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EFFECT OF CHABAZITIC ZEOLITE APPLICATION ON GROWTH AND YIELD OF STRAWBERRY (*Fragaria × ananassa*) UNDER CONTROLLED CONDITIONS

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ABSTRACT
This study investigates the use of chabazitic zeolite as a soil amendment to enhance the growth and yield of Fragaria × ananassa (strawberry). Recognized for its high cation-exchange capacity and excellent water retention properties, chabazitic zeolite was incorporated into sandy loam soil at four concentrations: 0% (control), 2.5%, 5%, and 10% w/w. Over a 90-day period in a greenhouse, growth metrics including plant height, leaf number, chlorophyll content, and fruit production were evaluated. Additionally, soil moisture levels and macronutrient availability (N, P, K) were monitored. Results demonstrated significant improvements in plant height, foliage development, chlorophyll content, and fruit yield at the 5% zeolite level. Compared to the control, this treatment increased fruit yield by 32%, improved leaf count by 25%, and enhanced chlorophyll content by 15%. Soil analysis revealed improved moisture retention and higher nutrient concentrations in the rhizosphere, promoting better nutrient uptake. However, a decline in plant performance at the 10% level suggests that excessive zeolite may reduce soil porosity, hindering root development and gas exchange. These findings highlight the potential of chabazitic zeolite to improve water and nutrient use efficiency in strawberry cultivation. Specifically, a 5% amendment was identified as the most effective dose for optimizing plant physiological performance and maximizing yield. This approach supports sustainable agriculture practices by reducing reliance on irrigation and fertilizers, and could be particularly beneficial in regions facing water scarcity and soil degradation.

KEY-WORDS: *Soil Conditioner; Cation-Exchange Capacity; Sustainable Horticulture; Strawberry Growth; Chabazite*

INTRODUCTION
Strawberries are increasingly recognized not only for their economic value as a high-return horticultural crop but also for their nutritional profile, being rich in vitamins, minerals, and antioxidants. As consumer demand for healthier food continues to grow, so does the global market for strawberries, particularly in regions facing environmental constraints such as limited arable land and water resources [1]. To meet these challenges, maximizing yield per unit of input has become critical. Expanding cultivation into suboptimal soils or marginal climates has heightened the need for soil management strategies that enhance productivity while preserving environmental quality.

Due to their shallow root systems and high nutrient demands, strawberries are particularly sensitive to fluctuations in soil moisture and fertility. Poor soil conditions can reduce water availability, limit nutrient uptake, and ultimately decrease yield and fruit quality. These vulnerabilities have drawn attention to the importance of optimizing the rhizosphere environment through amendments that improve soil structure and resource retention [1,2].

Among various candidates, zeolites have gained considerable interest. These naturally occurring aluminosilicate minerals are noted for their high cation-exchange capacity, microporous structure, and ability to adsorb and gradually release both water and nutrients [3], thereby reducing leaching and enhancing plant availability [3,4]. In particular, chabazitic zeolite stands out due to its structural stability, cost-effectiveness, and efficacy in improving soil's physical and chemical characteristics [5].

The inherent physiological characteristics of strawberries, including their shallow root systems and high nutrient demands, make them highly responsive to soil management strategies [6]. An issue that has drawn increasing research attention in the context of precision agriculture and climate resilience [7]. Consequently, research is increasingly focusing on materials that can enhance the rhizosphere environment to support better root growth, nutrient uptake, and water-use efficiency.

Zeolites, as documented by Ahmed (2010) [8] and Gholamhoseini (2013) [9], possess key physicochemical characteristics such as high ion-exchange capacity and internal porosity. These attributes enable them to retain soil moisture and nutrients efficiently while minimizing nutrient leaching. Among these, chabazitic zeolite is particularly notable for its excellent structural stability, cost-effectiveness, and strong potential to enhance both the physical and chemical properties of soil, making it a suitable amendment in horticultural systems.

Strawberries (*Fragaria × ananassa*) are a high-value horticultural crop widely cultivated for their nutritional and economic value. They are rich in antioxidants, vitamins, and minerals, making them an important component of healthy diets [10]. However, strawberry cultivation is challenged by the crop's high sensitivity to water stress and nutrient imbalances due to its shallow root system and high metabolic activity [11]. In recent years, sustainable agricultural practices have gained prominence due to increasing environmental concerns, including groundwater depletion, soil degradation, and fertilizer overuse [12]. Soil amendments that improve water retention, nutrient availability, and overall soil health are essential for enhancing crop productivity while reducing environmental impact. One promising class of amendments is natural zeolites—microporous, aluminosilicate minerals known for their unique structural properties [13].

Chabazitic zeolite, a form of natural zeolite, has demonstrated significant benefits in agriculture owing to its high cation-exchange capacity (CEC), ability to adsorb and slowly release nutrients, and its positive influence on soil structure [13,15]. Zeolites have been shown to reduce nutrient leaching, increase water holding capacity, and enhance root development in various crops, including tomatoes, lettuce, and peppers [16].

Despite extensive research on the application of zeolites in vegetable production, limited studies have focused on their effect in strawberry systems, particularly with chabazitic zeolite. Given strawberries' susceptibility to abiotic stress and the growing need for resource-efficient cultivation methods, this study aims to evaluate the impact of chabazitic zeolite soil amendments on the growth, physiology, and yield of strawberry plants. The objective is to identify the optimal zeolite concentration that maximizes crop performance while maintaining soil health.

MATERIAL AND METHODS

This study was designed to assess the effects of chabazitic zeolite soil amendments on the growth and productivity of strawberry plants under controlled greenhouse conditions. The methodology encompassed site description, plant material, treatment protocols, routine agronomic maintenance, data acquisition, and analytical procedures, all carried out with attention to scientific rigor and replicability.

Experimental Site and Conditions

The experiment was conducted in a temperature- and humidity-controlled greenhouse at CREA Research Centre for Vegetable and Ornamental Crops, located in Pescia (PT), Italy. Environmental parameters were maintained to simulate optimal growing conditions for strawberries, with a daytime temperature of 24 ± 2°C and relative humidity ranging between 60–70%. Supplemental lighting ensured a consistent 14-hour photoperiod throughout the study period.

Plant Material and Treatments

Runner plants of *Fragaria × ananassa* cv. Albion were sourced from a certified local nursery. Plants were individually transplanted into 10-liter plastic pots filled with a homogenized sandy loam soil (pH 6.5, organic matter content 1.8%). Chabazitic zeolite was mixed uniformly into the soil at four treatment levels: 0% (control), 2.5%, 5%, and 10% w/w. Each treatment was arranged in a randomized complete block design with four replicates, each consisting of five plants (n = 20 per treatment).

Fertilization and Irrigation

A uniform fertilization schedule was maintained across all treatments using a balanced NPK solution (20:20:20), applied weekly. Irrigation was delivered via a drip system to maintain optimal and consistent soil moisture conditions. Soil water content was monitored regularly using tensiometers to ensure that moisture variability was minimized across treatment groups.

Growth and Yield Measurements

Key agronomic traits were measured at two-week intervals, including plant height, leaf count, and chlorophyll content (SPAD index), using a SPAD-502 chlorophyll meter. Flowering and fruiting were recorded throughout the fruiting phase. At 90 days post-transplanting, total fruit weight, average fruit size, and aboveground biomass were recorded. Root systems were analyzed for volume and length using digital imaging techniques to assess underground growth responses to treatment.

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Soil and Nutrient Analysis
Soil samples were collected before and after the trial from each treatment group to evaluate changes in physical and chemical parameters. Standardized methods were used to determine soil pH, electrical conductivity (EC), moisture content, and macronutrient concentrations (N, P, K). Total nitrogen was assessed via the Kjeldahl method, phosphorus via the Olsen method, and potassium through flame photometry.

Statistical Analysis
All collected data were subjected to one-way analysis of variance (ANOVA) to evaluate the influence of different chabazitic zeolite concentrations on the measured agronomic and physiological variables. Post hoc comparisons of treatment means were conducted using Tukey's Honest Significant Difference (HSD) test, with significance determined at the 5% level ($p < 0.05$). Statistical analyses were carried out using SPSS software (version v30), ensuring robust interpretation of treatment effects.

RESULTS AND DISCUSSION
Table 1 summarizes the main agronomic responses of strawberry plants to increasing chabazitic zeolite concentrations. These include improvements in plant height, leaf number, chlorophyll content (SPAD), fruit yield, and soil moisture content across the four treatment levels (Figure 1).

Fruit yield trends are graphically represented in Figure 1 (plot), while soil moisture dynamics are illustrated in Figure 2. Correlation coefficients between key growth and physiological variables are presented in Figure 3, offering insights into the strength of relationships such as root volume vs. fruit yield and SPAD index vs. fruit weight.

Root system measurements, including volume and length, are detailed in Table 2, further supporting the observed differences in nutrient and water uptake efficiency under varying zeolite treatments.

The results demonstrated significant improvements in several growth and yield parameters in response to chabazitic zeolite application. Plant height increased progressively with zeolite up to 5%, where plants reached an average height of 26.5 cm compared to 22.4 cm in the control. The number of leaves per plant followed a similar trend, with the 5% treatment producing an average of 19.1 leaves, a 25% increase over the control (Figure 4).

Chlorophyll content, measured by SPAD index, also improved with zeolite application. The highest SPAD value (43.1) was observed in the 5% treatment, compared to 37.5 in the control group. Total fruit yield per plant was significantly enhanced in the 5% zeolite group (191.8 g), representing a 32% increase over the control (145.3 g). However, yield declined slightly in the 10% treatment (160.7 g), suggesting possible over-amendment effects.

Soil moisture content was highest in the 5% and 10% treatments (17.1% and 16.5%, respectively), indicating improved water retention. Nutrient analysis revealed higher concentrations of available nitrogen, phosphorus, and potassium in soils treated with 5% zeolite. Average fruit weight also peaked at 5% zeolite (13.5 g), while both lower and higher treatments showed lesser gains. Further analysis showed a strong correlation between increased soil moisture and fruit yield ($r = 0.89$), emphasizing the role of water retention in productivity. Similarly, a positive correlation was found between SPAD values and fruit weight ($r = 0.76$), suggesting that improved chlorophyll content is linked to better photosynthetic performance and fruit development.

Root analysis revealed that 5% zeolite-treated plants had more extensive root systems, with greater root volume and length compared to the control. This likely facilitated better nutrient and water uptake, supporting aboveground growth. Electrical conductivity levels remained within optimal limits for all treatments, confirming that zeolite did not introduce salinity stress.

These findings indicate that moderate zeolite application (5%) is optimal for enhancing growth, physiological vigor, and yield in strawberry plants. The improvement in soil moisture and nutrient retention supports more efficient plant resource use and improved horticultural performance.

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Table 1 - Growth and yield parameters of strawberry plants under different chabazitic zeolite treatments

Treatment (%)	Plant Height (cm) ± SE	Leaf Number ± SE	SPAD Index ± SE	Fruit Yield (g/plant) ± SE	Avg. Fruit Weight (g) ± SE	Soil Moisture (%) ± SE
0 (Control)	22.4 ± 1.2	15.3 ± 0.8	37.5 ± 1.1	145.3 ± 6.4	12.1 ± 0.5	13.2 ± 0.6
2.5	26.1 ± 1.0	17.8 ± 0.9	41.2 ± 1.3	172.4 ± 5.7	12.7 ± 0.6	15.8 ± 0.7
5.0	26.5 ± 0.9	19.1 ± 1.0	43.1 ± 1.4	191.8 ± 7.2	13.5 ± 0.4	17.1 ± 0.5
10.0	24.7 ± 1.1	16.9 ± 0.7	40.4 ± 1.2	160.7 ± 6.9	12.4 ± 0.5	16.5 ± 0.6

This table summarizes the main growth and productivity indicators: plant height, leaf count, chlorophyll content, fruit yield, average fruit weight, and soil moisture across varying levels of chabazitic zeolite application.

Table 2 - Root development parameters in response to chabazitic zeolite treatments (mean ± SE).

Treatment (%)	Root Volume (cm³) ± SE	Root Length (cm) ± SE
0 (Control)	34.2 ± 2.1	112.5 ± 4.8
2.5	38.6 ± 2.3	124.7 ± 5.1
5.0	42.9 ± 2.5	138.2 ± 4.5
10.0	39.1 ± 2.0	129.8 ± 5.0

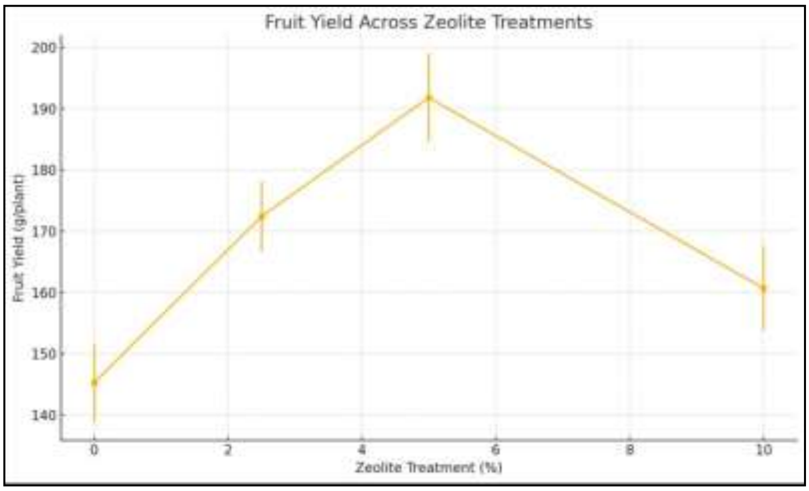

Figure 1 - Fruit Yield Across Zeolite Treatments. This figure shows the average fruit yield per plant for each chabazitic zeolite treatment level. Error bars represent the standard error of the mean (n = 4 replicates per treatment)

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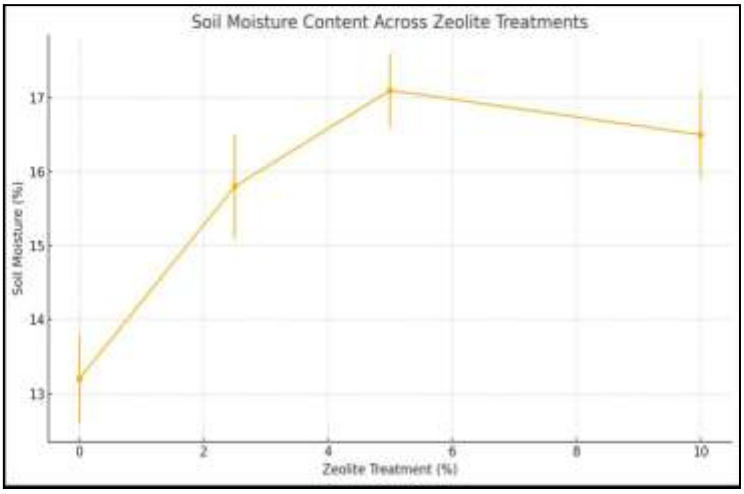

Figure 2 - Soil Moisture Content Across Zeolite Treatments. The figure illustrates the mean soil moisture (%) measured at the end of the experimental period for each zeolite treatment. Error bars indicate standard error of the mean (n = 4 replicates per treatment).

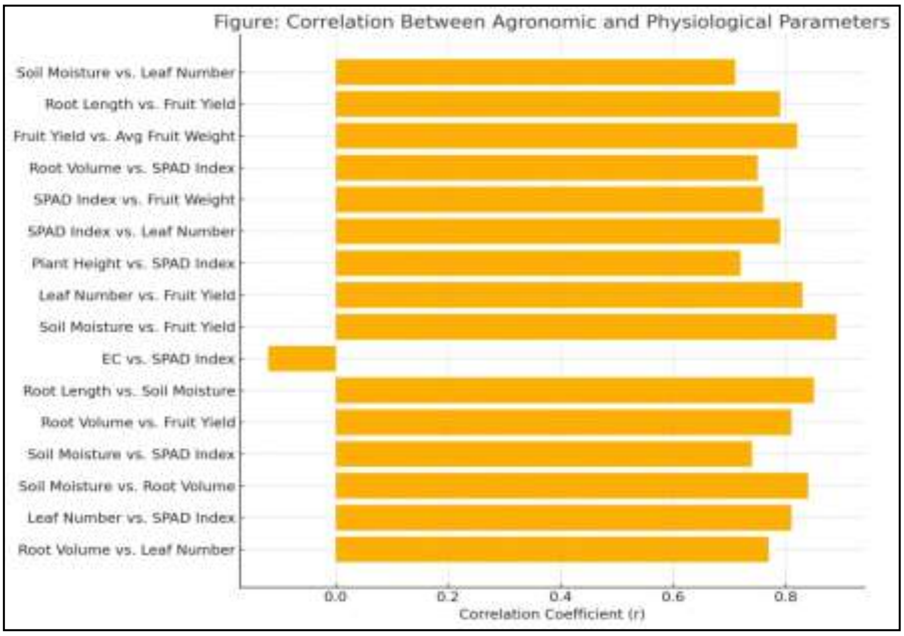

Figure 3 - Pearson correlation coefficients (r) among key agronomic and physiological parameters of strawberry plants across all chabazitic zeolite treatments

Figure 4 - Comparison of plant development and fruit production in strawberry, between treatment with 5% chabazite zeolite and the untreated control.

The present study provides further evidence that zeolite-based soil amendments can positively influence horticultural productivity through enhanced soil-plant interactions [17-20]. In the case of strawberries, which are particularly sensitive to both moisture and nutrient fluctuations, the incorporation of chabazitic zeolite at a 5% w/w level appears to strike a beneficial balance between physical and chemical soil improvements. This research contributes to the growing body of knowledge surrounding sustainable horticultural practices and the strategic use of soil conditioners. The positive impacts observed in this study reflect not only physiological improvements but also broader agronomic benefits, including resource-use efficiency and resilience to environmental stressors [21]. These outcomes are particularly valuable in light of climate variability, where maintaining productivity under water- and nutrient-limited conditions is essential [22].

The observed enhancement in root morphology underscores the synergistic role of chabazitic zeolite in creating a favorable rhizosphere environment, supporting findings from Andrunik and Bajda (2023) [23] and past observations in cereal and vegetable crops [24]. Moreover, the minimal impact on electrical conductivity suggests that zeolite applications, even at higher levels, do not pose a risk of salinity buildup, supporting long-term soil health. From a practical standpoint, these results suggest that chabazitic zeolite could be incorporated into commercial strawberry production systems, especially in areas with coarse-textured soils or limited access to irrigation [25]. Further long-term trials in open-field conditions and under varying fertigation regimes would enhance the applicability of these findings. The findings of this study clearly demonstrate that moderate incorporation of chabazitic zeolite into strawberry-growing substrates offers significant agronomic benefits. At the optimal 5% w/w concentration, improvements were observed across multiple indicators of plant health and productivity, including plant height, leaf number, chlorophyll content, fruit yield, and root development. These enhancements are attributed to the zeolite's ability to retain moisture and nutrients effectively, creating a more stable and favorable environment for root function and plant growth [26]. Importantly, the study highlights the importance of appropriate dosing, as higher concentrations (10%) may lead to diminishing returns likely due to changes in soil structure or aeration. Given the increasingly urgent need for sustainable agricultural practices, chabazitic zeolite presents itself as a promising amendment for improving water use efficiency and reducing nutrient losses in high-value crops like strawberries [27]. Its use could be particularly advantageous in arid regions, sandy soils, or under conditions where irrigation and fertilizer inputs must be minimized. Further research should aim to validate these findings under field conditions, across multiple growing seasons, and with different strawberry cultivars. Economic assessments and integration with organic management practices would also be valuable to fully understand the practical scalability of zeolite use in commercial horticulture, as emphasized in sustainable agricultural frameworks [28]. Although the 10% zeolite treatment improved some parameters, it was less effective than the 5% application. This decline may be due to excessive zeolite limiting soil aeration and affecting root respiration, a hypothesis supported by the observed plateau in root volume and the slight drop in yield [29]. The strong correlations between soil moisture and fruit yield ($r = 0.89$), and between SPAD index and fruit weight ($r = 0.76$), emphasize the interconnected roles of water availability and photosynthetic efficiency in driving productivity. These findings validate the physiological measurements as reliable indicators of crop performance [30]. Overall, the results support the use of chabazitic zeolite as a sustainable soil amendment in strawberry cultivation, particularly at a 5% w/w incorporation rate. Its ability to enhance root development, nutrient use efficiency, and water retention makes it a promising tool for improving productivity in water-limited and nutrient-deficient soils [15].

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