano alumina and silica						
Control		55.61c	287.13d	32.26d	18.50d	1475.83d
Nano alumina (10 ppm)		57.86c	302.27c	34.12c	19.83c	1676.00c
Nano silica (10 ppm)		62.36b	320.80b	35.48b	22.08b	1920.17b
Nano alumina (5.0 ppm) + Nano silica (5.0 ppm)		66.15a	345.46a	37.35a	25.00a	2457.75a
LSD at 5%		**3.16**	**0.67**	**0.45**	**0.86**	**53.02**
Sub main factor : Potassium and manganese treatments						
Control		59.64a	308.45c	34.34b	20.67b	1792.17c
K (2.5 cm^{3}L^{-1})		60.24a	312.34b	34.50b	21.08b	1874.42b
Mn (1.0 gL^{-1})		60.89a	315.43b	35.10a	21.42ab	1916.58ab
K (2.5 cm^{3}L^{-1})+ Mn (1.0 gL^{-1})		61.21a	319.44a	35.27a	22.25a	1946.58a
LSD at 5%		***NS**	**3.28**	**0.37**	**1.03**	**44.87**
Interaction						
Control	**Control**	54.98e	18.00i	283.00i	31.82g	1410.33h
	K (2.5 cm^{3}L^{-1})	55.65e	18.33i	287.29hi	31.95fg	1439.67h
	Mn (1.0 gL^{-1})	55.78e	18.67hi	287.70hi	32.56f	1497.00gh
	K (2.5 cm^{3}L^{-1})+ Mn (1.0 gL^{-1})	56.04e	19.00hi	290.52h	32.69f	1556.33fg
Nano alumina (10 ppm)	**Control**	57.21de	19.33ghi	298.00g	33.83e	1627.00ef
	K (2.5 cm^{3}L^{-1})	57.89de	19.67fghi	301.58fg	33.92e	1661.67e
	Mn (1.0 gL^{-1})	57.94de	19.67fghi	303.93fg	34.18de	1699.33de
	K (2.5 cm^{3}L^{-1})+ Mn (1.0 gL^{-1})	58.38cde	20.67efgh	305.56f	34.56cde	1716.00de
Nano silica (10 ppm)	**Control**	61.52bcd	21.33defg	314.75e	34.72cd	1753.33d
	K (2.5 cm^{3}L^{-1})	61.66bcd	21.67def	319.79de	34.97c	1931.00c
	Mn (1.0 gL^{-1})	62.91abc	22.00cde	322.88d	36.05b	1979.33c
	K (2.5 cm^{3}L^{-1})+ Mn (1.0 gL^{-1})	63.35ab	23.33bcd	325.76d	36.16b	2017.00c
Nano alumina (5.0 ppm)+ Nano silica (5.0 ppm)	**Control**	64.85ab	24.00abc	338.04c	36.98a	2378.00b
	K (2.5 cm^{3}L^{-1})	65.76ab	24.67ab	340.72bc	37.14a	2465.33ab
	Mn (1.0 gL^{-1})	66.93a	25.33ab	347.19b	37.60a	2490.67a
	K (2.5 cm^{3}L^{-1})+ Mn (1.0 gL^{-1})	67.05a	26.00a	355.91a	37.67a	2497.00a
LSD at 5%		**4.83**	**6.56**	**0.73**	**2.08**	**89.75**

Means within a row followed by a different letter (s) are statistically different at a 0.05 level
*NS= non- significant

As can be seen from the table that the highest values of plant height (cm), fresh and dry weights (g plant^{-1}), No. of leaves plant^{-1} and leaf area (cm^2 plant^{-1}) were realized with the combined treatment of potassium and manganese, followed by the treatment of manganese alone and then potassium alone, while the lowest values were achieved with untreated plants (control treatment without potassium and manganese). Specifically, the increasing rate in the dry weight values due to the studied potassium and manganese treatments compared to control treatment (without K and Mn) was 0.46, 2.21 and 2.7 % with potassium alone, manganese alone and combined treatment (K + Mn), respectively. Concerning the interaction effect, it is worth observing that the plants treated with nano-silica and nano-alumina combined with potassium and manganese simultaneously had the highest values of plant height (cm), fresh and dry weights (gplant^{-1}), No. of leaves plant^{-1} and leaf area (cm^2 plant^{-1}). In summary, these results show that the foliar application of nano-silica and nano-alumina combined with potassium and manganese had a positive effect on potato plant performance.

3.2. Photosynthetic pigments and Nutritional status of the leaves

The results of photosynthetic pigments and nutritional status of the leaves as affected by nano-silica and/or nano-alumina combined with potassium and/or manganese at 70 days from planting during the growing season of 2023/2024 are presented in Table 6. It can be seen from the data in Table 5 that , the highest values of photosynthetic pigments in potato leaves such as chlorophyll a& b and carotene (mg g^{-1}) and chemical constitutes in leaves such as nitrogen, phosphorus, and potassium (%) were realized with the combined treatment of nano-silica and nano-alumina followed by the treatment of nano-silica alone, then nano-alumina alone, while the lowest values were achieved with untreated plants (control treatment without nano-silica or nano-alumina). For instance, the nitrogen content increased by 8.4, 21.6 and 28.4 % with nano alumina alone, nano silica alone and combined treatment (nano alumina + nano silica), respectively compared to control treatment. Regarding the individual effect of potassium and manganese, the highest values of photosynthetic and nutritional indicators were realized with the combined treatment of potassium and manganese, followed by the treatment of manganese alone and then potassium alone, while the lowest values of photosynthetic and nutritional indicators were recoraded with untreated plants (control treatment without potassium and manganese). For instance, the increasing rate in the chlorophyll a values due to the studied potassium and manganese treatments compared to control treatment (without K and Mn) was 0.6,1.2 and 1.7 % with potassium alone, manganese alone and combined treatment (K + Mn), respectively. Concerning the interaction effect, the combined treatment of nano-silica and nano-alumina + potassium and manganese simultaneously was the superior, as it achieved the highest values of chlorophyll a& b and carotene (mg g^{-1}) as well as nitrogen, phosphorus and potassium (%).

Table 6. Effect of nano silica and/or nano alumina combined with potassium and/or manganese on potato photosynthetic pigments and chemical constituents of potato leaves after 70 days from planting during 2023/2024 season.

Treatments		Chlorophyll, mg g^{-1} a	Chlorophyll, mg g^{-1} b	Carotene, mg g^{-1}	N, %	P, %	K, %
Main factor : Nano alumina and silica							
Control		0.861d	0.639d	0.304d	2.96d	0.340d	2.70d
Nano alumina (10 ppm)		0.894c	0.673c	0.320c	3.21c	0.375c	2.88c
Nano silica (10 ppm)		0.946b	0.723b	0.353b	3.60b	0.411b	3.11b
Nano alumina (5.0 ppm) + Nano silica (5.0 ppm)		0.963a	0.758a	0.373a	3.80a	0.432a	3.32a
LSD at 5%		**0.014**	**0.016**	**0.006**	**0.17**	**0.007**	**0.10**
Sub main factor : Potassium and manganese treatments							
Control		0.908c	0.688c	0.331c	3.30b	0.382c	2.93b
K (2.5 cm^3L^{-1})		0.914bc	0.695b	0.337b	3.37ab	0.389b	2.99ab
Mn (1.0 gL^{-1})		0.919ab	0.702a	0.340a	3.43ab	0.392ab	3.02ab
K (2.5 cm^3L^{-1})+ Mn (1.0 gL^{-1})		0.924a	0.707a	0.343a	3.46a	0.395a	3.06a
LSD at 5%		**0.005**	**0.006**	**0.003**	**0.14**	**0.004**	**0.12**
Interaction							
Control	**Control**	0.851i	0.628j	0.296k	2.85g	0.334h	2.62f
	K (2.5 cm^3L^{-1})	0.861hi	0.637ij	0.305j	2.94fg	0.339gh	2.69ef
	Mn (1.0 gL^{-1})	0.863h	0.642hi	0.306j	3.00efg	0.342g	2.73def
	K (2.5 cm^3L^{-1})+ Mn (1.0 gL^{-1})	0.868h	0.650h	0.308ij	3.04defg	0.345g	2.75def
Nano alumina (10 ppm)	**Control**	0.886g	0.665g	0.314hi	3.12defg	0.363f	2.79cdef
	K (2.5 cm^3L^{-1})	0.890g	0.671fg	0.318gh	3.17def	0.376e	2.86cdef
	Mn (1.0 gL^{-1})	0.895fg	0.675fg	0.323fg	3.23de	0.378e	2.93bcde
	K (2.5 cm^3L^{-1})+ Mn (1.0 gL^{-1})	0.906f	0.682f	0.326f	3.31cd	0.382e	2.94bcd
Nano silica (10 ppm)	**Control**	0.938e	0.711e	0.347e	3.51bc	0.403d	3.02bc
	K (2.5 cm^3L^{-1})	0.942de	0.717de	0.352de	3.59abc	0.411c	3.11ab
	Mn (1.0 gL^{-1})	0.950cd	0.729cd	0.355cd	3.64ab	0.413c	3.12ab
	K (2.5 cm^3L^{-1})+ Mn (1.0 gL^{-1})	0.953bcd	0.733c	0.360c	3.65ab	0.417c	3.18ab
Nano alumina (5.0 ppm)+ Nano silica (5.0 ppm)	**Control**	0.957abc	0.749b	0.368b	3.74ab	0.428b	3.30a
	K (2.5 cm^3L^{-1})	0.962ab	0.756ab	0.372ab	3.79ab	0.430ab	3.31a
	Mn (1.0 gL^{-1})	0.966a	0.761a	0.376a	3.83a	0.433ab	3.32a
	K (2.5 cm^3L^{-1})+ Mn (1.0 gL^{-1})	0.968a	0.765a	0.378a	3.82a	0.435a	3.36a
LSD at 5%		**0.012**	**0.012**	**0.006**	**0.28**	**0.007**	**0.25**

Means within a row followed by a different letter (s) are statistically different at a 0.05 level

3.3. Tuber yield

Table 7 shows the effect of nano-silica and/or nano-alumina combined with potassium and/or manganese on potato tuber yield, including average tuber weight (g) and yield (ton fed^{-1}) at 115 days from planting during the growing season of 2023/2024.while Fig 4 shows the interaction effect of the studied treatments on tuber yield. Overall, the data in this Table indicate that the foliar application of nano-silica + nano-alumina as combined treatment led to the highest values of average tuber weight (g) and yield (ton fed^{-1}). The treatment of Nano-silica alone came in the second order followed by nano-alumina alone and lately the control treatment (without nano-silica or nano-alumina). The increasing rate in the tuber yield values was 5.6, 12.2 and 19.2 % with Nano alumina alone, Nano silica alone and combined treatment (nano alumina + nano silica), respectively compared to control treatment.

Table 7. Effect of nano silica and/or nano alumina combined with potassium and/or manganese on yield of potato at harvest stage during 2023/2024 season.

Treatments		Average tuber weight, g	No. of tuber $plant^{-1}$	Yield, ton fed^{-1}
Main factor : Nano alumina and silica				
Control		288.20d	2.13a	14.06d
Nano alumina (10 ppm)		309.11c	2.10b	14.85c
Nano silica (10 ppm)		331.97b	2.08bc	15.78b
Nano alumina (5.0 ppm) + Nano silica (5.0 ppm)		356.17a	2.06c	16.77a
LSD at 5%		**1.86**	**0.2**	**0.12**
Sub main factor : Potassium and manganese treatments				
Control		314.86d	2.09a	15.01d
K (2.5 cm^3L^{-1})		318.61c	2.10a	15.28c
Mn (1.0 gL^{-1})		323.72b	2.10a	15.50b
K (2.5 cm^3L^{-1})+ Mn (1.0 gL^{-1})		328.25a	2.09a	15.68a
LSD at 5%		**2.75**	**NS***	**0.13**
Interaction				
Control	**Control**	282.54k	2.12ab	13.73m
	K (2.5 cm^3L^{-1})	285.57jk	2.14a	13.96lm
	Mn (1.0 gL^{-1})	290.03ij	2.14a	14.16kl
	K (2.5 cm^3L^{-1})+ Mn (1.0 gL^{-1})	294.66i	2.13a	14.39jk
Nano alumina (10 ppm)	**Control**	302.83h	2.11abc	14.61ij
	K (2.5 cm^3L^{-1})	307.40gh	2.10abc	14.76hi
	Mn (1.0 gL^{-1})	311.00fg	2.10abc	14.96gh
	K (2.5 cm^3L^{-1})+ Mn (1.0 gL^{-1})	315.20f	2.09abcd	15.07g
Nano silica (10 ppm)	**Control**	324.52e	2.07cd	15.35f
	K (2.5 cm^3L^{-1})	327.85e	2.10abc	15.74e
	Mn (1.0 gL^{-1})	335.46d	2.08bcd	15.94de
	K (2.5 cm^3L^{-1})+ Mn (1.0 gL^{-1})	340.05d	2.07cd	16.08cd
Nano alumina (5.0 ppm)+ Nano silica (5.0 ppm)	**Control**	349.54c	2.05d	16.33c
	K (2.5 cm^3L^{-1})	353.62bc	2.06cd	16.66b
	Mn (1.0 gL^{-1})	358.39ab	2.06cd	16.92ab
	K (2.5 cm^3L^{-1})+ Mn (1.0 gL^{-1})	363.11a	2.07cd	17.18a
LSD at 5%		**5.51**	**0.05**	**0.27**

Means within a row followed by a different letter (s) are statistically different at a 0.05 level
*NS= non- significant

Additionally, the same Table illustrates that the highest values of average tuber weight (g) and yield (ton fed^{-1}) were realized when plants treated with the combined treatment of potassium and manganese. The treatment of manganese alone came in the second order, while the treatment of potassium alone came in the third order. On the contrary, the lowest values were achieved with untreated plants (control treatment without potassium and manganese). For instance, the tuber yield increased by 1.79, 3.26 and 4.46 % with potassium alone, manganese alone and combined treatment (K + Mn), respectively compared to control treatment. Notably, the interaction effects between nano-silica and/or nano-alumina combined with potassium and/or manganese was highly significant (Table 7 and Fig 4), as the highest values of average tuber weight (g) and yield (ton fed^{-1}) were achieved under the combined treatment of Nano-silica and Nano-alumina + potassium and manganese.

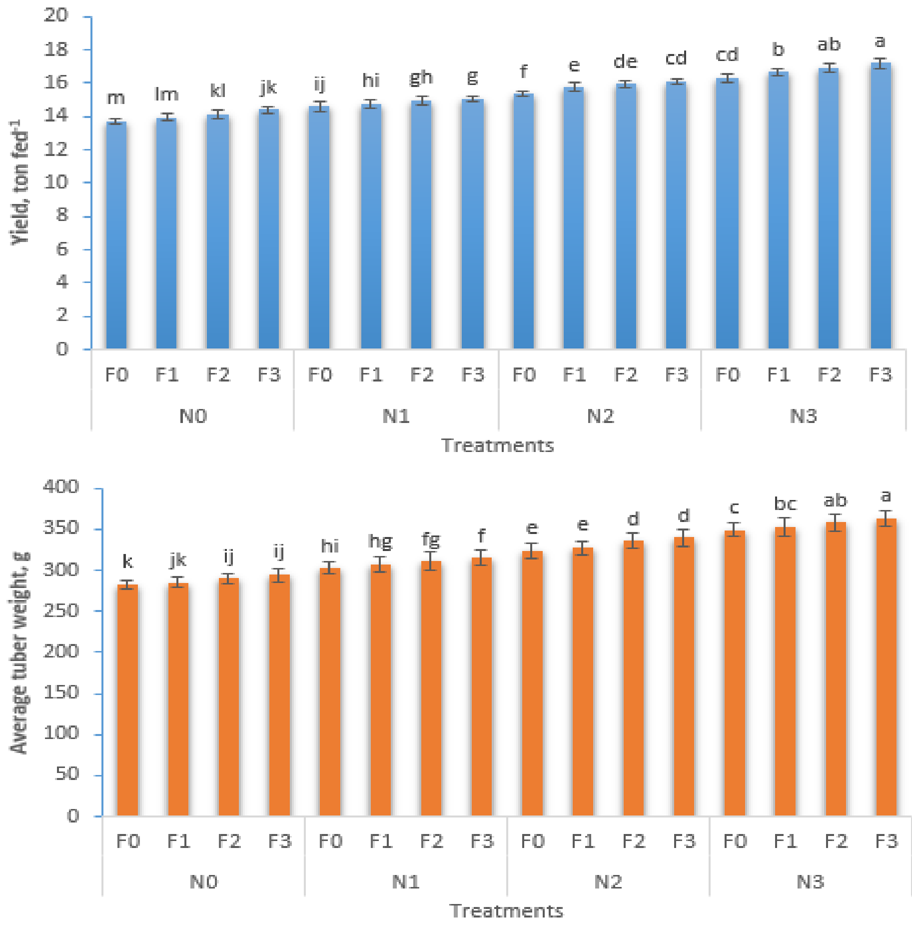

Fig. 4. Interaction effect of nano silica and/or nano alumina combined with potassium and/or manganese on yield of potato at harvest stage during 2023/2024 season.

N0: Control (without Nano silica or alumina), **N1:** Nano alumina (10 ppm), **N2:** Nano silica (10 ppm), **N3:** Nano alumina (5.0 ppm) + Nano silica (5.0 ppm), **F1:** Control (without K or Mn), **F1:** K (2.5 cm^3L^{-1}), **F2:** Mn (1.0 gL^{-1}), **F3:** K (2.5 cm^3L^{-1})+ Mn (1.0 gL^{-1})

3.4. Nutritional status of the tubers

The nutritional status of the tubers as affected by nano-silica and/or nano-alumina combined with potassium and/or manganese at harvest during the growing season of 2023/2024 are presented in Table 8. It can be seen from the data in Table 8 that , the highest values of chemical constitutes in tuber such as nitrogen, phosphorus, and potassium (%) were realized with the combined treatment of nano-silica and nano-alumina followed by the treatment of nano-silica alone, then nano-alumina alone, while the lowest values were achieved with untreated plants (control treatment without nano-silica or nano-alumina). Regarding the individual effect of potassium and manganese, the highest values of nitrogen, phosphorus and potassium contents (%) in the tubers were realized with the combined treatment of potassium and manganese, followed by the treatment of manganese alone and then potassium alone, while the lowest values of nutritional indicators(NPK,%) were recorded with untreated plants (control treatment without potassium and manganese). For instance, the nitrogen content in tuber increased by 7.75, 12.5 and 18.96 % with Nano alumina alone, Nano silica alone and combined treatment (Nano alumina + Nano silica), respectively compared to control treatment. On the other hand, the nitrogen content in tuber increased by 1.2, 2.0 and 4.0 % with potassium alone, manganese alone and combined treatment (K + Mn), respectively compared to control treatment. The interaction effects among the studied treatments were significant, as the most effective combination in terms of NPK content in the harvested tubers was observed when potato plants treated with the combined treatment of nano-silica and nano-alumina + potassium and manganese simultaneously.

Table 8. Effect of nano silica and/or nano alumina combined with potassium and /or manganese on the tuber chemical status at harvest stage during 2023/2024 season.

Treatments		N, %	P, %	K, %
Main factor : Nano alumina and silica				
Control		2.32d	0.296d	2.20d
Nano alumina (10 ppm)		2.50c	0.312c	2.33c
Nano silica (10 ppm)		2.61b	0.340b	2.52b
Nano alumina (5.0 ppm) + Nano silica (5.0 ppm)		2.76a	0.360a	2.77a
LSD at 5%		**0.07**	**0.004**	**0.03**
Sub main factor : Potassium and manganese treatments				
Control		2.50b	0.321c	2.39c
K (2.5 cm^3L^{-1})		2.53ab	0.326b	2.43bc
Mn (1.0 gL^{-1})		2.55ab	0.329a	2.48ab
K (2.5 cm^3L^{-1})+ Mn (1.0 gL^{-1})		2.60a	0.332a	2.52a
LSD at 5%		**0.09**	**0.003**	**0.06**
Interaction				
Control	**Control**	2.28h	0.289k	2.12j
	K (2.5 cm^3L^{-1})	2.30gh	0.297j	2.15ij
	Mn (1.0 gL^{-1})	2.33fgh	0.299j	2.25hi
	K (2.5 cm^3L^{-1})+ Mn (1.0 gL^{-1})	2.36fgh	0.301j	2.27h
Nano alumina (10 ppm)	**Control**	2.46efg	0.307i	2.29gh
	K (2.5 cm^3L^{-1})	2.47efg	0.310hi	2.32gh
	Mn (1.0 gL^{-1})	2.50def	0.314gh	2.34fgh
	K (2.5 cm^3L^{-1})+ Mn (1.0 gL^{-1})	2.57cde	0.317g	2.38fg
Nano silica (10 ppm)	**Control**	2.54cde	0.335f	2.44ef
	K (2.5 cm^3L^{-1})	2.59bcde	0.338ef	2.52de
	Mn (1.0 gL^{-1})	2.62a-e	0.343de	2.54de
	K (2.5 cm^3L^{-1})+ Mn (1.0 gL^{-1})	2.67abcd	0.346d	2.59cd
Nano alumina (5.0 ppm)+ Nano silica (5.0 ppm)	**Control**	2.71abc	0.355c	2.70bc
	K (2.5 cm^3L^{-1})	2.76ab	0.359bc	2.75ab
	Mn (1.0 gL^{-1})	2.77ab	0.362ab	2.80ab
	K (2.5 cm^3L^{-1})+ Mn (1.0 gL^{-1})	2.79a	0.366a	2.84a
LSD at 5%		**0.18**	**0.006**	**0.11**

Means within a row followed by a different letter (s) are statistically different at a 0.05 level

3.5. Tuber quality (biochemical traits)

Table 9 indicates that there has been a significant effect due to the studied treatments on the biochemical traits of potato tubers. Vitamin C (VC, mg $100g^{-1}$), total carbohydrates (%), dry matter (%), total sugars (%) and total dissolved solids (TDS, %) were estimated as quality traits at harvest during the growing season of 2023/2024. Overall, the data in this Table indicate that the foliar application of nano-silica + nano-alumina as combined treatment led to the highest values of all studied quality traits followed by Nano-silica alone, which came in the second order. While the treatment of nano-alumina alone came in the third order and lately the control treatment (without nano-silica or nano-alumina).

Table 9. Effect of nano silica and/or nano alumina combined with potassium and /or manganese on the tuber quality traits at harvest stage during 2023/2024 season.

Treatments		Vitamin C mg 100g^{-1}	T. Carbohydrates, %	Dry matter, %	Total sugars, %	*TDS %
Main factor : Nano alumina and silica						
Control		21.81d	26.19d	20.45d	4.86d	6.07d
Nano alumina (10 ppm)		22.77c	26.80c	21.18c	5.06c	6.37c
Nano silica (10 ppm)		23.55b	27.93b	22.01b	5.26b	7.22b
Nano alumina (5.0 ppm) + Nano silica (5.0 ppm)		24.23a	28.70a	22.62a	5.48a	7.63a
LSD at 5%		**0.14**	**0.06**	**0.30**	**0.06**	**0.10**
Sub main factor : Potassium and manganese treatments						
Control		22.89c	27.15b	21.37a	5.11c	6.68d
K (2.5 cm^{3}L^{-1})		22.98bc	27.34ab	21.47a	5.14bc	6.78c
Mn (1.0 gL^{-1})		23.15ab	27.53a	21.60a	5.18ab	6.85b
K (2.5 cm^{3}L^{-1})+ Mn (1.0 gL^{-1})		23.33a	27.62a	21.83a	5.22a	6.98a
LSD at 5%		**0.20**	**0.29**	**NS***	**0.05**	**0.04**
Interaction						
Control	**Control**	21.51i	25.99g	20.30f	4.81g	6.00m
	K (2.5 cm^{3}L^{-1})	21.67hi	26.04g	20.30f	4.84g	6.04lm
	Mn (1.0 gL^{-1})	21.99gh	26.31fg	20.59f	4.86fg	6.11kl
	K (2.5 cm^{3}L^{-1})+ Mn (1.0 gL^{-1})	22.07g	26.43efg	20.61f	4.95ef	6.13jk
Nano alumina (10 ppm)	**Control**	22.58f	26.66ef	21.03ef	5.00de	6.21ij
	K (2.5 cm^{3}L^{-1})	22.73ef	26.72ef	21.07ef	5.03de	6.29hi
	Mn (1.0 gL^{-1})	22.74ef	26.87ef	21.06def	5.08d	6.35h
	K (2.5 cm^{3}L^{-1})+ Mn (1.0 gL^{-1})	23.01e	26.97e	21.58cde	5.10d	6.62g
Nano silica (10 ppm)	**Control**	23.46d	27.67d	21.77bcde	5.21c	6.89f
	K (2.5 cm^{3}L^{-1})	23.45d	27.86cd	21.a-e92	5.23bc	7.19e
	Mn (1.0 gL^{-1})	23.58d	28.07cd	22.0abcd3	5.28bc	7.33d
	K (2.5 cm^{3}L^{-1})+ Mn (1.0 gL^{-1})	23.71cd	28.13cd	22abc.31	5.32b	7.46c
Nano alumina (5.0 ppm)+ Nano silica (5.0 ppm)	**Control**	24.01bc	28.30bc	22.3abc6	5.43a	7.60b
	K (2.5 cm^{3}L^{-1})	24.08bc	28.73ab	22.57ab	5.47a	7.61b
	Mn (1.0 gL^{-1})	24.29ab	28.86ab	22.72ab	5.49a	7.62ab
	K (2.5 cm^{3}L^{-1})+ Mn (1.0 gL^{-1})	24.55a	28.93a	22.81a	5.53a	7.70a
LSD at 5%		**0.40**	**0.57**	**0.96**	**0.10**	**0.09**

Means within a row followed by a different letter (s) are statistically different at a 0.05 level
*NS= non- significant
*TDS= Total dissolved solid

Another important finding was that the highest values of Vitamin C (VC, mg 100g^{-1}), total carbohydrates (%), dry matter (%), total sugars (%) and total dissolved solids (TDS, %) in harvested tubers were realized with the combined treatment of potassium and manganese, followed by the treatment of manganese alone and then potassium alone, while the lowest values were recorded with untreated plants (control treatment without potassium and manganese). For example, the dry matter of tuber increased by 3.56, 7.62 and 10.61 % with nano alumina alone, nano silica alone and combined treatment (nano alumina + nano silica), respectively compared to control treatment. On the other hand, the nitrogen content in tuber increased by 0.46, 1.07 and 2.15 % with potassium alone, manganese alone and combined treatment (K + Mn), respectively compared to control treatment. The interaction between Nano silica and/or Nano alumina combined with potassium and /or manganese treatments further emphasized the synergistic role of the studied treatments, as the combined treatment of Nano silica and Nano alumina + potassium and manganese resulted in the highest values of all aforementioned tuber quality traits.

4. Discussion

Taken together, these results suggest that there is a positive association between nano-silica, nano-alumina, potassium and manganese in improving the potato performance, quality and productivity. This association might be explained by the fact that nano-silica may have been a supportive element in enhancing the resistance of potato plants to any environmental stress, as it strengthens the cell walls of higher plants, thus improving their physiological structure. It may also have helped increase photosynthetic efficiency, thereby improving leaf structure and reducing transpiration. Furthermore, Nano-silica may have stimulated the activity of antioxidant enzymes, which helped reduce oxidative damage under any environmental stress. This vital role was reflected in increasing chemical and chlorophyll content, and consequently, increased biomass in the potato plant. Moreover, it cannot be overlooked that the potential role of nano-silica was in enhancing the water absorption in the tissues of potato plants and retention, as well as improving transport within the potato plant. In addition to its unique role in improving photosynthetic efficiency, hence improves the number and weight of tubers. The obtained results are in harmony with those of **De-Sousa et *al.* (2019); Wadas, (2021); Puppe *et al.* (2024)**.

On the other hand, Nano-alumina is considered a catalyst for some vital enzyme processes in higher plants and phenolic compounds, and this may have contributed to improving the self-defense of the grown potato against fungal diseases. Nano-alumina also helps regulate the absorption of trace elements, and this vital role may have a positive impact on potato vegetative growth. Improving the efficiency of nutrient absorption has had a positive impact on increased tuber size and overall productivity. The findings are in agreement with those of **Riahi *et al.* (2012); Belhamel *et al.* (2020); Dağlıoğlu *et al.* (2022).** It is also important to note that the presence of both silica and alumina in nanoscale forms significantly increased their efficiency, as their presence in nanoscale forms may have accelerated their absorption and penetration into potato plant tissues, thus maximizing their role. All of the above explains the synergistic effect of nano-silica, nano-alumina when sprayed on potato plants as a combined or single treatment (**Riahi *et al.* 2012; De-Sousa et *al.* 2019**).

Generally, the results obtained confirm that silica and alumina played an important role in promoting tuber size uniformity, perhaps due to their unique role in directly influencing vegetative growth parameters and physiological activity of the potato plant. Silica may have contributed to enhance the potato's ability to tolerate various environmental stress, including water deficit and salinity; hence, it may have positively impacted the efficiency of water and nutrient uptake as well as improved the balanced distribution of stored substances within the tubers. Its unique role positively reflected on the tuber size uniformity, as it may also have played a vital role in strengthening cell walls, contributed to regular cell division and tuber growth. On the other hand, alumina may have indirectly influenced the regulation of enzymatic activity within the potato tissues, as it is a potential source of small amounts of aluminium. It may have contributed to the stability of the biological processes which responsible for the formation of tubers under the studied conditions. Therefore, it can be said that there is a potential synergistic effect between silica and alumina when the potato plants were received them together as a combined treatment, as confirmed by the obtained findings. Their interaction may have improved the root growth environment or as named tube environment. Also, this combined treatment may have enhanced the efficiency of water and nutrient absorption in potato tissues. Generally, it can be noticed that this combined treatment positively impacted tuber formation, size regularity and quality, as this effect may have attributed to the unique role e of silica in strengthening the cell walls and increasing the potato plant resistance to environmental stress, while alumina may have contributed to improved cell division and balanced growth of potato. Their presence together may also have improved the creation of a balanced environment that promotes uniform tuber growth, reducing tuber size variations and thus improving the marketable quality of the crop. The obtained results are in harmony with those of **De-Sousa et *al.* (2019**); **Wadas, (2021); Puppe *et al.* (2024)**.

On the other hand, the potassium acetate used in this investigation contains 50% potassium, which may have enhanced the synthesis and transport of sugars to the tubers. Furthermore, foliar spraying of potassium acetate may have improved the water balance within potato plants, thus increasing their ability to tolerate any environmental stress. Acetate is an organic group which may have played a vital role in accelerating the absorption of nutrients. Therefore, the foliar spraying of potassium acetate may have increased the concentration of dry matter in potato tubers and improved their quality. These results are in accordance with the findings of **Abdelhalem, (2022)**; **Hussein, (2023)** and **El-Metwally *et al.* (2025).**

On the other hand, manganese had a vital role in improving potato performance and productivity due it its critical role in the formation of chlorophyll and stimulating cell division in higher plants, as it is a component of several enzymes directly related to photosynthesis and respiration. Furthermore, its chelated form may have facilitated its absorption by the potato, and this may have positively affected potato growth through improved vegetative growth and photosynthetic efficiency, thus increasing productivity (**Makhlouf, 2023**). Therefore, spraying potassium acetate and chelated manganese had a synergistic effect, as the combined treatment led to a balance between vegetative growth and tuber formation, positively affecting the nutritional content and quality of tubers.

Increasing rates in the yield parameters and quality indicators clearly indicate that nano-silica and alumina treatments had a greater impact on potato yield and most quality traits than potassium and manganese treatments. This is attributed to the fact that silica and alumina effectively contribute to enhancing physiological and biochemical processes within the plant, including efficient nutrient uptake, increased stress resistance, and strengthened cell walls. This makes their effect more pronounced in experimental conditions than potassium and manganese, despite their well-known importance. The obtained results agree with those of (**Sheta *et al.* 2025)**.Generally, it can be said that the obtained results due to the combined treatment of Nano-silica, Nano-alumina, potassium and manganese is attributed to the synergistic effect of them together as mentioned above.

5. Conclusion

One of the main challenges facing potato cultivation is tuber size uniformity. So, the current study hypothesized that the silica, alumina, potassium and manganese would have a synergistic impact on potato tuber size uniformity. Based on the obtained results, the highest values of all related to potato tuber yield and quality were achieved with the combined treatment of nano-silica + nano-alumina + potassium + manganese. In other words, it can be concluded that spraying silica and alumina nanoparticles, in conjunction with spraying potassium acetate and manganese chelate (Mn-EDTA) as a combined treatment, effectively contributes to improving potato growth performance and yield due to the synergistic effect among the nano-treatments and the nutrients used. Therefore, this study recommends the incorporation of this approach into potato fertilization programs. Also, it can be said that this study represents a preliminary trial and forms the basis for longer trials in the future.

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