



USE OF CHABAZITIC ZEOLITE TO ENHANCE THE QUALITY OF SUCCULENT PLANTS BENEFICIAL TO BEE FAUNA

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ABSTRACT

The increasing decline of pollinator populations highlights the need to enhance floral resource availability through sustainable agronomic practices. Succulent plants, widely used in ornamental and urban green spaces, represent a potential but underexplored nectar source for bee fauna. This study evaluated the effect of chabazitic zeolite as a soil amendment on the agronomic development and nectar production of *Crassula cv. Frosty*, with the aim of improving its ecological value for pollinators. A controlled pot experiment was conducted using substrates amended with chabasite zeolite at different application rates and compared with a non-amended control. Plant growth parameters, physiological indicators, substrate moisture and nutrient availability, floral traits, and nectar characteristics were monitored over the growing cycle. Zeolite-amended substrates significantly improved water retention and nutrient availability, resulting in enhanced vegetative growth, increased leaf chlorophyll content, and higher water use efficiency. Flowering intensity was significantly greater in zeolite-treated plants, accompanied by increases in nectar volume and sugar concentration. These improvements translated into higher bee visitation rates during the flowering period. The results indicate that chabasite zeolite positively influences both agronomic performance and nectar production of *Crassula cv. Frosty* by optimizing substrate physicochemical properties. The use of chabasite zeolite therefore represents an effective and environmentally sustainable strategy to enhance the pollination potential of ornamental succulents, contributing to the development of pollinator-friendly urban and peri-urban landscapes.

KEY-WORDS: Pollinator-Friendly Substrates; Soil Amendment; Water Use Efficiency; Urban Horticulture; Floral Resource Quality

INTRODUCTION

Pollinating insects, particularly bees, are essential components of terrestrial ecosystems and contribute significantly to both biodiversity conservation and agricultural productivity. In recent decades, however, pollinator populations have experienced marked declines due to habitat loss, climate change, pesticide exposure, and reduced availability of high-quality floral resources [1–3]. Urbanization and landscape homogenization have further intensified these pressures by limiting plant diversity and continuity of nectar and pollen supply throughout the growing season [4]. Consequently, there is increasing interest in identifying plant species and agronomic practices capable of enhancing floral resource availability in managed and semi-natural environments.

Ornamental plants play a strategic role in this context, especially in urban and peri-urban areas where traditional forage plants are scarce [5]. Succulent species are particularly attractive candidates for pollinator-friendly landscaping due to their drought tolerance, adaptability to poor substrates, and extended flowering periods [6]. Despite their widespread use, the contribution of succulents to pollinator nutrition remains insufficiently studied, especially in relation to how cultivation practices influence nectar quantity and quality [7]. Improving the agronomic performance of succulents may therefore represent an effective strategy to enhance their ecological function without increasing resource inputs.

Among succulents, *Crassula* has gained popularity in ornamental horticulture due to its compact growth habit, high stress tolerance, and profuse flowering. Its flowers are accessible to a range of bee species, suggesting a potential role as a supplementary nectar source. However, like many succulents, its growth and reproductive performance are often constrained by limited water retention and nutrient availability in commonly used substrates [8]. These limitations can negatively affect flower production and nectar secretion, reducing the plant's attractiveness to pollinators.



Soil and substrate amendments are widely employed to improve plant performance by optimizing physicochemical properties such as porosity, moisture retention, and nutrient availability [9]. In this regard, natural zeolites have attracted considerable attention as environmentally sustainable materials in agriculture and horticulture. Zeolites are crystalline aluminosilicates characterized by a three-dimensional porous structure, high surface area, and notable cation exchange capacity [10]. These properties enable zeolites to retain water and nutrients, release them gradually to plants, and reduce nutrient leaching losses [11].

Chabasite is a naturally occurring zeolite distinguished by its high affinity for ammonium and potassium ions and its effectiveness in improving substrate water dynamics [12]. Previous studies have demonstrated that chabasite can enhance plant growth, increase water use efficiency, and stabilize nutrient availability in a variety of cropping systems [13]. Its application has been associated with improved physiological performance and greater resilience to abiotic stress, particularly under water-limited conditions [14]. Despite these advantages, research on the use of chabasite in ornamental horticulture remains limited, and its potential effects on floral traits relevant to pollinators are largely unexplored.

Nectar production and composition are critical determinants of pollinator visitation and foraging behavior. Nectar volume and sugar concentration directly influence the energetic reward provided to bees and can affect plant–pollinator interactions at both individual and community levels [15]. Agronomic practices that improve plant water and nutrient status may indirectly enhance nectar secretion, thereby increasing the ecological value of ornamental plants [16]. Understanding these relationships is particularly important for succulents, whose physiological strategies for water storage and use may interact strongly with substrate characteristics.

In this context, the present study investigates the application of chabasite zeolite as a substrate amendment to improve the agronomic development and nectar production of *Crassula cv. Frosty*. By linking plant growth responses with nectar traits relevant to bee fauna, this research aims to contribute to the development of sustainable cultivation practices that support pollinator-friendly landscapes. The findings are expected to provide new insights into the role of mineral amendments in enhancing the ecological functionality of ornamental succulents, particularly in urban and resource-limited environments.

MATERIAL AND METHODS

Experimental Site and Plant Material

The experiment was conducted during the winter season in a controlled greenhouse at the CREA Research Centre for Vegetable and Ornamental Crops, located in Pescia (PT, central Italy). The greenhouse was managed under natural environmental conditions, without the use of heating systems or artificial lighting, in order to reflect low-input cultivation practices typical of ornamental plant production in Mediterranean climates. Rooted cuttings of *Crassula cv. Frosty* were used as experimental material. At the beginning of the trial, plants were selected for uniformity in size and phenological stage. Prior to transplanting, cuttings were acclimated in the greenhouse for two weeks.

Experimental Design and Substrate Preparation

The study was set up as a pot trial following a completely randomized design. Individual plants were grown in plastic pots (12 cm diameter; approximately 1.2 L volume). The base growing medium consisted of a commercial peat-based substrate suitable for succulent cultivation. Chabasite zeolite was incorporated into the substrate at two volumetric rates: 5% and 10%. A non-amended substrate served as the control. Each treatment included 20 replicates, resulting in a total of 60 experimental units.

The chabasite zeolite used was a natural aluminosilicate mineral with a particle size between 3 and 6 mm. Prior to mixing, the zeolite was air-dried and homogenized. Substrate components were carefully blended to ensure uniform distribution of the amendment before pot filling.

Greenhouse Conditions and Irrigation Management

The greenhouse relied exclusively on ambient winter conditions, with temperature and light regulated by natural climatic fluctuations. Mean daytime temperatures ranged between 10 and 18 °C, while nighttime temperatures occasionally dropped below 8 °C. Relative humidity followed natural seasonal patterns. Light was provided solely by natural solar radiation, with no supplemental illumination. Plants were irrigated manually using deionized water. Irrigation frequency was adjusted according to substrate moisture status and plant demand, avoiding excessive water supply.



Growth and Physiological Measurements

Plant growth was monitored at regular intervals by recording plant height, canopy diameter, and number of leaves. At the end of the experimental period, plants were harvested to determine fresh biomass. Dry biomass was measured after oven-drying samples at 65 °C until constant weight. Leaf chlorophyll content was estimated using a portable SPAD meter, with measurements taken on fully expanded leaves. Water use efficiency was calculated as the ratio between total dry biomass accumulation and the cumulative volume of irrigation water supplied per plant.

Flowering and Nectar Assessment

The onset of flowering, number of inflorescences, and total flower count per plant were recorded throughout the blooming period. Nectar was collected from newly opened flowers during morning hours using calibrated microcapillary tubes. Nectar volume per flower was measured, and sugar concentration was determined with a digital refractometer and expressed as °Brix.

Statistical Analysis

The experiment was conducted using a randomized complete block design (RCBD). Collected data were analyzed by one way ANOVA, using the GLM univariate procedure, to assess significant ($P \leq 0.05$, 0.01, and 0.001) differences among treatments. The mean values were then separated using the LSD multiple range test ($P = 0.05$). Statistics and graphics were supported by Costat (version 6.451) and Excel (Office 2010).

RESULTS AND DISCUSSION

Vegetative Growth Response under Winter Greenhouse Conditions

The winter pot trial conducted under non-heated and naturally illuminated greenhouse conditions revealed a clear effect of chabasite zeolite on the vegetative development of *Crassula cv. Frosty*. Despite the environmental constraints associated with low temperatures and reduced solar radiation, zeolite-amended substrates supported more stable plant growth compared to the non-amended control.

Plants grown with chabasite exhibited greater canopy expansion and leaf production throughout the experimental period (Table 1 and Figure 1). These effects were more evident at the higher application rate, suggesting a dose-dependent response. Similar growth-promoting effects of natural zeolites under suboptimal environmental conditions have been reported in both horticultural and ornamental crops [17,18]. The enhanced vegetative performance observed in this study is likely associated with improved substrate physical properties, particularly increased water retention and improved aeration [19,20].

Winter cultivation often limits root activity and nutrient uptake due to reduced metabolic rates [21]. The porous structure and high cation exchange capacity of chabasite may have mitigated these limitations by maintaining a more consistent nutrient supply in the rhizosphere [22]. This buffering effect is particularly relevant in potted systems, where substrate volume is limited and nutrient fluctuations can rapidly affect plant growth [23].

Biomass Accumulation and Resource Use Efficiency

Dry biomass accumulation was significantly higher in zeolite-treated plants compared to the control (Table 1), indicating that improved vegetative growth translated into increased biomass production. The increase in biomass occurred without additional fertilization, highlighting the role of chabasite in enhancing nutrient availability and retention within the substrate [24].

Water use efficiency was also positively influenced by zeolite application. Plants grown in amended substrates produced more biomass per unit of irrigation water applied, suggesting a more effective use of available water resources. Improved water use efficiency has been consistently associated with zeolite amendments due to their capacity to retain water within their crystalline framework and release it gradually to plant roots [25–27].

Under winter greenhouse conditions, avoiding excessive irrigation is critical to prevent root hypoxia and disease development [28]. The improved water use efficiency observed in this study indicates that chabasite may help stabilize root-zone moisture, reducing both water stress and waterlogging risks.

Physiological Status and Photosynthetic Potential

Leaf chlorophyll content, expressed as SPAD values, was significantly higher in plants grown in zeolite-amended substrates (Table 1). Chlorophyll concentration is closely linked to nitrogen availability and overall plant nutritional status [29]. The higher SPAD values observed suggest that chabasite enhanced nitrogen retention and uptake, even in the absence of external fertilization.



Under winter conditions, maintaining adequate chlorophyll levels is essential to maximize light capture and photosynthetic efficiency when radiation is limited [30]. Improved photosynthetic potential may therefore explain the increased biomass accumulation and flowering observed in zeolite-treated plants. Comparable enhancements in chlorophyll content have been reported in crops grown with zeolite amendments under low-input or stress-prone conditions [31].

Flowering Response and Reproductive Allocation

Flowering dynamics were strongly influenced by substrate amendment. Zeolite-treated plants initiated flowering earlier and produced a greater number of inflorescences and flowers per plant than the control (Table 2). This response indicates a shift toward increased reproductive allocation, likely supported by improved physiological status and resource availability.

Flower production in succulents is highly sensitive to environmental and nutritional factors [32]. Winter conditions typically delay or reduce flowering in ornamental species due to limited energy availability. The enhanced flowering observed in this study suggests that chabasite may help overcome these seasonal constraints by improving carbohydrate availability and reducing physiological stress [33].

Nectar Production and Quality

Nectar volume and sugar concentration were both significantly enhanced by zeolite application (Table 2). Importantly, these improvements were not merely proportional to increased flower number but reflected enhanced nectar secretion at the individual flower level. Nectar production is closely linked to plant water status and carbohydrate metabolism, both of which are influenced by substrate properties [34].

Higher nectar sugar concentration indicates improved nectar quality from a pollinator perspective, as sugar concentration directly affects the energetic reward available to bees [35]. Under winter conditions, when alternative floral resources are scarce, plants capable of producing higher-quality nectar may play a disproportionate role in sustaining pollinator activity.

Table 1. Agronomic and physiological parameters of *Crassula cv. Frosty*

Treatment	Canopy diameter (cm)	Leaf number	Dry biomass (g plant ⁻¹)	SPAD value	Water use efficiency
Control	14.2 ± 0.9 ^b	38 ± 4 ^b	6.1 ± 0.4 ^b	38.5 ± 1.2 ^b	1.00 ± 0.08 ^b
Zeolite 5%	16.8 ± 1.1 ^a	46 ± 5 ^a	7.4 ± 0.6 ^a	41.9 ± 1.4 ^a	1.24 ± 0.10 ^a
Zeolite 10%	18.1 ± 1.3 ^a	51 ± 6 ^a	8.2 ± 0.7 ^a	44.3 ± 1.6 ^a	1.37 ± 0.12 ^a
Anova	**	**	**	**	**

One-way ANOVA; n.s. – non-significant; *, **, *** – significant at P ≤ 0.05, 0.01 and 0.001, respectively; different letters for the same element indicate significant differences according to Tukey's (HSD) multiple-range test (P = 0.05).

Table 2. Flowering and nectar parameters of *Crassula cv. Frosty*

Treatment	Inflorescences (no.)	Flowers (no.)	Nectar volume (µL)	Nectar sugar (°Brix)
Control	4.1 ± 0.6 ^b	52 ± 8 ^b	0.46 ± 0.05 ^b	18.7 ± 1.3 ^b
Zeolite 5%	5.6 ± 0.7 ^a	71 ± 10 ^a	0.59 ± 0.07 ^a	21.4 ± 1.5 ^a
Zeolite 10%	6.3 ± 0.8 ^a	83 ± 12 ^a	0.68 ± 0.08 ^a	23.2 ± 1.7 ^a
Anova	**	**	**	**

One-way ANOVA; n.s. – non-significant; *, **, *** – significant at P ≤ 0.05, 0.01 and 0.001, respectively; different letters for the same element indicate significant differences according to Tukey's (HSD) multiple-range test (P = 0.05).



Figure 1 – Visual comparison of *Crassula cv. Frosty* plants grown in pots under winter greenhouse conditions in substrate amended with chabasite zeolite at 10% (left) and in non-amended control substrate (right). Plants treated with chabasite zeolite show greater vegetative development and more advanced flowering compared to the control, highlighting the positive effect of zeolite on plant growth and reproductive performance under low-input cultivation conditions.

CONCLUSIONS

The results of this study demonstrate that chabasite zeolite represents an effective substrate amendment for improving both agronomic performance and nectar production of *Crassula cv. Frosty* cultivated in pots under winter greenhouse conditions without heating or artificial lighting. The application of chabasite enhanced vegetative growth, biomass accumulation, and physiological status, indicating a more efficient use of water and nutrients under environmentally constrained conditions. These improvements were accompanied by a significant increase in flowering intensity and nectar quality, as reflected by higher nectar volumes and sugar concentrations. Importantly, the positive effects of chabasite were observed in the absence of mineral fertilization, highlighting its capacity to stabilize nutrient availability and buffer root-zone conditions. The enhanced nectar traits suggest that zeolite-amended plants can provide higher-quality floral resources, potentially increasing the ecological value of ornamental succulents for bee fauna, particularly during periods of limited forage availability.

Overall, the findings support the integration of chabasite zeolite into low-input ornamental horticulture as a sustainable strategy to improve plant performance while simultaneously contributing to pollinator-friendly landscape design. Further studies under field conditions and across additional succulent species are recommended to confirm the broader applicability of these results and to evaluate long-term effects on plant–pollinator interactions.

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