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Potentiality of non-thermal plasma as an innovative technique for ameliorating wheat productivity under saline soil conditions

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THE CURRENT research tried to exploit the non-thermal plasma (NTP) technology as a neoteric approach for boosting the productivity and quality of salt-stressed wheat. The growth of germinated wheat grains was assessed under laboratory conditions following seed pretreatment with six NTP exposure times (0.0, 1.0, 2.0, 3.0, 4.0 and 5.0 minutes, min). As well, yield traits and grain nutrient uptakes were evaluated after seed pretreatment with three plasma exposure times (0.0, 1.0, and 2.0 min) in soil having three levels of electrical conductivity (EC): low (3.0 dS m^{-1} EC), medium (5.5 dS m^{-1} EC), and high (7.0 dS m^{-1} EC). Findings exhibited that the heaviest seedling dry biomass was recorded with NTP exposure times for 1.0, 2.0, 3.0 and 5.0 min, surpassing the control treatment (0.0 min). NTP exposure time for 1.0 min surpassed the corresponding control treatment in spikes number m^{-2}, spikes weigh m^{-2} and grain yield by 1.28 and 1.36, 1.27 and 1.37, and 1.34 and 1.33 folds, under medium and high salinity, respectively. NTP had no noticeable effect on wheat yield attributes under low salinity level. Further, the amelioration in nutrient uptakes was more pronounced with application of 1.0 min of NTP for N and K uptakes under medium salinity and for P and K uptakes under high salinity. Eventually, it could be concluded that application of NTP as a one-minute seed priming in wheat possessed obvious improvements in grain yield and quality under salt stress, indicating the useful action of plasma in inducing salt tolerance.

Keywords: Plasma technology, Salt tolerance, Seed priming, Soil sustainability, Wheat productivity

Introduction

Wheat (*Triticum aestivum* L.) occupies a substantial situation among cereals worldwide, contributing a significant portion of protein daily and calories intake (Noureldin et al., 2013; Saudy, 2014; Iqbal et al., 2021; Kizilgeci et al., 2021). Wheat fulfills approximately 21% of the world's food demands and it is a unique source of protein (Hossain and da Silva, 2013; Saudy et al., 2023) along with various minerals and fibers (Saudy and Mubarak, 2015; Shewry and Hey, 2015, Alzahrani et al., 2021). Nevertheless, physiology and productivity of wheat is threatened globally by changing in climate which associated with probable stresses, especially those related to water availability and use, such as salinity, drought, heat and unfavorable conditions (Yadav et al., 2020; Salem et al., 2022; Hadid et al., 2023; Abdo et al., 2024; Youssef et al., 2025).

Universally, soil salinity is a critical problem that is increasing with climate change, threatening the agricultural sector, particularly in arid and semi-arid regions such as the Mediterranean (Mukhopadhyay et al., 2021; Mubarak et al., 2021; Salem et al., 2021; Emam et al., 2025a). More than 20-25 of the arable lands, which could increase to 50% by 2050, are affecting by salinity (Hassani et al., 2021). In saline soils, it is difficult for plant roots to absorb water and nutrients due to the low osmotic potential of the soil solution, thus hindering plant growth (Lasheen et al., 2024; Rachappanavar et al., 2024; Ataya et al., 2025; Shaaban et al., 2025). The suppression in plant growth under salt effect could be ascribed to altering various several

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physiological processes via excess accumulation of reactive oxygen species (ROS) which determinately influence photosynthetic efficiency, leaf water status and stomata performance, cell membrane integrity (El hag, 2023; Helal et al., 2024; Hadid et al., 2024; Ramadan et al., 2025). Under harsh circumstances, disturbance in nutrients homeostasis and water uptake and photosynthetic apparatus were reported, and ultimately decline low yield and quality (Iqbal et al., 2021; Saudy et al., 2020a; Saudy et al., 2020b; Shaaban et al., 2023a; Shahin et al., 2023).

To mitigate the hazard effects of salinity and promote plant growth, numerous tactics involving using chemicals and/or organic materials were utilized. It has been documented that seed priming can enhance plant growth and productivity under ecological pressures (Said et al., 2021; Abd El-Mageed et al., 2022; Fathi et al., 2023; Samadi et al., 2024). However, the use of physical methods is not common in this situation. In this context, application of non-thermal plasma (NTP) as an innovative technique of seed priming pretreatment could introduce a safe and ecofriendly strategy in alleviation of salt stress injuries (Sheteiwy et al., 2019; Saudy et al., 2025).

NTP as a recent physical seed priming tool has shown prominent ability in stimulating the stress tolerance of plants, securing good germination while boosting crop productivity (Sivachandiran and Khacef, 2017; Perea-Brenes et al., 2023). This technique takes advantage of the synergistic action of high-energy molecules, which include vibrating atoms, excited particles, and electromagnetic emissions (Szili et al., 2017; Bourke et al., 2018). As an advanced practice in agriculture, NTP can be employed as pretreatment for seeds, improving germination, and seedling growth while protecting against disease (Mumtaz et al., 2023; Soulier et al., 2024).

Despite its useful consequences in enhancing various stress tolerance (Kumar, 2022), NTP action in ameliorating seedling growth and increasing wheat salinity tolerance still needs explorations. Relaying on the unique features of NTP, the current research hypothesized that plasma-pretreated grains could provide an innovative practice to mitigate the adverse effects of salinity on wheat plants. Therefore, plasma-pretreated grains of wheat were germinated under laboratory condition to obtain the most suitable plasma exposure time based on germination percentage and seedling growth. Next, promising plasma exposure times were chosen for evaluation under saline soil in an open field to investigate the potential ability of plasma to alleviate salinity stress.

Materials and Methods:

Plant material

The grains of wheat cultivar Misr–1 were used in all applied procedures of the current wok. An amount of healthy grains was used as a control treatment (untreated grains). On the other hand, another amount of grains were gently coated by lignin as described by Elgendy et al. (2024). Next, the coated grains were undergone to plasma with different exposure times to be used in laboratory and open field experiments as will explained below

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Plasma treatment setup

Wheat grains were subjected to surface modification using a low-pressure, non-thermal radiofrequency (RF) plasma system operating at 13.56 MHz. The plasma reactor, illustrated schematically in Figure 1, was a cylindrical plate capacitive discharge system (PICO plasma system) designed to receive a good amount of seeds and ensure uniform plasma exposure. The seeds were placed at a specified distance from the plasma discharge zone and exposed to controlled rotation during treatment to ensure uniform surface exposure and minimize localized heating or thermal damage. Figure 1 illustrates schematic diagram of the low-pressure 13.56 MHz RF capacitive plasma reactor (PICO system) used in seed treatment. As described in Table 1, during operation processes of the plasma set, several parameters were selected based to avoid thermal degradation while confirming sufficient interaction between plasma generated reactive species, such as reactive oxygen species (ROS) and reactive nitrogen species (RNS) and the seed surface. The selected power level (60 W) was sufficient to initiate plasma discharge without causing physical damage to the seed coat. At the same time, the relatively low gas flow rate facilitated extended residence time of reactive species near the seed surface.

Experimental procedures

The current research had two levels of experimentations. The first experiment was undertaken on the first of October 2022 at the Environment Lab, Agronomy department, Faculty of Agriculture, Ain Shams University to survey and choose the appropriate plasma exposure time (s) for wheat seedlings growth. While, the second experiment was performed in open field having different salinity levels, at Fayoum Governorate, Egypt (29° 18' N and 30° 56' E), in 2022 and 2023 winter seasons to measure the performance of wheat yield traits and grain nutritional value after pretreating grains by plasma.

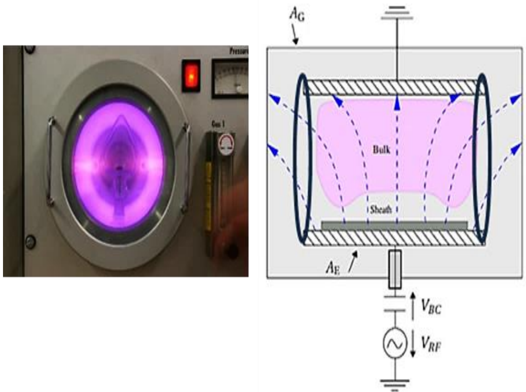

Fig. 1. Schematic diagram of the low-pressure 13.56 MHz RF capacitive plasma reactor (PICO system) used in grain treatment; the operating power was 60 W.

Table 1. Plasma process parameters for treating wheat grains.

Parameter	Value	Description
Discharge power	60. 00W	Applied RF power to initiate plasma discharge
Frequency	13.56 MHz	Standard RF frequency for capacitive coupling
Gas type	Dry air	Working gas used in the plasma chamber
Gas flow rate	1.50 sccm	Controlled by a mass flow controller
Chamber pressure	0.90 mbar	Maintained using a rotary vacuum pump
Exposure time	1.00-5.00 min	Selected to balance reactivity and avoid seed damage
Plasma configuration	Cylindrical plate capacitive RF reactor	Ensures uniform exposure over the seed surface
Seed positioning	Rotated cylindrical plate	Smooth treatment and prevents overheating

Laboratory study

Grains of wheat were treated by five plasma exposure times (1.0, 2.0, 3.0, 4.0 and 5.0 minutes, min), in addition to the untreated grains (non-plasma treated grains, 0.0 min). The germination test was carried out following the rules determined by International Seed Testing Association (ISTA). Briefly, the top-of-paper method in 4 replicates × 100 grains was utilized. Ten grains of Misr-1 cultivars were placed on petri dish (15 cm diameter) which previously lined with filter paper (Whatman#1 International, Maidstone, UK) as growing media. Firstly, the filter paper was wetted with 7.0 mL, and then grains were moistened by an additional 5.0 mL of distilled water on the 5^{th} and 9^{th} days after starting the experiment. Under the ambient conditions (20±1 ºC) of the Lab, the plasma treatments were distributed in a completely randomized design with four replicates. No germination percentage reductions were observed for all studied plasma treatments. After completing the test (15 days later), the produced seedlings were collected to assess seedling length. Further, seedlings were then oven- dried at 105 ºC for 24h to quantify the dry biomass.

Open field experiment

Before sowing, soil samples were collected from a depth 0–30 cm to evaluate the initial averages of physical (Klute, 1986) and chemical (Page et al., 1982) properties of the experimental soil. The experimental soil had texture of sandy loam. Chemically, the soil involved organic matter of 0.52% and calcium carbonate of 5.44% with pH of 7.82. According to the measured electrical conductivity (EC), the soil of the study location classified averagely as low (3.0 dS m^{-1} EC), medium (5.5 dS m^{-1} EC) and high (7.0 dS m^{-1} EC) salinity. Under these three salinity classes, plasma-pretreated grains of wheat (plasma exposure times, i.e. 1.0 and 2.0 min), in addition to the untreated grains (0.0 min) were sown. The experiment was tailored in a split-plot design with four replicates, where the main plots included salinity levels, while plasma treatments occupied the sub-plots.

With preparing the land, the ordinary single super phosphate (15.5% P_2O_5), at a rate of 240 kg ha^{-1}, was incorporated. Next, soil was divided into experimental unit sized of 10.5 m^2 (3.5 m × 3.0 m). On 27^{th} and 26^{th} November 2021 and 2022, wheat grains were sown in lines, with distance of 10 cm, at a rate of 170 kg grains ha^{-1}. At 30 and 45 days after sowing (DAS), ammonium nitrate (33.5% N) at a rate of 260 kg N ha^{-1} was added into two equal batches. Plants were watered during growth cycle via common furrow irrigation pattern, with freshwater having 0.35 dS m^{-1} EC and pH of 6.90. At full maturity (on 11^{th} and 1^{st} May 2022 and 2023), wheat plants were harvested from one square meter per plot to assess plant height, spikes number m^{-2}, spikes weight m^{-2}, spike length, weight of 1000 grains, and grain yield.

As for nutritional status of the grains, total nitrogen (N) content was measured, employing the apparatus of micro-Kjeldahl (AOAC, 2012). Phosphorus (P) content was colorimetrically quantified via the Thermo Scientific Evolution 350 UV-Vis spectrophotometer (Waltham, MA, USA) (Chapman and Parker, 1961). Also, potassium (K) content was estimated using a flame photometer (BWB-Flash Photometer, Berkshire, UK) as illustrated by Page et al. (1982). Afterwords, grain nutrient uptakes were computed.

Analyzing data

Analysis of variance (ANOVA) as one-way was carried out for the laboratory experiment, exploiting the mathematical model in formula 1. Concerning the open field experiment, the homogeneity test of Levene's was performed confirming the normality and homogeneity of the data for the two seasons. Thus, the combined data analysis was run as two-way ANOVA utilizing the mathematical model in formula 2. The measured data were analyzed (Casella, 2008) via the Costat software program, Version–6.303 (2004). When the F–test was significant ($p<0.05$), the treatment means were separated utilizing Duncan's multiple-range test.

$$Y_{ij} = \mu + \tau_i + \beta_j + \varepsilon_{ij} \quad \text{........ (1)}$$

Where: Y_{ijk} is response, μ is an overall mean effect, τ is the treatment, β is the block effect, and ε_{ij} is error

$$Yijk = \mu + \tau i + \beta j + \varepsilon ij + \gamma k + (\tau\gamma)ik + (\beta\gamma)jk + \delta ijk \quad \text{........ (2)}$$

Where: i = 1,...,t, j = 1,...,r, k = 1,...,g, Yijk = response, μ = overall mean effect, τi = whole plot treatment, βj = whole plot block, εij = whole plot error, γk = split plot treatments, (τγ)ik = treatment interaction, (βγ)ik = block-treatment interaction, δijk = split plot error

Results and Discussion

Seedling growth

Interestingly, the plasma exhibited no significant damage to the germinated wheat grains, while all grains successfully sprouting at different times of plasma exposure, with a 100% germination percentage for all. Results divulged that there were significant differences between plasma exposure time treatments on seedling growth of wheat grown under lab condition. In this respect, 1.0 min along with 3.0 min of NTP treatment produced maximal seedling length (Figure 2). The increases in seedling length were 12.0 and 10.9% with 1.0 and 3.0 min, respectively, compared to 0.0 min. While, the heaviest seedling dry biomass (Figure 3) was recorded with 1.0, 2.0, 3.0 and 5.0 min, surpassing the control treatment (0.0 min) by about 19.7, 18.7, 28.1 and 15.7%, respectively. Deteriorative effect on seedling growth of wheat was observed with 4.0 min reducing seedling dry biomass significantly than the control treatment. Therefore, and taken the cost of plasma treatment in consideration, the choice was made to apply the treatments of 1.0 and 2.0 min under open field conditions. The modulation in seedling growth by plasma application could be attributed to change in seed-surface features, activity of enzymes and phytohormones and metabolic pathways (Scholtz et al., 2021, Šerá et al., 2021). Owing to presence of active particles in NTP, seed surface was modified, hence hydrophilicity and water uptake were enhanced (Varnagiris et al., 2020; Holc et al., 2021). It has been noticed that the imbibition and wettability were found to be proportionally linked to duration of plasma treatment, probably due to the chemical modification of lipid layers in the seeds (da Silva et al., 2017). Furthermore, plasma treatments stabilize the atmospheric nitrogen and the accumulation of nitrogenous acids, which could enrich the seeds (Judée et al., 2018). Additionally, NTP influences seed phytohormones and protein expression of the seedlings (Mildažiene et al., 2019), and subaltern metabolites content (Ivankov et al., 2020; Mildažiene et al., 2020). Accordingly, wheat seedling growth was improved with NTP application.

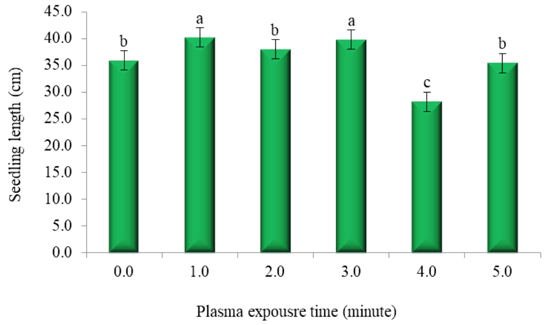

Fig. 2. Response of seedling length of wheat to non-thermal different plasma exposure times. Different letters within bars refers that there are significant variations at 0.05 level of probability. Means were separated based on Duncan's multiple range test (*P<0.05*).

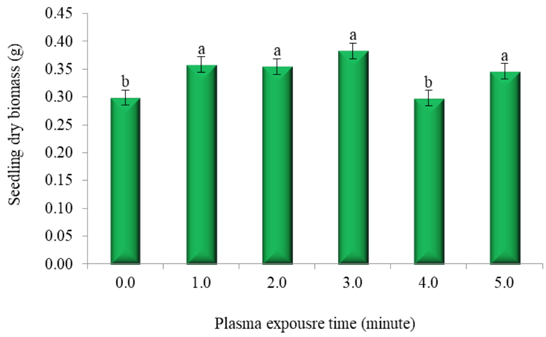

Fig. 3. Response of seedling dry biomass of wheat to different non-thermal plasma exposure times. Different letters within bars refers that there are significant variations at 0.05 level of probability. Means were separated based on Duncan's multiple range test (*P<0.05*).

Yield traits

As illustrated in Table 2, wheat plant height, spike length and weight of 1000 grains did not significantly ($p>0.05$) respond to NTP treatment. While, different values for spikes number m^{-2}, spikes weigh m^{-2} and grain yield were observed at medium (5.5 dS m^{-1}) and high (7.0 dS m^{-1}) salinity levels owing to application of different NTP exposure times. In this regard, NTP exposure times for 1.0 min surpassed the corresponding check treatment (0.0 min) in spikes number m^{-2}, spikes weigh m^{-2} and grain yield by 1.28, 1.27 and 1.34 folds, respectively, under medium salinity. The corresponding increases amounted to 1.36, 1.37 and 1.33 folds respectively, under high salinity. NTP had no noticeable effect on spikes number m^{-2}, spikes weigh m^{-2} and grain yield of wheat under low salinity (3.0 dS m^{-1}) salinity level. It is certain that plant metabolic processes and associated physo-biochemical responses are critically affected by salt stress. In this situation, due to the disturbances in physiological and biochemical performance associated with salinity, seed germination declined (Rabie and Almadini, 2005), and the systems of photosynthesis were disrupted (Naveed et al., 2020; Alsamadany et al., 2022; Shalaby et al., 2023), hence plant biomass decreased (Kamran et al., 2019; Lasheen et al., 2024). Further, the homeostasis of nutrients becomes disorganized under salt stress since accumulation of minerals declines (Bonachela et al., 2022; El-Beltagi et al., 2023; Ramadan et al., 2024). Therefore, depression in growth and productivity with low grain quality of wheat was expected under salt stress.

Table 2. Response of yield traits of wheat cultivar Misr-1 to non-thermal plasma treatment under different salinity levels.

Variable		Plant height (cm)	Spikes number m^{-2}	Spikes weigh m^{-2} (kg)	Spike length (cm)	Weight of 1000 grains (g)	Grain yield (t fed^{-1})
S1	0.0 min	110.6ab	496.3a	1.76ab	15.4b	5.08a	4.11b
	1.0 min	113.1ab	472.0ab	1.69ab	16.1ab	4.91a	4.04bc
	2.0 min	120.8a	458.0ab	1.74ab	16.9ab	5.25a	4.06b
S2	0.0 min	110.0ab	384.3bc	1.47bc	16.0ab	5.01a	3.45bc
	1.0 min	110.9ab	490.0a	1.87a	15.4b	5.23a	4.61a
	2.0 min	115.0ab	436.6ab	1.72ab	16.5ab	5.28a	4.24ab
S3	0.0 min	103.0b	330.3c	1.25c	16.1ab	5.08a	3.05c
	1.0 min	110.3ab	450.3ab	1.71ab	16.9ab	4.75a	4.06b
	2.0 min	107.8ab	384.0bc	1.39bc	16.4ab	4.88a	3.31bc

S1, S2 and S3: soil salinity at 3.0, 5.5 and 7.0 dS m^{-1}, respectively; 0.0 min: non-treated grains, 1.0 and 2.0 min treating grains by non-thermal plasma for 1.0 and 2.0 minutes, respectively). Fed: Feddan (area of 4200 m^2). Different letters within columns refers that there are significant variations at 0.05 level of probability. Means were separated based on Duncan's multiple range test (*P<0.05*).

On the other site, remarkable improvements in productivity and grain nutritional status of wheat were achieved with application of NTP moderately and high soil salinity. The action of antioxidant enzymes and gene expression associated with the stress response can be regulated by plasma (Iranbakhsh et al., 2018; Bian et al., 2024). NTP may somewhat obviate the negative impacts of salt stress (Bafoil et al., 2019). It has been clearly confirmed in previous studies, augmentation of antioxidant enzymes and accumulation of various osmolytes are significant biological events that retain cell moisture and adjust the physiological balance under oxidative stresses. (Mishra and Panda, 2017; Bhattacharjee and Dey, 2018; Gupta et al., 2020). Herein, the mitigation of salinity effects resulting from NTP treatment can be interpreted as being due to its ability to raise osmotic protection levels while stimulating the activity of antioxidant enzymes and photosynthetic potential (Adhikari et al., 2020; Kumar, 2022; Perea-Brenes et al., 2023).

Grain nutrient uptake

Wheat grain N, P and K uptakes were significantly influenced by plasma pretreatments under salinity levels (Table 3). It has been noted that plasma has no substantial noticeable action on nutrient contents under low salinity conditions (3.0 EC). While, NTP exposure time for 1.0 min boosted N grain uptake by about 86.8% greater than the corresponding control treatment under medium salinity. Under high salinity, the change P grain uptake was more pronounced with appellation of NTP for 1.0 min, exceeding the corresponding control treatment by 70.3%. Also, NTP exposure time for 1.0 min modified the K grain uptake under medium and high salinity, outperforming the corresponding control treatments by14.4 and 65.8%, respectively.

It is well known that the utilization deficiency of water and nutrient is a critical event affecting plant growth, metabolism, yield and quality (Saudy et al., 2018; Saudy et al., 2022; Elkot et al., 2023; Mansour et al., 2025). Due to the overproduction of ROS as a result of oxidative stresses, lipids in the cell membrane are oxidized and proteins are disassembled (Zandalinas et al., 2018; Kuromori et al., 2022), which increases osmotic pressure while reducing water and nutrient uptake and impairing the efficiency of photosynthetic activity (Gill and Tuteja, 2010; El-Metwally and Saudy, 2021; Shaaban et al., 2023b). Therefore, low nutrients use efficiency as a result of oxidative stress caused depression in seed quality (Saudy et al., 2020c; Emam et al., 2025b). On the other hand, plasma played a beneficial role in induction of tolerance to oxidative stress, and enhancing the uptake of nutrients and water under unfavorable conditions (Adhikari et al., 2020). Since plasma stimulates the secretory capacity of roots to release organic acids, nutrient uptake increased (Zhao et al., 2021).

Table 3. Response of grain nutrient uptake (kg fed-1) of wheat to non0thermal plasma treatment under different salinity levels.

Variable		Nitrogen uptake	Phosphorus uptake	Potassium uptake
S1	0.0 min	90.51ab	133.1a	15.0ab
	1.0 min	72.82ab	119.8a	14.0ab
	2.0 min	81.79ab	120.4a	15.7a
S2	0.0 min	57.69b	120.5a	9.7c
	1.0 min	107.76a	126.0a	11.1ab
	2.0 min	86.36ab	121.1a	10.5abc
S3	0.0 min	58.97b	53.6d	7.9c
	1.0 min	71.41ab	91.3b	13.1ab
	2.0 min	56.94b	74.0c	9.4c

S1, S2 and S3: soil salinity at 3.0, 5.5 and 7.0 dS m^{-1}, respectively; 0.0 min: non-treated grains, 1.0 and 2.0 min treating grains by non-thermal plasma for 1.0 and 2.0 minutes, respectively). Fed: Feddan (area of 4200 m^2). Different letters within columns refers that there are significant variations at 0.05 level of probability. Means were separated based on Duncan's multiple range test (*P<0.05*).

Conclusion

In conclusion, the utilization of non-thermal plasma for 1-minute as an sophisticated seed priming method in wheat showed distinctive enhancements in seedling growth with induced tolerance to salinity, and ensuring high grain yield and nutritional value. Thus, non-thermal plasma could be employed as a promising and eco-friendly seed priming strategy in wheat cultivation under salt-influenced soils. However, future studies are needed to deeply explain the physiological and molecular relationship between plasma effects and different metabolic pathways in plant cells, especially under salinity.

Consent for publication:

All authors declare their consent for publication.

Author contribution:

H.S.S., M.F.H., M.M., W.R.A., M.F.M.I., A.T.E.: designed the trials; H.S.S., M.F.H., W.R.A., M.F.M.I.: collected the data; H.S.S., M.F.H., M.M., M.F.M.I.: analyzed the data and wrote the drafted manuscript; H.S.S., W.R.A., M.M., A.T.E.: revised and finalized the article. Whole authors agree with the article contents and with its submission.

Conflicts of Interest:

The authors declare that they have no conflict of interest.

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