Journal of Animal & Plant Sciences, 35(1): 2025, Page: 131-143
ISSN (print): 1018-7081; ISSN (online): 2309-8694
https://doi.org/10.36899/JAPS.2025.1.0010

HARNESSING VOLCANIC ASH-BASED FORMULATION TO IMPROVE THE GROWTH AND YIELD OF MAIZE (*Zea mays*) UNDER CONTRASTING SOIL TEXTURES

K. N. Vinoth[1], R. Jerlin[1*], V. Manonmani[1], M. Djanaguiraman[2], T. Eevera[1], J. Renugadevi[1], V. Vakeshwaran[1], and S. Kavitha[1]

[1]Department of Seed Science and Technology, Tamil Nadu Agricultural University, Coimbatore- 641003, India.
[2]Department of Crop Physiology, Tamil Nadu Agricultural University, Coimbatore- 641003, India.

*Corresponding Author's Email: rjerlin@tnau.ac.in

ABSTRACT

As the global population is on the rise, food production must double by 2050 to meet demand. The excessive use of fertilizer for increasing the soil fertility leads to soil degradation and soil microbial diversity reduction. To address this issue, appropriate eco-friendly fertilizer management strategies without comprising the yield should be identified. With this notion, the study was taken up with volcanic ash-based formulation to increase the growth and productivity of maize in a sustainable way. Volcanic ash was tried both as seed coating and foliar spray to improve the productivity of maize. A laboratory experiment was conducted to optimize the dosage for seed coating using volcanic ash-based formulation, with different concentrations *viz.,* 0, 2, 4, 6, 8 and 10 ml kg^{-1} of seeds. The results indicated that seed coating with volcanic ash @ 10 ml kg^{-1} of seeds significantly improved seed quality, yielding a maximum germination rate of 100%, shoot length of 23.2 cm, root length of 29.1 cm, dry matter production of 2.2 g $seedlings^{-10}$ and seedling vigour index I of 5230. Following the standardization of the optimal seed coating dosage, field trials were conducted with the best performed treatment at two locations with different soil types *viz.,* Department of Seed and Technology farm (E_1) with sandy clay loam and Farmers field (E_2) with sandy loam during November 2023 to February 2024. The combination of seed coating (10 ml kg^{-1}) and foliar application (500 L ha^{-1}) on the 30^{th} and 50^{th} days after sowing with volcanic ash-based formulation showed the best results. In E_1, this treatment recorded higher plant height (241 cm), dry matter (93.5 g $plant^{-1}$), crop growth rate (5.794 g m^{-2} day^{-1}), 100-seed weight (33.0 g) and seed yield (6556 kg ha^{-1}). In E_2, plant height (224 cm), dry matter (88.88 g $plant^{-1}$), crop growth rate (5.442 g m^{-2} day^{-1}), 100-seed weight (32.38 g) and seed yield (6073 kg ha^{-1}) were recorded. Thus, it has been concluded that, volcanic ash formulation could be used as a potential base for the supplementation of nutrients to both seeds and plants in a sustainable approach amidst the chemical-based fertilizers.

Key words: Maize, volcanic ash, coating, protein, α-amylase

Published first online December 20, 2024 Published final February 18, 2025

INTRODUCTION

Maize (*Zea mays*), the 'Queen of cereals' is known for its essential source of nutrition for millions of people and thereby plays a key role in global food security. In India, maize crop holds 10.04 million ha area, 33.62 million metric tons production and 3.34 tons ha^{-1} productivity (FAO, 2022). Global maize production in underdeveloped and intermediate countries is struggling with lower productivity due to soil fertility variations and socio-economic constraints (Shiferaw, 2023). A study revealed a prolonged decline in maize production globally with an annual reduction of 0.17 million metric tons per year (Ray *et al.,* 2019). This indicates a significant annual decrease of 0.7% in the world's supply of food calories derived from maize. To feed the increasing global population, maize production must be increased by 2.2% annually.

To mitigate the low nutrient availability of soil, suitable fertilizer management can be advocated. Volcanic ash is a naturally available organic material that has the capacity for slow release of macro- and micro-nutrients which is essential for the plant growth and development. While, primary macronutrients such as nitrogen, phosphorus and potassium may be limited, volcanic ash provides crucial trace elements. These elements play critical roles in enzymatic processes within soil microbes, enhancing nutrient uptake and overall plant health (Ciriminna *et al.,* 2022). Research related to volcanic ash usage in agriculture is scarce. However, volcanic ash is used as a soil amendment to increase the germination rate, growth rate and to produce healthy plants which reflects on high yield (Seward and Edwards, 2012). It was also notable that volcanic ash can also improves the physical and chemical properties of the soil and maximizes productivity of various crops (Desoky *et al.,* 2018). By creating a fertile and resilient soil environment that is conducive for rapid vegetation regrowth, volcanic ash promotes the complete establishment of crop. A report by Shoji and Takahashi (2002) clearly depicts the high fertility status of volcanic ash soil present in Japan which is known for increasing the productivity of valuable horticultural crops. Hence, volcanic ash soil could be considered as an eco-friendly alternative for ensuring the agricultural productivity of crops. But, it should be maintained with proper cultivation practices to maintain the same fertility potential. Since, volcanic ash acts as an effective soil conditioner for alkaline soils, it improves the soil structure and water retention capacity of plants and enhances the nutrient availability to plants (De la Rosa *et al.,* 2023). Similar improvement of soil fertility status and crop growth was also reported in melon (Xue *et al.,* 2024), small-leaved lime (Piccolo *et al.,* 2024), shallot (Panjaitan, 2023) and sweet potato (Floyd *et al.,* 1998). The application of excessive fertilizer harms the physical and chemical properties of soil. Hence, it is ideal to explore an alternative approach for delivering nutrients to crops in an eco-friendly approach. In line, there are several established methods like soil application, seed treatment and foliar spray for the supplementation of nutrients to plants (Johnson *et al.,* 2005). Among which, soil application is a traditional method followed, but it needs large quantities of fertilizers because of the increased cost of cultivation and potential limitations in nutrient-use efficiency within soil. Therefore, the next alternative cost-effective method is seed treatment and foliar application, the former involves the coating of seeds with the required amount of seed coating mixture that reduces the fertilizer dosage and also increases the seedling growth (Rocha *et al.,* 2019). Foliar application is characterized as the direct application of nutrients into foliage and are found to be more efficient method for direct application of nutrients. Foliar application was found to exhibit optimal efficacy during day time when stomata are fully open, facilitating maximized nutrient absorption and reduced wastage of excessive nutrients (Ronga *et al.,* 2019; Battacharyya *et al.,* 2015). Various reports by Fertahi *et al.* (2024), Kassem *et al.* (2024) and Kumari *et al.* (2024) also explained the optimistic impact of supplying nutrients through seed and foliar. Thus, with this background, it could be hypothesized that application of volcanic ash in the form of seed coating and foliar application has the capability to improve the germination, establishment and ultimately yield in a sustainable way. Hence, an investigation was taken up in maize COH(M) 8 under sandy clay loam and sandy loam soil conditions. Therefore, the main focus of the study revolves around with the objective of (i) optimizing the dosage for seed coating with volcanic ash-based seed coating formulation and (ii) evaluating the influence of volcanic ash-based formulation as seed coating and foliar application on crop yield.

MATERIALS AND METHODS

The hybrid maize COH(M) 8 seeds were obtained from the Department of Millets, Tamil Nadu Agricultural University (TNAU), Coimbatore, Tamil Nadu and surface sterilized with sodium hypochloride before the initiation of the experiment. The hybrid maize variety COH(M) 8 recently released by TNAU is recommended for the western agro-climatic zone of Tamil Nadu to achieve improved growth performance and yield. Volcanic ash was obtained from M/s. Plasil Organics, Hyderabad, Telangana. It is an abundant natural material containing silicon, potassium, phosphorus and magnesium. The optimal use of volcanic ash enhances maize growth and development. The volcanic ash-based formulation used for seed coating and foliar spray developed by the Department of Seed Science and Technology (DSST), TNAU, Coimbatore were utilized for this study. The hybrid maize COH(M) 8 seeds were subjected to volcanic ash-based seed coating with a rotary coater for one minute per kg of seeds and the coated seeds were shade dried overnight. The optimum concentration of volcanic ash-based seed coating formulations were determined for maize growth under laboratory condition with varying dosages including control (non-coated seeds), 2 ml kg^{-1}, 4 ml kg^{-1}, 6 ml kg^{-1}, 8 ml kg^{-1} and 10 ml kg^{-1}. Germination test was conducted through roll towel method with five replicates of 100 seeds each under controlled conditions at the DSST laboratory, TNAU, Coimbatore during 2023. The Completely Randomized Design was employed for conducting the experiments.

Two field experiments were conducted at the farm of DSST (11° 0′ 55.894″ N, 76° 56′ 1.265″ E) (E_1) at TNAU, Coimbatore and at Farmer's field (11° 5′ 1.198″ N, 77° 10′ 4.659″ E) (E_2) at Kaniyur, Coimbatore, during *Rabi* season, 2023-2024. Field experiment was conducted using Randomized Block Design with the treatments as control (non-coated seeds), coated seed @ 10 ml kg^{-1} (CS) (best performing treatment under laboratory condition) and coated seed @ 10 ml kg^{-1} + foliar application with formulation at 500 L ha^{-1} (CS + FS). Foliar spraying was performed at 30 and 50 days after sowing (DAS) of the maize crop. Sowing was performed by dibbling method in the ridge-and-furrow, maintaining a spacing of 60 cm between ridges and 30 cm between hills within each ridge during November 2023. The initial physico-chemical properties of soil samples from the experimental sites were obtained from Soil Testing and Technology Advisory Centre, TNAU, Coimbatore (Table 1). No soil fertilizer were applied to the crop during the entire experimental period from November 2023 to March 2024.

Characterization of volcanic ash: The structural and optical properties of volcanic ash and volcanic ash-based formulation were characterized using Field Emission Scanning Electron Microscopy (FE-SEM) (Model: Quanta 250 FEG-SEM). Elemental analysis of volcanic ash and volcanic ash-based formulation was performed with Energy Dispersive X-ray Analysis (EDAX), which was coupled with an FE–SEM instrument. The macro- and micro-nutrient compositions of volcanic ash were identified and quantified by using inductively coupled plasma–mass spectrometry (Model: Thermo Scientific™ iCAP™ RQ - single quadrupole ICP–MS).

Physiological traits: Germination test was conducted under controlled environmental conditions (germination chamber) at a constant temperature of 25 ± 2°C, a relative humidity of 95 ± 3% and 1500 lux to optimize seedling growth. Parameters such as germination percentage and normal seedlings were determined according to ISTA (2022) guidelines. The seedling vigour index (Abdul-Baki and Anderson, 1973) and final dry matter production (DMP) were subsequently calculated (Jeong *et al.,* 2020).

Allometry and photosynthetic attributes: Field experiments were conducted at the DSST farm (E_1) and at Farmer's field (E_2). At E_1, the soil texture was identified as sandy clay loam with a neutral pH of 7.37. The available organic carbon and nitrogen content were 4.3 g kg^{-1} and 210 kg ha^{-1} respectively. At E_2, the soil was sandy loam with slightly acidic pH of 6.8 and the available organic carbon and nitrogen content were 3.6 g kg^{-1} and 168 kg ha^{-1} respectively (Table 1). Sowing was conducted on November 6, 2023 for both field experimental plots. Ten plants were randomly selected from each replication and growth parameters were recorded. The average plant height was recorded from the base of the plant to the tip at 90 days after sowing (DAS) and leaf area per plant was measured at the third leaf from the top of the plant using leaf area meter at 60 DAS. The leaf area index was calculated at 60 DAS described by Pandey *et al.* (2015) (1). The DMP was recorded after complete desiccation of the plants through a hot air oven using the formula outlined by Jeong *et al.* (2020). The crop growth rate (CGR) was determined according to Charles-Edwards (1982) and expressed as $gm^{-2}\ day^{-1}$ (2). A total of 250 mg of physiologically active third leaves were collected at 65 DAS and homogenized in the laboratory using acetone method to calculate chlorophyll 'a', chlorophyll 'b' and total chlorophyll content. The optical densities at 645 nm and 663 nm were measured using a spectrophotometer following the method of Arnon (1949) (3, 4, 5).

(1) $$\text{Leaf Area Index} = \frac{\text{L x W x K x Number of leaves per plant}}{\text{Spacing (cm}^2\text{)}}$$

where,

L- Maximum length of the leaf, W- Maximum width of the leaf, K- Constant factor (0.747)

(2) $$CGR = \frac{DW2 - DW1}{\rho\ (t2 - t1)}$$

Where,

DW1 and DW2 - plant dry weight at t1 and t2 respectively

t1 and t2 - time interval at 90 and 60 days respectively

ρ - ground area occupied by the plant (m^2)

(3) $$\text{Chlorophyll 'a'} = (12.7 \text{ x OD at } 663) - (2.69 \text{ x OD at } 645) \text{ X } \frac{V}{1000 \text{ X } W}$$

(4) $$\text{Chlorophyll 'b'} = (22.9 \text{ x OD at } 645) - (2.69 \text{ x OD at } 663) \text{ X } \frac{V}{1000 \text{ X } W}$$

(5) $$\text{Total chlorophyll} = (8.02 \text{ x OD at } 663) - (20.62 \text{ x OD at } 645) \text{ X } \frac{V}{1000 \text{ X } W}$$

(6)

Where,

V - Final volume of acetone extract

W – Fresh weight of leaf sample in gram

Yield traits: The cobs were harvested at 105 DAS and dried leaves were separated from cobs to remove surface moisture to improve seed drying, storage and avoid pest and disease attack. After that, the cob length, girth and weight were measured with ten samples of each treatment. The kernels were separated using a maize sheller and number of kernels cob^{-1}, test weight of kernels and yield ha^{-1} were recorded 10 days after harvesting.

Biochemical analysis of resultant seeds: The amount of protein in resultant seeds was measured by Bradford colorimetric method (Bradford 1976). Starch content was estimated using an iodine test in which sugar was used as a reference (Sullivan, 1935). The α-amylase activity was estimated through the procedure described by Paul *et al.* (2017) and total carbohydrate content of seeds was estimated using the hydrolysis method (AOAC, 1984).

Statistical design: Field and lab experiments were conducted using randomized block and completely randomized block design respectively with five replications. Values were expressed as a mean ± Standard error. Data analysis was performed using SPSS software version 16.0, where ANOVA was conducted before applying Duncan's multiple range test (DMRT) to identify statistically significant differences ($p \leq 0.05$) between treatment means. Origin software version 2024b was used to plot the graph.

RESULTS AND DISCUSSION

***Invitro* characterization of volcanic ash:** The microstructure and morphology of volcanic ash particles and volcanic ash-based formulation were examined through FE-SEM in the FE-SEM in the present study. The volcanic ash particles exhibited an irregular texture with coarse surfaces. Size of the volcanic ash particles observed by FE-SEM were ranged from approximately 30 nm to 300 µm with varied shapes (Fig. 1A and 1B). The stereo-pair images captured by FE-SEM enable accurate measurements, revealing that ash particles can vary from angular to subangular forms (Mills and Rose, 2010). Whereas in volcanic ash-based formulation, the volcanic ash particles were microencapsulated within polymeric materials, demonstrating an effective coating over particles. The crystalline structure of volcanic ash was visible within polymeric substances (Fig. 2A) and the polymeric substance formed a continuous sheet and may also act as an outer covering on the volcanic ash particles, ensuring a uniform coating over the seeds as obtained in the present study (Fig. 2B).

The various elements of volcanic ash and volcanic ash-based formulation were analysed using EDAX coupled with FE-SEM providing insights into its elemental distribution. The primary component in volcanic ash was silicon (83.07%), which was reduced to 68.44% in the formulated product due to the incorporation of additional elements that are not present in the volcanic ash. The formulation includes potassium (17.07%), sodium (3.60%), chlorine (8.48%), copper (1.00%) and bromine (0.74%) which were absent in the volcanic ash (Table 2). The presence of nutrients in the formulation ensures that the plants receive necessary macronutrients and micronutrients throughout their developmental stages, contributing to nutrient availability, stress resistance, supports greater growth, photosynthesis and yield. Barone *et al.* (2021) reported that volcanic ash contains high amount of silicon (49%) followed by potassium, titanium, aluminium, iron, manganese, magnesium, sodium and calcium. Foliar application of silicon has been shown to improve stress resistance and increased the chlorophyll content were noted in maize (Ahmed *et al.,* 2023).

The macro- and micronutrient compositions of volcanic ash were quantified by ICP-MS.ICP-MS is highly sensitive and can detect trace elements at very low concentrations, making it ideal for identifying a wide range of elements in volcanic ash. It uses plasma to ionize the sample and analyzes ions based on their mass-to-charge ratio. In contrast, EDAX, is less sensitive and mainly detects surface elements with higher atomic numbers (greater than 11), requiring larger concentrations for detection. Due to these differences, ICP-MS identifies more elements, while EDAX detects only a few present in higher amounts. In the present study, the volcanic ash samples contained more macronutrients such as phosphorous (2.75 g kg^{-1}), potassium (6.22 g kg^{-1}), magnesium (1.77 g kg^{-1}) and calcium (4.02 g kg^{-1}) (Fig. 3A) and micronutrients such as iron (44.78 g kg^{-1}), cobalt (0.03 g kg^{-1}), sodium (0.85 g kg^{-1}), zinc (0.13 g kg^{-1}) and manganese (0.44 g kg^{-1}) and lower quantity of nickel, copper, molybdenum and boron (Fig. 3B). Similar findings were reported by Ermolin *et al.* (2017), who assessed volcanic ash morphology through SEM (Scanning Electron Microscopy) and the element contents were estimated through ICP–MS.

Influence of physiological traits: Seed coating with volcanic ash-based formulations at every concentration significantly enhanced germination percentage, root length, shoot length, DMP and vigour index compared to control in the germination chamber. Specifically, seed coating with 10 ml kg^{-1} of volcanic ash-based formulation resulted in a 10% increase in germination over the control. Shoot length exhibited improvement of 25.4%, 22.4%, 20.2%, 15.5% and 6.0% at concentrations of 10, 8, 6, 4, and 2 $mlkg^{-1}$respectively. Similarly, root length increased by 25.4%, 23.7%, 17.5%, 15.4% and 8.2% at the same respective concentrations (Table 3). Each increase in seed coating dosage led to a corresponding rise in DMP and vigour index II, with improvements ranging from 13.6% to 45.2% for DMP and from 16.0% to 51.3% for vigour index, compared to the control. The highest increase in both biomass and vigour index was observed at10 $mlkg^{-1}$ dosage of seed coating formulation (Table 3). The enhanced physiological performance in terms of germination, root length, shoot length, DMP and vigour index could be attributed to the presence of silica, calcium and other essential minerals in the volcanic ash. These minerals would have improved water absorption during seed imbibition, which in turn boosted dry matter production and seedling vigour. Seed coating with controlled macro- and micronutrients facilitates optimized nutrient delivery and enhances seed germination and seedling vigour (Afzal *et al*., 2020). Supporting this, Sun *et al.* (2021) reported that maize seeds imbibed with silicon (@ 0 to 25 gl^{-1}) exhibited improved physiological, morphological and biochemical parameters in seedlings. Silicon at 15 gl^{-1} specifically increased germination by 38%, along with notable improvements in seedling length, DMP, vigour index and chlorophyll content.

Influence of soil properties: In the present study, differences in the performance between the experimental plot at the DSST farm (E_1) and at the Farmer's field (E_2) can be attributed to variations in their initial physico-chemical properties (Table 1). E_1 characterized with a sandy clay loam texture which exhibited superior results compared to E_2 which had a sandy loam texture. The soil in E_1 had a neutral pH of 7.37 and an EC of 0.24 dSm^{-1} (non-saline), while E_2 exhibited a slightly acidic pH of

6.68 and a lower EC of 0.03 dSm^{-1} (non-saline) (Table 1). The higher clay content in E_1 (31.34%) contributed to improved water and nutrient retention favoring maize growth, whereas in E_2, with a lower clay content (17.69%) was less efficient in retaining water and nutrients (Table 1). This enhanced retention in E_1 likely to increase the availability of essential nutrients, also the available nitrogen levels were 210 kg ha^{-1} in E_1 and 168 kg ha^{-1} in E_2 reflecting the overall fertility advantage of the E_1 soil parameters (Table 1). Additionally, E_1 had a higher organic carbon content (4.3 g kg^{-1}) compared to E_2 (3.6 g kg^{-1}), further supporting soil fertility, root growth, microbial activity and nutrient uptake (Table 1). Although E_2 had higher initial levels of potassium and phosphorus, its lower clay content would have reduced its capacity to retain water and nutrients, increasing the risk of nutrient leaching and limiting sustained crop growth. The volcanic ash-based formulation was effective in both soil types, but the sandy clay loam of E_1 provided a more favourable environment for plant growth, resulting in enhanced performance. According to Chukwudi *et al.* (2021), significant variations in growth and yield attributes were observed across maize varieties grown under varying conditions. Sandy clay loam soil provided a more favourable environment for maize growth compared to loamy sandy soil

Allometry characterization: Significant differences among various treatments (control, CS and CS+FS) were observed in both the field experimental plots *viz.,* the DSST farm (E_1) and farmer's field (E_2) (2023-2024). Taller plants generally have more biomass and a greater capacity for photosynthesis, potentially leading to better nutrient acquisition and light capture. In this study at 90 DAS, plant height was measured in both experimental plots. In E_1 plot, CS+FS treatment resulted in a 12.8% and 5.34% increased plant height compared to control and CS, respectively. Similarly, E_2 plot, CS+FS treatment showed a 12.0% and 7.5% increased plant height compared to control and CS respectively (Table 4). At 60 DAS, compared with those in control and CS, the leaf area and leaf area index in E_1 were 8.45% and 4.5% and 12.5% and 7.1% were maximum respectively. Similarly, treatment CS+FS resulted in 7.50% and 2.7% and 11.5% and 3.8% greater values in E_2 than those in the control and CS, respectively (Table 4). Leaf area affects the plant's ability to capture sunlight for photosynthesis, which drives growth and energy production. More leaf area generally results in more photosynthetic activity, leading to increased biomass accumulation and grain yield. These results revealed that treatment CS+FS was superior in both the experimental plots because of the combination of seed treatment and foliar application with the volcanic ash-based formulation at 30 and 50 DAS.

The presence of phosphorous and potassium in this formulation promotes healthy nodal root growth and regulates stomatal conductance, respectively. Strong roots allow plants to access nutrients and water from the soil, which is helpful for increasing the plant height. The application of phosphorous fertilizer results in increased root density and root surface area in corn seedlings (Fink *et al.,* 2016). Similarly, foliar application of silica improved plant growth, leaf area, fresh weight, dry weight, yield and seed quality as reported by Bassiouni *et al.* (2020) in paddy and Jam *et al.* (2023) in safflower. Also, Farshidi *et al.* (2012) reported increased leaf area and specific leaf area in canola.

Dry matter accumulation reflects the biomass production of a plant includes leaves, stems and grains. High dry matter production indicates a greater availability of photosynthates for conversion into grains, thereby supporting higher yields. In both the experimental plots, the treatment CS+FS recorded significant increase in DMP (28.85% and 21.45% for E_1, 12.26% and 10.47% for E_2) and crop growth rate (14.30% and 13.61% for E_1, 9.82% and 7.80% for E_2) over control and CS respectively at 90 DAS (Table 4). These findings suggest that increased leaf area due to CS+FS treatment is directly associated with greater DMP and crop growth rates. The CS+FS treatment resulted in increased plant height, number of leaves and larger leaf area, which would have aided to accumulate more photosynthates in the shoots, leading to a maximized DMP and crop growth rate. Jawahar *et al.* (2020) reported that the combined application of silicon through soil and foliar methods enhanced root growth and soil silicon availability, which led to increased dry matter production and nutrient uptake in maize plants.

Influence of photosynthetic pigments: In both the field experimental plots *viz.,* the DSST farm (E_1) and farmer's field (E_2), CS+FS treatment recorded significantly increased chlorophyll content (a, b and ab). CS+FS registered increased chlorophyll 'a' by 14.4% and 6.8% for control and CS respectively, in E_1 and by 12.3% and 5.2% for control and CS respectively, in E_2 (Fig. 4A). Chlorophyll 'b' was notably greater in CS+FS by 13.4% and 7.7% for control and CS respectively in E_1 and E_2 revealing increased chlorophyll 'b' in CS+FS by 13.3% than control and 6.4% than CS (Fig. 4B). The total chlorophyll content in CS + FS recorded increase of 14.1% and 7.1% compared to control and CS respectively in E1. In E2, the increases were 12.7% and 5.6% for control and CS respectively (Fig. 4C). The maximum chlorophyll content was achieved by CS+FS treatment in both the experiments due to the combination of seed coating and foliar application of volcanic ash-based formulation at 30 and 50 DAS. This proved that, plants effectively absorbed and utilized nutrients such as silica, magnesium and phosphorous in the treated plots. A reduced photosynthetic rate leads to reduced plant growth and *vice versa*. The decrease in chlorophyll content is due to reduction in internal leaf carbon dioxide (Parveen and Ashraf, 2010).

Silicon promotes relatively high photosynthetic rates due to improved chlorophyll content and the activity of key enzymes such as *Rubisco* and NADP-dependent glyceraldehyde-3-phosphate dehydrogenase (Parveen and Ashraf, 2010; Gong *et al.,* 2005). Silicon also restricts water loss through transpiration, maintains internal water status within plants, keeps leaves erect for better light capture and enhances overall photosynthetic efficiency (Abdalla, 2009; Amin *et al.,* 2014). Xie *et al.* (2014) reported that the use of silicon as soil fertilizer maximized the total chlorophyll content, photosynthetic rate, stomatal conductance and minimized the transpiration rate and intercellular carbon dioxide levels in maize plants. Kanjana (2020) reported that Nano foliar application of magnesium to cotton increased growth and yield parameters, with 2.5% increase in chlorophyll content and yield by 42.2% over those of untreated plants.

Yield traits: Significance difference was observed between the treatments (control, CS and CS+FS) and the experimental plots (E_1 and E_2) in postharvest analysis parameters such as cob length, girth, weight, number of seeds per cob, 100 seed weight and seed yield. Cob size, weight and number of seeds per cob are the final indicators of the yield potential. A plant that can effectively channel its energy to produce larger, heavier cobs with more seeds will yield more. In this study, cob length in CS+FS treatment registered an increase of 24.2% and 18.3% over control treatment in E_1 and E_2 respectively (Table 5). Cob girth in CS+FS was 8.15% and 8.0% increased than control in E_1 and E_2, respectively. Cob weight in CS+FS was 20.9% and 18.7% greater than control in E_1 and E_2, respectively (Table 5). Number of seeds per cob recorded in CS+FS (743 in E_1 and 728 in E_2) was greater than that of control (671 in E_1 and 657 in E_2). The 100-seed weight recorded in the CS+FS (33.0 in E_1 and 32.38 in E_2) was higher than recorded in control (29.12 in E_1 and 28.61 in E_2) (Table 5). This study undoubtedly displays that the CS+FS treatment, maximized all growth and yield parameters. An increase in seed yield was associated with an increase in the photosynthesis rate, cob length, cob weight, number of seeds cob^{-1} and 100-seed weight in the CS+FS treatment. This volcanic ash-based formulation contains various micronutrients, macronutrients and useful heavy metals that are utilized by plants for their growth and development. Moreover, the combination of seed coating and foliar application was performed twice, at 30 (during the vegetative stage) and 50 DAS (during the initial reproductive stage), to increase the photosynthetic rate of plants and dry matter production which led to greater seed yield.

Desoky *et al.* (2018) revealed that volcanic ash is a multi-nutrient rock silicate fertilizer contains essential nutrients which release into agricultural fields; therefore, it has improved soil properties and fertility, thereby improving agricultural production. Miah *et al.* (2000) demonstrated the positive effect of the combination of volcanic ash and sewage sludge compost on enhancing crop growth and production in wheat. Zakharikhina *et al.* (2022) opined that volcanic ash used as soil amendment recorded increased yield in potato and timothy. Similarly, Liang *et al.* (2024) reported that application of volcanic ash increased plant growth in mung bean and achieved a carbon dioxide sequestration rate of 0.14 kg CO_2 m^{-2} month^{-1}.

Biochemical changes on resultant seeds: Seed coating and foliar application of the volcanic ash-based formulation significantly improved carbohydrate, starch, α-amylase and protein contents compared with those of the control in both E_1 and E_2. The results revealed significant differences among the treatments and no significant differences were noted between the locations. Among the treatments, CS+FS remained the best compared with the CS and control treatments, which increased 8.5% carbohydrate content, 59% α-amylase content, 6.9% starch content and 19.3% protein content in the resultant seeds compared with those of the control in E_1 (Fig. 5). Similarly, compared with the control, E_2 improved the carbohydrate content, α-amylase content, starch content and protein content of the resultant seeds by 7.5%, 60%, 6.0% and 16.5% respectively (Fig. 5).

Foliar application of volcanic ash-based formulations delivers the essential nutrients directly to the stomata and cuticles, increases yield and protein content and saving time than traditional methods. Starch is a vital storage carbohydrate for plant growth and its content does not directly regulate growth processes. Instead, starch levels fluctuate throughout various growth stages. This fluctuation might be linked to competition for a shared building block between starch synthesis and sucrose production (Stitt and Zeeman, 2012). Iron and potassium content in the formulation increased the biochemical value of maize through CS+FS treatment. These findings suggest that iron deficiency can reduce seed protein content because of the direct positive effect of iron on protein synthesis. The application of iron to maize increased the starch content and protein content in low-pH calcareous soil (Ramzani *et al.,* 2017). Seeds with abundant carbohydrates, α-amylase, starch and proteins are highly vigoured. The presence of higher starch, soluble proteins and sugars offer readily available energy and immediate nutrients that give greater capacity to mobilize these reserves during germination which results in healthy seedling growth (Kim *et al.,* 2011).

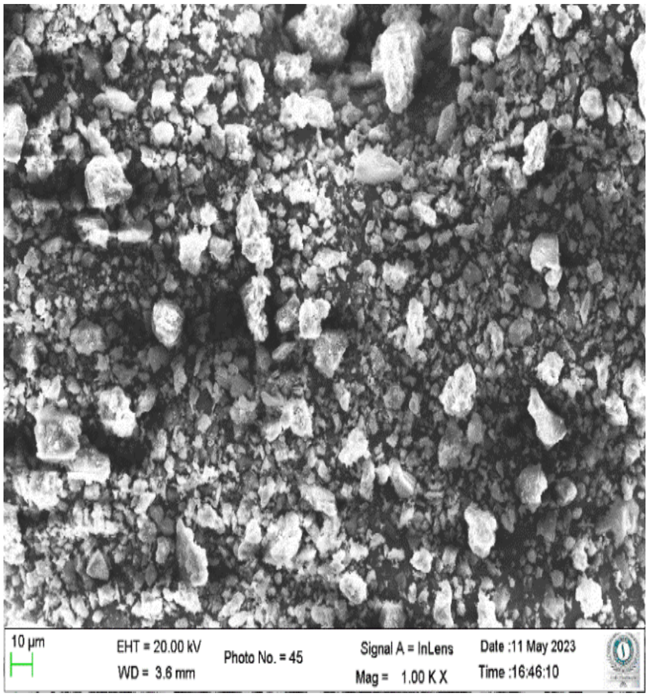


Fig.1A. overview of volcanic ash with the wide range of particles

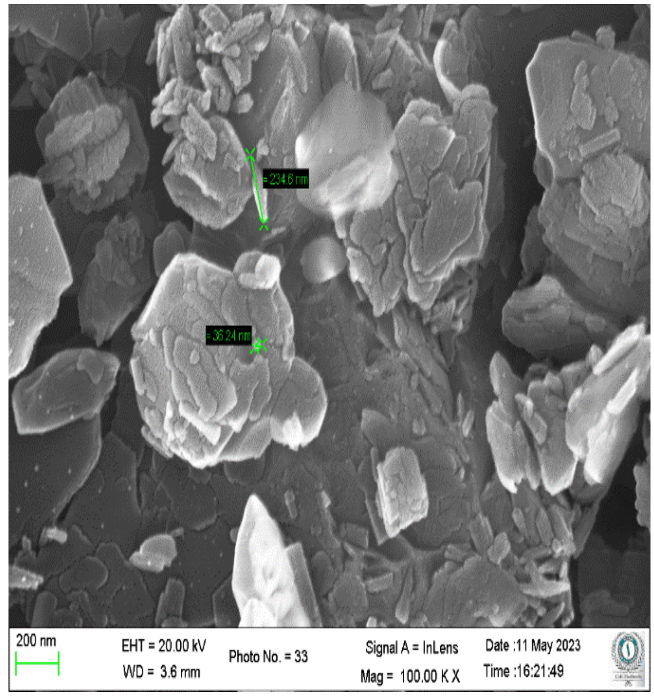


Fig.1B. volcanic ash particles size ranges from 30-300 nm

Fig. 1. Field Emission Scanning Electron Microscope (FE-SEM) image of Volcanic ash particles

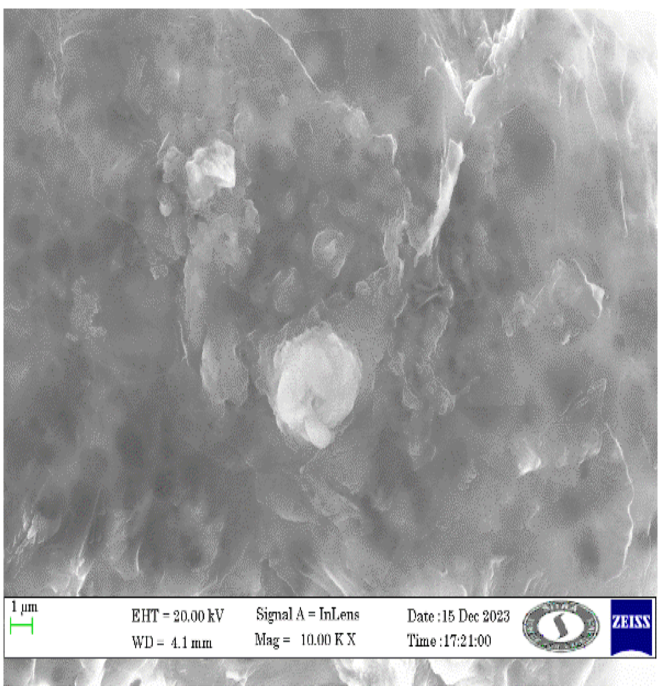


Fig.2A. Volcanic ash particles inside the polymeric substances

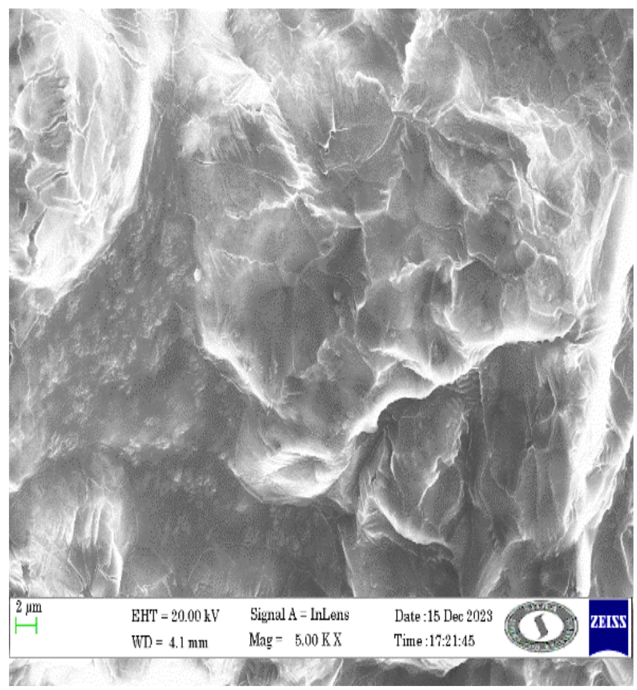
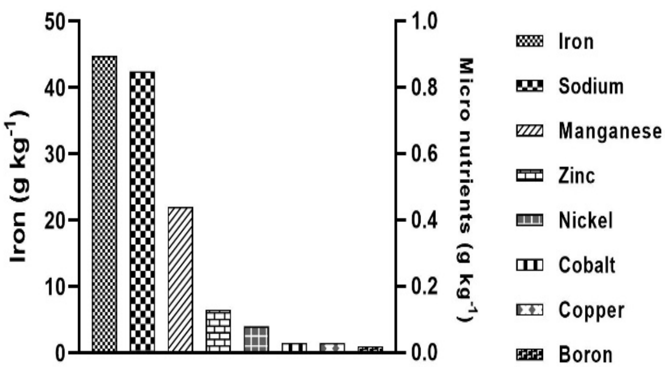


Fig.2B. Outer most sheet like layer of the polymeric substances

Fig.2. Field Emission Scanning Electron Microscope (FE-SEM) image of Volcanic ash particles micro-encapsulated in polymeric substances

3A



3B

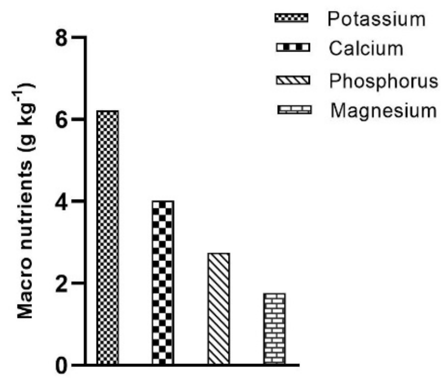
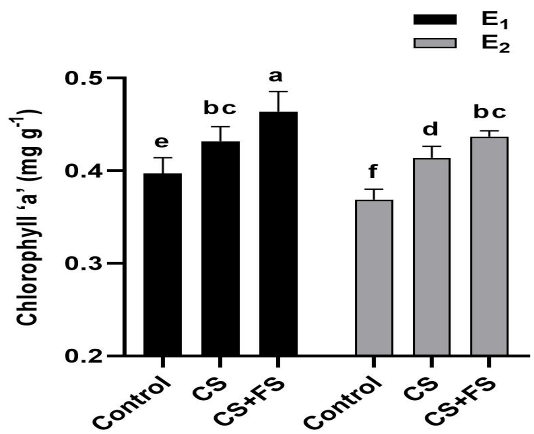


Fig.3. Estimation of micro (3A) and macro nutrients (3B) in the volcanic ash through Inductively coupled plasma mass spectrometry

4



4B

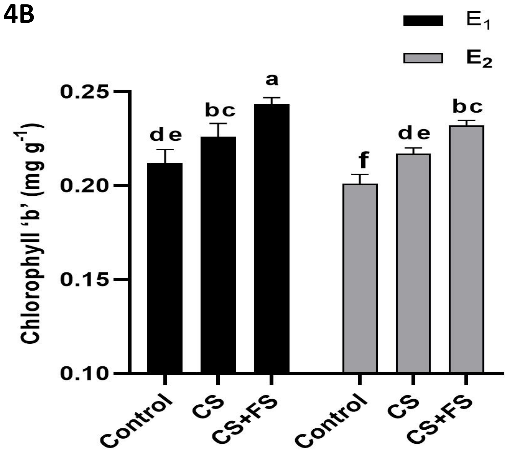
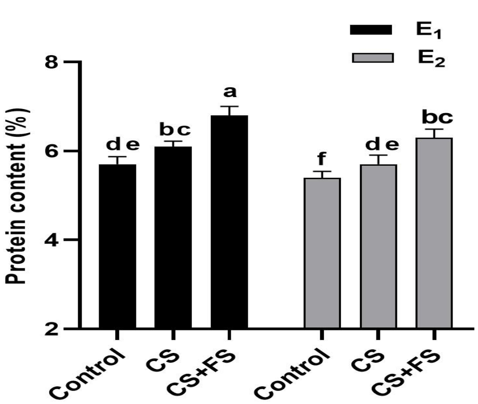
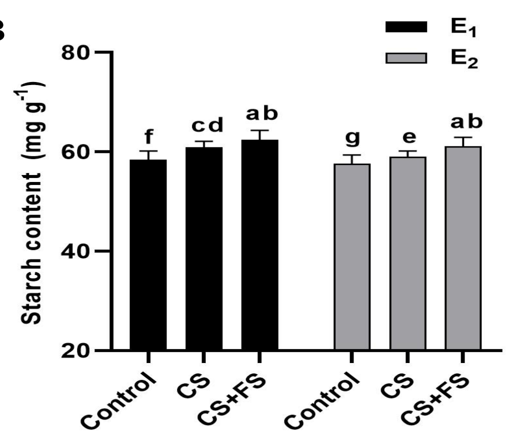


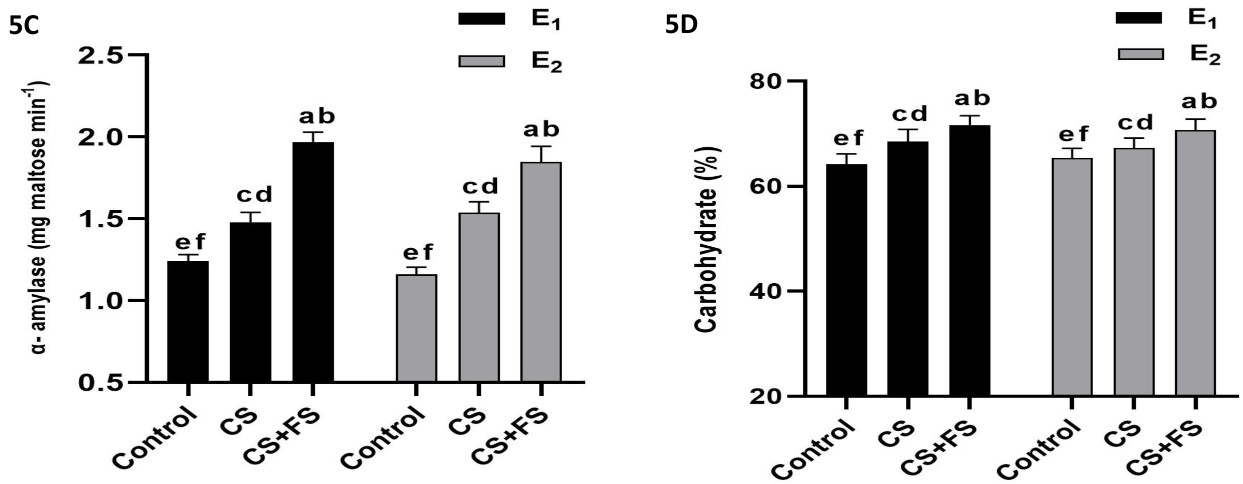
Fig. 4. Effect of volcanic ash- based formulation on chlorophyll content of maize COH(M) 8
Control (Non-coated seeds), CS - coated seed @ 10 ml kg^{-1} and CS+FS - Seed coating @ 10 ml kg^{-1} + Foliar application with formulation at 500 L ha^{-1}. E_1 and E_2 indicates the DSST farm and Farmer's field respectively. Standard error at n = 5. Different letters indicate significant differences between treatments ($p \leq 0.05$).

5A



5B





Control (Non-coated seeds), CS - coated seed @ 10 ml kg^{-1} and CS+FS - Seed coating @ 10 ml kg^{-1} + Foliar application with formulation at 500 L ha^{-1}. E_1 and E_2 indicates the DSST farm and Farmer's field respectively. Standard error at n = 5. Different letters indicate significant differences between treatments ($p \leq 0.05$).

Table 1. Initial physico- chemical properties of the experimental plots.

Details	DSST Farm, TNAU (E_1)	Farmer's Field, Kaniyur (E_2)
I. Taxonomical class		
Mechanical analysis		
Clay (%)	31.34	17.69
Silt (%)	19.31	22.54
Fine Sand (%)	26.07	26.91
Coarse sand (%)	23.14	32.86
Textural class	Sandy clay loam	Sandy loam
II. Physico-chemical properties		
Soil reaction (pH)	7.37	6.68
Electrical conductivity (dSm^{-1})	0.36	0.24
III. Chemical properties		
Organic carbon (g kg^{-1})	4.3	3.6
Available N (kg ha^{-1})	210	168
Available P (kg ha^{-1})	18.7	22.6
Available K (kg ha^{-1})	112	146
Exchangeable Ca (c mol (p^{+}) kg^{-1})	1.42	1.28
Exchangeable Mg (c mol (p^{+}) kg^{-1})	4.12	4.35
$CaCl_2$ S (mg kg^{-1})	11.9	8.6
Available Fe (mg kg^{-1})	3.22	2.28
Available Mn (mg kg^{-1})	3.91	2.74
Available Zn (mg kg^{-1})	1.88	0.67
Available Cu (mg kg^{-1})	1.51	0.79

Table 2. Elemental composition of volcanic ash by Energy dispersive X-ray analysis (EDAX)

Element	Volcanic ash (%)	Volcanic ash-based formulation (%)
Silicon	83.07	68.44
Magnesium	3.54	0.44
Aluminum	4.90	-
Potassium	1.05	17.07
Calcium	3.74	-
Titanium	0.38	-

Iron	3.33	0.22
Sodium	-	3.60
Magnesium	-	0.44
Chlorine	-	8.48
Copper	-	1.00
Bromine	-	0.74
Totals	100.00	100.00

Table 3. Standardisation of volcanic ash-based seed coating formulation on physiological parameters of maize COH(M) 8.

Treatments	Germination (%)	Shoot length (cm)	Root length (cm)	Dry matter production (mg seedlings^{-10})	Vigour index I	Vigour index II
Control	90 ± 1.38^{ef}	17.3 ± 0.30^{e}	21.1 ± 0.38^{f}	1.18 ± 0.02^{ef}	3510 ± 53.62^{ef}	106 ± 2.81^{ef}
2 ml kg^{-1}	90 ± 0.90^{ef}	18.0 ± 0.27^{d}	22.2 ± 0.34^{e}	1.26 ± 0.02^{ef}	3618 ± 75.31^{ef}	113 ± 4.09^{ef}
4 ml kg^{-1}	92 ± 1.88^{cd}	18.5 ± 0.39^{bc}	24.0 ± 0.50^{cd}	1.41 ± 0.03^{cd}	3910 ± 67.72^{cd}	130 ± 3.89^{cd}
6 ml kg^{-1}	94 ± 2.11^{cd}	19.6 ± 0.41^{bc}	24.6 ± 0.51^{cd}	1.53 ± 0.03^{cd}	4155 ± 63.47^{cd}	150 ± 3.81^{cd}
8 ml kg^{-1}	96 ± 1.00^{b}	21.8 ± 0.44^{bc}	26.7 ± 0.35^{b}	1.91 ± 0.05^{b}	4656 ± 46.33^{b}	183 ± 6.61^{b}
10 ml kg^{-1}	100 ± 1.33^{a}	23.2 ± 0.21^{a}	29.1 ± 0.26^{a}	2.18 ± 0.04^{a}	5230 ± 39.56^{a}	218 ± 7.86^{a}
CD (P≤0.05)	3.77	1.25	1.59	0.12	248.56	9.32

Data are means ± Standard error at n = 5. Different letters indicate significant differences between treatments (p ≤ 0.05).

Table 4. Effect of volcanic ash-based seed coating formulation on allometry parameters of maize COH(M) 8.

Experimental plot	Treatments	Plant height at 90 DAS (cm)	Leaf area at 60 DAS (cm^2)	Leaf area index at 60 DAS	Dry matter production 90 DAS (g plant^{-1})	Crop growth rate (g m^{-2} day^{-1})
E_1	Control	210 ± 3.21^{de}	487 ± 7.44^{de}	4.9 ± 0.07^{de}	72.56 ± 1.51^{e}	4.965 ± 4.82^{de}
	CS	228 ± 4.75^{bc}	508 ± 10.57^{bc}	5.2 ± 0.11^{bc}	81.46 ± 1.36^{c}	5.225 ± 5.23^{c}
	CS+FS	241 ± 4.17^{a}	532 ± 8.21^{a}	5.6 ± 0.10^{a}	93.5 ± 1.32^{a}	5.794 ± 5.62^{a}
E_2	Control	197 ± 3.01^{f}	468 ± 7.15^{f}	4.6 ± 0.07^{f}	68.24 ± 1.42^{f}	4.701 ± 4.56^{f}
	CS	207 ± 4.31^{de}	492 ± 10.2^{de}	5.0 ± 0.10^{de}	77.78 ± 1.28^{d}	5.017 ± 5.02^{de}
	CS+FS	224 ± 3.88^{bc}	506 ± 8.76^{bc}	5.2 ± 0.09^{bc}	86.88 ± 1.22^{b}	5.442 ± 5.28^{b}
CD (P≤0.05)		7.18	16.51	0.17	2.46	0.17

Control (Non-coated seeds), CS - coated seed @ 10 ml kg^{-1} and CS+FS - Seed coating @ 10 ml kg^{-1} + Foliar application with formulation at 500 L ha^{-1}. E_1 and E_2 indicates the DSST farm and Farmer's field respectively. Standard error at n = 5. Different letters indicate significant differences between treatments (p ≤ 0.05).

Table 5. Effect of volcanic ash-based seed coating formulation on yield parameters of maize COH(M) 8.

Experimental plot	Treatments	Cob length (cm)	Cob girth (cm)	Cob weight (single) (g cob^{-1})	No. of seeds cob^{-1}	100 seed weight (g)	Yield (kg ha^{-1})
	Control	16.52 ± 0.25^{e}	15.46 ± 0.24^{cd}	191 ± 2.92^{e}	671 ± 2.89^{ef}	29.12 ± 0.4^{ef}	6044 ± 11.55^{d}
E_1	CS	18.22 ± 0.38^{bc}	15.83 ± 0.33^{cd}	216 ± 4.50^{bc}	718 ± 2.31^{cd}	31.78 ± 0.66^{cd}	6194 ± 10.39^{b}
	CS+FS	20.52 ± 0.36^{a}	16.72 ± 0.29^{ab}	231 ± 2.13^{a}	743 ± 1.15^{a}	33.00 ± 0.57^{ab}	6556 ± 4.62^{a}
	Control	15.21 ± 0.23^{f}	15.00 ± 0.23^{ef}	176 ± 3.66^{f}	657 ± 6.55^{ef}	28.61 ± 0.60^{ef}	5714 ± 8.66^{f}
E_2	CS	17.15 ± 0.37^{d}	15.3 ± 0.32^{ef}	197 ± 3.53^{d}	708 ± 3.74^{cd}	31.08 ± 0.54^{cd}	5867 ± 6.35^{e}
	CS+FS	18.00 ± 0.31^{bc}	16.2 ± 0.28^{ab}	209 ± 3.41^{bc}	728 ± 1.74^{b}	32.38 ± 0.49^{ab}	6073 ± 5.77^{c}
CD (P≤0.05)		0.58	0.52	7.21	16.29	1.03	25.20

Control (Non-coated seeds), CS - coated seed @ 10 ml kg^{-1} and CS+FS - Seed coating @ 10 ml kg^{-1} + Foliar application with formulation at 500 L ha^{-1}. E_1 and E_2 indicates the DSST farm and Farmer's field respectively. Standard error at n = 5. Different letters indicate significant differences between treatments (p ≤ 0.05).

Conclusion: It is concluded that treating hybrid maize COH(M) 8 seeds with volcanic ash-based seed coating formulation @10 ml kg^{-1} increased germination and vigour due to the presence of macro and micro nutrients in the volcanic ash. Under field conditions, the volcanic ash-based formulation as a combination of seed coating (@ 10 ml kg^{-1} of seeds) and foliar application (@ 500 L ha^{-1}) at 30 and 50 DAS performed better, both under sandy clay loam and sandy loam. Since, soil condition and environmental factors also plays a major role in crop production, the outcomes might differ if applied under more extreme soil conditions like saline, alkaline or highly compacted soils and also during different seasons.

Acknowledgements: The authors acknowledge Department of Seed Science and Technology for providing the facilities to carry out the research.

Conflict of Interest: Authors state that there is no conflict of interest

Author's contribution: K.N. Vinoth: conducted the experiment and collected the all data; R. Jerlin: mentor, correction and finalization of paper; V. Manonmani and J. Renugadevi: Facilitation and guidance for laboratory and field experiments; M. Djanaguiraman and T. Eevera: helped in planning the research work; V. Vakeshwaran and S. Kavitha: guided in data compilation and analysis.

Funding: Not Applicable

Research content: The research content of manuscript is original and has not been published elsewhere.

Consent to publish: All authors agree to publish the paper in Journal of Animal and Plant Sciences.

REFERENCES

Abdalla, M.M. (2009). Sustainable effects of diatomites on the growth criteria and phytochemical contents of *Vicia faba* plants. 4th Conference on Recent Technologies in Agriculture, Faculty of Agriculture, Cairo University, Giza, Egypt. 1076-1089 p. https://doi.org/10.5251/abjna.2010.1.5.1076.1089

Abdul-Baki, A.A. and J.D. Anderson (1973). Vigor determination in soybean seed by multiple criteria. Crop. Sci.. 13(6):630-3. https://doi.org/10.2135/cropsci1973.0011183X001300060013x

Afzal, I., T. Javed, M. Amirkhani and A.G Taylor (2020). Modern seed technology: Seed coating delivery systems for enhancing seed and crop performance. Agriculture. 10(11): 526. https://doi.org/10.3390/agriculture10110526

Amin, M., R. Ahmad, S. M. A. Basra and G. Murtaza (2014). Silicon induced improvement in morpho-physiological traits of maize (*Zea Mays* L.) under water deficit. Pakistan J. Agric. Sci. 51(1).

AOAC. (1984). Official method of analysis of the association of official Agriculture Chemist,14th edition, Washington D.C.

Arnon, D.I. (1949) Copper enzymes in isolated chloroplasts. Polyphenol oxidase in *Beta vulgaris*. Plant. Physiol. *24*(1), 1. https://doi.org/10.1104/pp.24.1.1

Ahmed, S., M. Iqbal, Z. Ahmad, M.A. Iqbal, A. Artyszak, A.E. Sabagh and A. Hossain (2023). Foliar application of silicon-based nanoparticles improve the adaptability of maize (*Zea mays* L.) in cadmium contaminated soils. Environ. Sci. Pollut. Res. 30(14), 41002-41013. https://doi.org/10.1007/s11356-023-25189-0

Bassiouni, S.M., M.S. Abdel-Aal and O.A. Ali (2020). Productivity and quality of rice as influenced by foliar spray of different silicon sources and rates under salinity soil conditions. Int. J. Plant Prod. 11(12):1201-6. https://doi.org/10.21608/jpp.2020.149789

Battacharyya, D., M.Z. Babgohari, P. Rathor and B. Prithiviraj (2015). Seaweed extracts as biostimulants in horticulture. Sci. Hortic. - 196:39-48. https://doi.org/10.1016/j.scienta.2015.09.012

Bradford, M.M. (1976). A rapid and sensitive method for the quantitation of microgram quantities of protein utilizing the principle of protein-dye binding. Anal. Biochem. 72(1-2):248-54. https://doi.org/10.1006/abio.1976.9999

Barone, G., C. Finocchiaro, I. Lancellotti, C. Leonelli, P. Mazzoleni, C. Sgarlata and A. Stroscio (2021). Potentiality of the use of pyroclastic volcanic residues in the production of alkali activated material. Waste. Biomass Valori.12, 1075-1094. https://doi.org/10.1007/s12649-020-01004-6

Charles-Edwards, D.A. (1982). Physiological determinants of crop growth. Sydney: Academic Press. London.41 (1):88-93.

Chukwudi, U.P., F.R. Kutu and S. Mavengahama (2021). Influence of heat stress, variations in soil type and soil amendment on the growth of three drought–tolerant maize varieties. Agronomy, 11(8), 1485. https://doi.org/10.3390/agronomy11081485

Ciriminna, R., A. Scurria, G. Tizza, and M. Pagliaro (2022). Volcanic ash as multi-nutrient mineral fertilizer: Science and early applications. J. Sci. Food Agric. 2(11), 528-534. https://doi.org/10.1002/jsf2.87

El-Desoky, A., A. Hassan and A. Mahmoud (2018). Volcanic ash as a material for soil conditioner and fertility. J. soil sci. agric. eng. 9(10):491-5. https://doi.org/10.21608/jssae.2018.36445

De la Rosa, J.M., S.M. Pérez-Dalí, P. Campos, A. Sánchez-Martín, J.A. González-Pérez, and A.Z.

Miller (2023). Suitability of volcanic ash, rice husk ash, green compost and biochar as amendments for a Mediterranean alkaline soil. Agronomy, 13(4), 1097. https://doi.org/10.3390/agronomy13041097

Ermolin, M.S., P.S. Fedotov, V.K. Karandashev and Shkinev (2017). Methodology for separation and elemental analysis of volcanic ash nanoparticles. J. Anal. Chem. 72:533-41. https://doi.org/10.1134/S1061934817050069

FAO (2022). Food and Agriculture Organization of the United Nations, International Fund for Agricultural Development, UNICEF, World Food Programme, and World Health Organization the State of Food Security and Nutrition in the World, Repurposing Food and Agricultural Policies to Make Healthy Diets More Affordable. Food and Agriculture Organization, Rome (Italy).65-70 p

Farshidi, M., A. Abdolzadeh and H.R. Sadeghipour (2012). Silicon nutrition alleviates physiological disorders imposed by salinity in hydroponically grown canola (*Brassica napus* L.) plants. Acta Physiol. Plant. 34:1779-88. https://doi.org/10.1007/s11738-012-0975-1

Fink, J.R., A.V. Inda, J. Bavaresco , A.R. Sánchez-Rodríguez, V. Barrón, J.Torrent and C. Bayer (2016) . Diffusion and uptake of phosphorus, and root development of corn seedlings, in three contrasting subtropical soils under conventional tillage or no-tillage. Biol. Fertil. Soils. 52:203-10. https://doi.org/10.1007/s00374-015-1067-3

Floyd, C.N., R.D.B. Lefroy and E.J. D'souza (1988). Soil fertility and sweet potato production on volcanic ash soils in the highlands of Papua New Guinea. Field Crops Res. *19*(1), 1-25. https://doi.org/10.1016/0378-4290(88)90030-5

Fertahi, S., W. Elhaissoufi, A. Bargaz, F. Touchaleaume, Y. Habibi, A. Oukarroum and A. Barakat (2024). Lignin-rich extracts as slow-release coating for phosphorus fertilizers. Prog. Org. Coat. *190*, 108394. https://doi.org/10.1016/j.porgcoat.2024.108394

Gong, H., X. Zhu, K. Chen, S. Wang and C. Zhang (2005). Silicon alleviates oxidative damage of wheat plants in pots under drought. Plant sci. 169(2):313-21. https://doi.org/10.1016/j.plantsci.2005.02.023

ISTA (2022). International Rules for Seed Testing, International Seed Testing Association, Wallisellen, Switzerland.

Jam, B.J., F. Shekari,B. Andalibi, R. Fotovat,V. Jafarian, J. Najafi, D. Uberti and A. Mastinu (2023) . Impact of silicon foliar application on the growth and physiological traits of *Carthamus tinctorius* L. exposed to salt stress. Silicon. 15(3):1235-45. https://doi.org/10.1007/s12633-022-02090-y

Jawahar, S., K. Suseendran, C. Kalaiyarasan, S. Ramesh, S.R. Vinodkumar and K. Arivukkarasu (2020). Effect of silicon on dry matter yield and nutrient uptake of hybrid maize.

Jeong, H.W., H.R. Lee, H.M. Kim, H.M. Kim, H.S. Hwang and S.J. Hwang (2020). Using light quality for growth control of cucumber seedlings in closed-type plant production system. Plants. 9(5):639. https://doi.org/10.3390/plants9050639

Johnson, S.E., J.G. Lauren, R.M. Welch and J.M. Duxbury (2005). A comparison of the effects of micronutrient seed priming and soil fertilization on the mineral nutrition of chickpea (*Cicer arietinum*), lentil (*Lens culinaris*), rice (*Oryza sativa*) and wheat (*Triticum aestivum*) in Nepal. J. Exp. Agric. 41(4):427-48. https://doi.org/10.1017/S0014479705002851

Kanjana, D. (2020). Foliar application of magnesium oxide nanoparticles on nutrient element concentrations, growth, physiological, and yield parameters of cotton. J. Plant Nutr. 43(20):3035-49. https://doi.org/10.1080/01904167.2020.1799001

Kim, H.T., U.K. Choi, H.S. Ryu, S.J. Lee and O.S Kwon (2011). Mobilization of storage proteins in soybean seed (*Glycine max* L.) during germination and seedling growth. Biochim Biophys Acta, Proteins Proteomics. 1814(9):1178-87. https://doi.org/10.1016/j.bbapap.2011.05.004

Kassem, I., E.H. Ablouh, F.Z. El Bouchtaoui, M. Jaouahar and M. El Achaby (2024). Polymer coated slow/controlled release granular fertilizers: Fundamentals and research trends. Prog. Mater. Sci. 101269. https://doi.org/10.1016/j.pmatsci.2024.101269

Kumari, P., N. Kumari, C. Mohan, C. Chinglenthoiba and K.T. Amesho (2024). Environmentally benign approach to formulate nanoclay/starch hydrogel for controlled release of zinc and its application in seed coating of *Oryza Sativa* plant. Int. J. Biol. Macromol. 257; 128278. https://doi.org/10.1016/j.ijbiomac.2023.128278

Liang, B., J. Wei, S. Wu and H. Hao (2024). Synergistic advantages of volcanic ash weathering in saline soils: CO_2 sequestration and enhancement of plant growth. Sci. Total Environ. 925:171825. https://doi.org/10.1016/j.scitotenv.2024.171825

Miah, M.Y., M.K Wang and M. Chino (2000). Wheat grown on volcanic ash with slow releasing nitrogen fertilizer and amended with sewage sludge compost. Commun. Soil Sci. Plant Anal. 31(5-6):695-703. https://doi.org/10.1080/00103620009370470

Mills, O.P. and W.I. Rose (2010). Shape and surface area measurements using scanning electron microscope stereo-pair images of volcanic ash particles. Geosphere. 6(6):805-11. https://doi.org/10.1130/GES00558.1

Pandey, P., V. Ramegowda and M. Senthil-Kumar (2015). Shared and unique responses of plants to multiple individual stresses and stress combinations: physiological and molecular mechanisms. Front. Plant Sci. 6:723. https://doi.org/10.3389/fpls.2015.00723

Parveen, N.U. and M.U. Ashraf (2010). Role of silicon in mitigating the adverse effects of salt stress on growth and photosynthetic attributes of two maize (*Zea mays* L.) cultivars grown hydroponically. Pakistan J. Bot. 42(3):1675-84.

Paul, S. and A. Roychoudhury (2017). Seed priming with spermine and spermidine regulates the expression of diverse groups of abiotic stress-responsive genes during salinity stress in the seedlings of indica rice varieties. Plant Gene. 11:124-32. https://doi.org/10.1016/j.plgene.2017.04.004

Piccolo, E.L., C. Ceccanti, G. Lauria, G. Santonocito, I. Rosellini, B. Pezzarossa and M. Landi (2024). From lava to leaf: Physiological responses and trace element mobility in *Tilia cordata* L. trees grown in volcanic ash amended urban soil. Urban For. Urban Green. *99*, 128458. https://doi.org/10.1016/j.ufug.2024.128458

Panjaitan, E. (2023). Effect of chicken manure and volcanic ash on the growth and production of shallot (*Allium ascalonicum* L.) and P availability in paddy field. Int. J. Bus. Innov. Res. 2(05), 79-95.

Ramzani, P.M., M. Khalid, S. Anjum, W.U. Khan, M. Iqbal and S. Kausar (2017). Improving iron bioavailability and nutritional value of maize (*Zea mays* L.) in sulfur-treated calcareous soil. Arch. Agron. Soil. Sci. 63(9):1255 66. https://doi.org/10.1080/03650340.2016.1266484

Ray, D.K., P.C. West, M. Clark, J.S. Gerber, A.V. Prishchepov and S.Chatterjee (2019). Climate change has likely already affected global food production. PloS one. 14(5): e0217148. https://doi.org/10.1371/journal.pone.0217148

Rocha I., Y. Ma, P. Souza-Alonso, M. Vosátka, H. Freitas, R.S. Oliveira. (2019) Seed coating: a tool for delivering beneficial microbes to agricultural crops. Front. Plant Sci. 10, 1357. https://doi.org/10.3389/fpls.2019.01357

Ronga, D., E. Biazzi, K. Parati, D. Carminati, E. Carminati and A. Tava (2019). Microalgal biostimulants and biofertilisers in crop productions. Agronomy. 9(4):192. https://doi.org/10.3390/agronomy9040192

Seward, W. and B. Edwards (2012). Testing hypotheses for the use of Icelandic volcanic ashes as low cost, natural fertilizers. InEGU General Assembly Conference Abstracts. 11493p.

Shiferaw, Y.A. (2023). Mapping disaggregate-level agricultural households in South Africa using a hierarchical bayes small area estimation approach. agriculture. 13(3): 631. https://doi.org/10.3390/agriculture13030631

Shoji, S. and T. Takahashi (2002). Environmental and agricultural significance of volcanic ash soils. Glob. Environ. Res. -English Edition-.6(2):113-35.

Stitt, M. and S.C. Zeeman (2012). Starch turnover: pathways, regulation and role in growth. *Current Opinion in Plant Biology*. 1;15(3):282-92. https://doi.org/10.1016/j.pbi.2012.03.016

Sullivan, J.T. (1935). The estimation of starch with special reference to woody plants. Purdue University. https://doi.org/10.1093/jaoac/18.4.621

Sun, Y., J. Xu, X. Miao, X. Lin, W. Liu and H. Ren (2021). Effects of exogenous silicon on maize seed germination and seedling growth. J. Sci. Rep. 11(1):1014. https://doi.org/10.1038/s41598-020-79723-y

Xie, Z., F. Song, H. Xu, H. Shao and R. Song (2014). Effects of silicon on photosynthetic characteristics of maize (*Zea mays* L.) on alluvial soil. Sci. World J. 718-716. https://doi.org/10.1155/2014/718716

Xue, D., Y. Wang, H. Sun, L. Fu, L. Zhu, J. Iu and C. Wu (2024). Effects of soil conditioner (volcanic ash) on yield quality and rhizosphere soil characteristics of Melon. Plants, 13(13), 1787. https://doi.org/10.3390/plants13131787

Zakharikhina, L.V., Y.S Litvinenko and V.V. Gainatulina (2022). Volcanic ash application in agricultural practice. Univers J. Agric. Res. 10(1):77-87. https://doi.org/10.13189/ujar.2022.100107.