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Article

Effect of Mussel Shells as Soil pH Amendment on the Growth and Productivity of Rosemary (*Rosmarinus officinalis* L.) Cultivation

Alexios Lolas [1,*], Aikaterini Molla [2], Konstantinos Georgiou [1], Chrysoula Apostologamvrou [1], Alexandra Petrotou [1] and Konstantinos Skordas [1]

[1] Laboratory of Marine Biology, Department of Ichthyology & Aquatic Environment, University of Thessaly, Fytokou Street, 38446 Volos, Greece; kostasgeorgiou@uth.gr (K.G.); chapostol@uth.gr (C.A.); apetrotou@uth.gr (A.P.); kskord@uth.gr (K.S.)

[2] Hellenic Republic, Ministry of Rural Development and Food, Acharnon 2 Street, 10176 Athens, Greece; amolla@uth.gr

* Correspondence: allolas@uth.gr; Tel.: +30-6976517801

Abstract: Mussel shells, with their calcium carbonate content, serve as a natural pH buffer, aiding in neutralizing acidic soils and, consequently, enhancing nutrient availability for plants. The aim of this study was to evaluate the effect of treating soils with mussel shells as a soil pH amendment on the agronomic characteristics and productivity of *Rosmarinus officinalis*. A pot experiment was set up for two growing years. The treatments were amended using different doses of mussel shells. Overall, the treatments were the following: C: unamended soil (control); T1: 0.1%; T2: 0.3%; T3: 0.5%; T4: 1%; T5: 3%; T6: 6%. Plant height was higher in pots amended with 6% mussel shells and reached the value of 32.2 cm in the first year and 51 cm in the second. The application of mussel shells increased the branch length by 53.4–58.7% and the number of branches per plant by 61.3–62% in T6 compared to the control. The total yield of fresh and dry weight in the 1st and 2nd year was ordered as follows: T6 > T5 > T4 > T3 > T2 > T1 > C. In conclusion, while the established optimal quantity for neutralizing soil pH is 300 g of mussel shells per 10 kg of soil, it has been observed that a ratio of 600 g of mussel shells proves more effective in terms of both the productivity and agronomic characteristics of rosemary.

Keywords: liming; *Mytilus galloprovincialis*; agronomic characteristics; aromatic-medicinal plants; circular economy

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1. Introduction

The beneficial uses of aromatic–medicinal plants (AMP) have been known since ancient times [1]. Nowadays, the mass use of cosmetics has grown rapidly since film and television, and, particularly now, social networks have become widespread [2]. According to the WHO, the majority of people (more than 80%) all over the world rely on AMP for their everyday health needs [3,4].

One of these plants is *Rosmarinus officinalis* L., commonly known as rosemary, which belongs to the Lamiaceae family [5]. *Rosmarinus officinalis* is traditionally cultivated in the Mediterranean region for its pharmaceutical and cosmetical properties [6,7]. It is an aromatic plant with needle-like leaves that is cultivated worldwide. In folk medicine, rosemary has been used to treat renal colic, dysmenorrhea, and muscle spasms. Besides antifungal, antiviral, antibacterial, antitumor, and antithrombotic properties, rosemary has antinociception, antidepressant, and antiulcerogenic properties [8–10]. Several medicinal applications of *Rosmarinus officinalis* have been identified, such as the treatment of the nervous system, cardiovascular system, digestive system, genitourinary system, menstrual system, liver dysfunction, respiratory problems, and skin diseases [10].

Nowadays, soil acidification is one of the major problems in the agricultural sector, and it can lead to the degradation of the farmlands [11,12]. Almost 40% of the arable land fields are characterized by low pH (<5.5). Nitrogen, sulfur, and carbon dioxide emissions in the atmosphere are responsible for soil acidification. Moreover, the extended use of synthetic nitrogen fertilization is an important contributor to soil acidity [13].

Recently, the need to decrease soil acidity has become significant for the agricultural section. Numerous research studies have attempted to find out alternative ways to overcome the negative effects of soil acidity on physicochemical properties and soil fertility as well as on plant productivity [14]. The most common method to neutralize soil acidity is the application of lime. Lime reacts with hydrogen ions (H^+) in soil, leading to the formation of water and carbon dioxide. The reaction helps raise the soil pH by reducing the concentration of acidic hydrogen ions. This pH adjustment is essential because many plant nutrients are more readily available to plants in slightly acidic-to-neutral pH ranges [15].

Various studies observed that mussel shells have the potential to serve as a soil amendment in acidic soils, offering an alternative to conventional commercial lime [16,17]. The positive effects of mussel shells in various fields have been mentioned by many researchers [16,18–20]. Furthermore, every year, a large amount of aquaculture by-products are disposed of in landfills or sea, causing seriously negative effects on the environment [21,22]. This issue aligns with the principles of the circular economy, an approach that emphasizes sustainability, resource efficiency, and minimizing waste. In the context of the circular economy, the focus is on promoting a closed-loop system where products and materials are reused, recycled, or repurposed rather than discarded as waste [23]. By incorporating aquaculture by-products, like mussel shells, into agricultural practices as soil amendments, circular economy principles are put into action. This not only mitigates the environmental impact of disposal but also transforms waste into a valuable resource, contributing to more sustainable and eco-friendly agricultural practices. Adopting a circular economy principles helps conserve resources, reduce environmental degradation, and promote a more holistic and responsible approach to waste management [24]. The use of shells by-products (such as mussel shells) as an alternative practice management in decreasing soil acidity is an innovative, eco-friendly, and sustainable approach that offers several potential benefits. The mussel shell use is expected to replace the common soil amendments, including marl, chalk, industrial by-products, organic wastes, crop residues, and limestone, in order to obtain new sources of calcium carbonate [13,14,25]. The calcium carbonate content in mussel shells acts as a natural pH buffer, helping to neutralize acidic soils. This is particularly beneficial in regions where soil acidity is a challenge, as it can enhance nutrient availability to plants [12].

According to the literature, no studies have been conducted regarding the use of mussel shells as soil improvement in the cultivation of rosemary.

In the framework of circular economy and in conjunction with the fact that mussel shells are considered to be a promising soil acidic amendment, the aim of this study was to evaluate the effect of treated soils with mussel shells as soil pH amendment on agronomic characteristics and productivity of *Rosmarinus officinalis*.

2. Materials and Methods

2.1. Study Area and Plant Material

A pot experiment was set up for two growing years (2022 and 2023) at the Department of Ichthyology and Aquatic Environment campus of the University of Thessaly in Central Greece (latitude of 39°23′16″ and longitude of 22°56′28″). The area is characterized by hot, dry summers with an average temperature and humidity of 25.6 °C and 57.4%, respectively, and cool, humid winters with an average temperature and humidity of 15.1 °C and 72.8% (Mediterranean climate). Rosemary cuttings of 5 cm in size were obtained from a local nursery and were immediately transplanted into plastic pots.

2.2. pH of the Used Soils

The pH values (Table 1) of the soils were measured two times, at the beginning of the pot experiment (May 2022) and 7 months later (November 2022).

Table 1. pH (Mean ± SD) of the used soils 0 and 210 days from the beginning of the experiment.

Treatments	0 Days	210 Days
	pH	
C	4.26 ± 0.06	4.28 ± 0.04
T1	5.74 ± 0.12	5.55 ± 0.27
T2	6.09 ± 0.04	5.96 ± 0.12
T3	6.64 ± 0.03	6.68 ± 0.22
T4	6.97 ± 0.03	6.91 ± 0.14
T5	7.19 ± 0.02	7.08 ± 0.12
T6	7.23 ± 0.04	7.14 ± 0.1

2.3. Meteorological Data

The meteorological data (temperature and precipitation) were provided from the nearby meteorological station of the Hellenic National Meteorological Service, which is installed in the Volos area.

2.4. Experimental Design

The pot experiment design was the randomized completed block (RCB), which included 7 different soil pH treatments whereby each treatment was replicated four times, and in total, 28 pots were established. The treatments were amended using different doses per 10 kg of soil, respectively. The mussel shells underwent a rinsing process with distilled water, followed by air drying in an oven set at 40 °C for a total of 24 h. Subsequently, dried shells were ground using a mortar and pestle and sieved through a 1 mm stainless sieve. Then, the acquired powder was mixed with 10 kg of soil in different ratios (C = 0 g, T1 = 10 g, T2 = 30 g, T3 = 50 g, T4 = 100 g, T5 = 300, and T6 = 600 g of mussel shell powder) [26].

Plants were transplanted into pots of 35 cm length and 36 cm internal diameter on 3 May 2022, and the plants were immediately watered. During the experiment, the pots were watered at least twice per week to ensure the maintenance of a consistent moisture level. In total, in the 1st year, the irrigation water was 100 mm, and in the 2nd year, it was 120 mm. The irrigation was conducted using a drip irrigation system according to the irrigation needs for rosemary cultivation. The fertilization of plants was conducted manually using the biological fertilizer Prima Humica, Ledra Fertilizers, Thessaloniki, Greece composed of 68–78% organic matter, 5% total N, 3% P_2O_5, and 0.0% K_2O. Specifically, in the 1st year, 200 g/pot was applied, 100 g with the transplantation (3 May 2022), and 100 g after the 1st cutting (16 July 2022). In the 2nd year, 100 g per pot was incorporated on 5 May 2023, and the other 100 g after the 1st harvest on 18 July 2023.

For the two growing years, plant height (cm), plant branch length (cm), number of branches per plant, and fresh and dry weight were calculated for all the treatments. Moreover, all the measurements were conducted in the 1st year on 15 July (1st cutting) and on 17 September (2nd cutting) and in the 2nd year on 17 July (1st cutting) and on 20 September (2nd cutting). The plant height and the branch length in each pot were calculated using a tape. The plants were harvested by hand at 10 cm above the soil surface and immediately weighed to record the fresh weight using a mobile balance. Afterwards, the material from each pot was dried in an oven at 60 °C until the plants reached a constant weight and were reweighed.

2.5. Statistical Analysis

The data were analyzed for one-way ANOVA using the "STATGRAPHICS Centurion" software package (v.18.1.01, Statgraphics Technologies, Inc., The Plains, VA, USA) according to the LSD for a 95% level of significance ($p < 0.05$).

3. Results and Discussion

3.1. Meteorological Data

Figure 1 displays the meteorological data, with a focus on temperature and rainfall patterns. Mean temperatures peaked in July (30.5 °C) and August 2023 (29.3 °C). Throughout the entire growing period from April 2022 to October 2023, the average temperature stood at 20.6 °C. In terms of rainfall, 2022 witnessed the highest precipitation in August and the lowest in May. Conversely, in 2023, September recorded the highest rainfall, while July marked the month with the least precipitation.

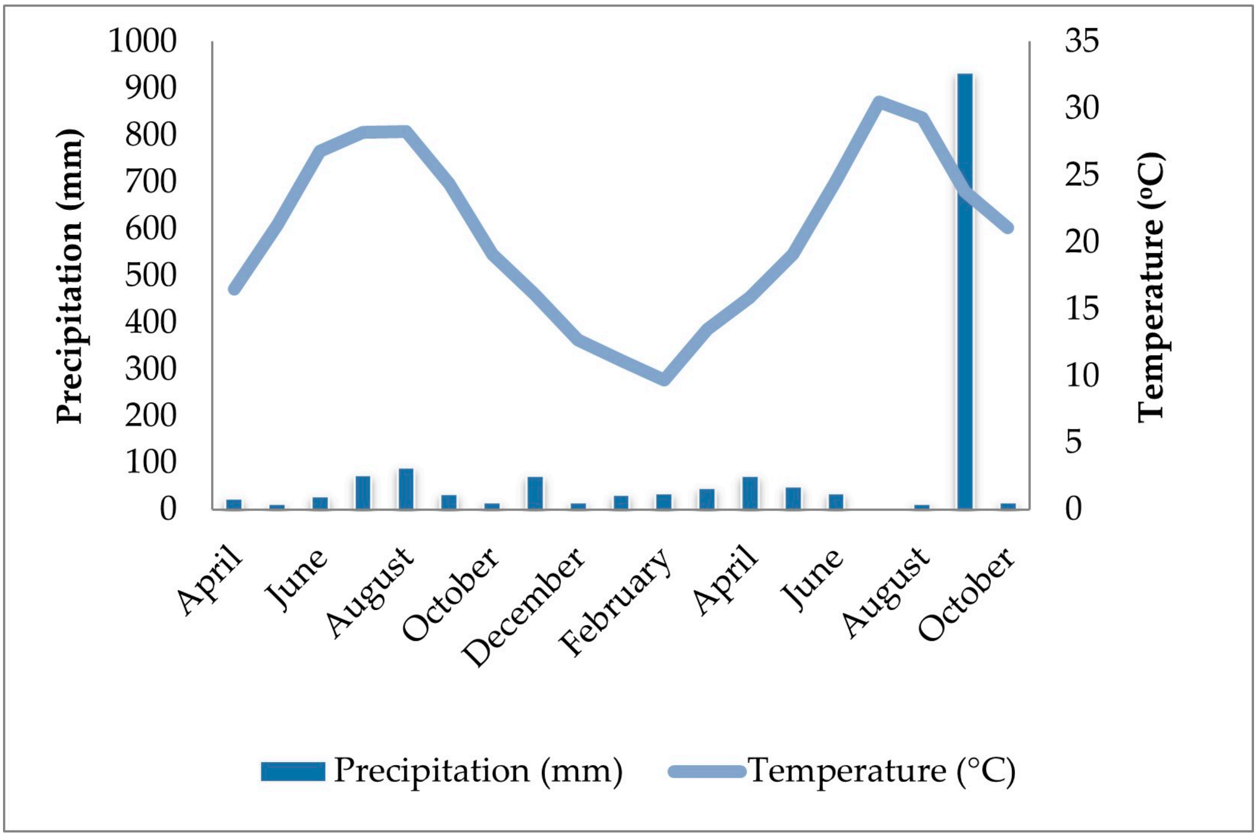

Figure 1. Air temperature and total precipitation during the studied period (April 2022–October 2023).

3.2. Agronomic Characteristics

3.2.1. Plant Height

Plant height data are illustrated in Figure 2 (1st year) and Figure 3 (2nd year), revealing noteworthy trends. Across different pH soil treatments, the mean plant height ranged from 12.9 ± 0.06 to 32.2 ± 0.37 cm in the first year and expanded to 21.3 ± 0.74 to 51.0 ± 1.01 cm in the second year. Notably, over both study years, pots amended with 6% mussel shells consistently exhibited higher plant height, while the control treatment showed the lowest. Statistically significant differences emerged between treatment T6 and the others. In the first year, compared to the control, treatments T1, T2, T3, T4, T5, and T6 displayed increases of 33.7%, 38.2%, 40.4%, 48.7%, 52.6%, and 59.8%, respectively. Similarly, in the second year, the observed increments for the same treatments were 45.7%, 48.4%, 47.9%, 50.2%, 51.2%, and 58.2%.

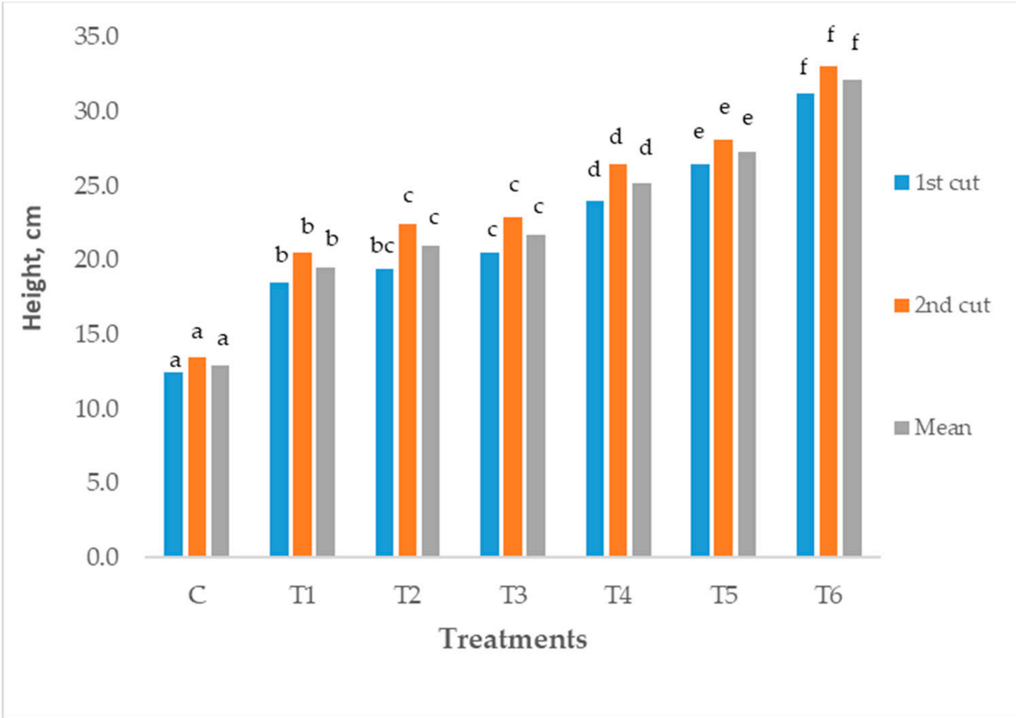

Figure 2. Plant height (cm) during the first growing year under the different soil types. Different lowercase letters represent statistical differences between treatments, $p < 0.05$.

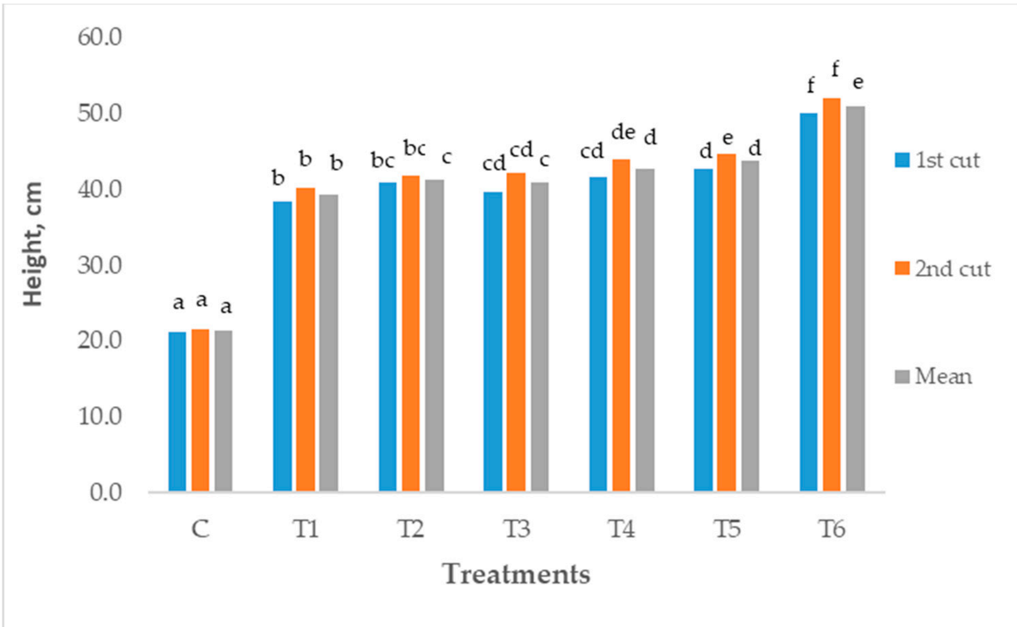

Figure 3. Plant height (cm) during the second growing year under the different soil types. Different lowercase letters represent statistical differences between treatments, $p < 0.05$.

3.2.2. Branch Length—Number of Branches per Plant

Data regarding the branch length of plants in the 1st and 2nd years for the different soil types are shown in Table 2. The application of mussel shells as soil amendment increased the branch length. In the first year, the highest branch length was noticed in the T6 pots (31 cm). Furthermore, T6 treatment increased significantly by 14.9% (T5) to 39.4% (T1) in comparison with the other amended treatments. In the second year, all the treatments showcased an increase in the branch length in both cuts. Moreover, in the second year, among T6 and the other treatments, the increase in branch length was lower compared to the first year. The rise follows the following order: 58.7% (C) > 23.2% (T1) > 20.3% (T2) > 18.4% (T3) > 16.1% (T4) > 14.2% (T5).

Table 2. Effect of the different soil types on branch length of plants (cm) the 1st and 2nd year.

Treatments	1st Year (2022)		2nd Year (2023)	
	1st Cut	2nd Cut	1st Cut	2nd Cut
C	12.3 ± 0.56 a	13.1 ± 0.48 a	20.5 ± 1.57 a	21.3 ± 1.49 a
T1	18.4 ± 0.75 b	20.4 ± 0.68 b	38.0 ± 0.64 b	39.7 ± 1.56 b
T2	19.4 ± 0.62 bc	22.2 ± 1.41 c	39.1 ± 1.28 bc	41.4 ± 1.82 c
T3	20.4 ± 0.96 c	22.8 ± 1.04 c	40.5 ± 1.01 cd	41.9 ± 1.44 cd
T4	23.8 ± 1.11 d	26.3 ± 0.49 d	41.5 ± 0.85 de	43.3 ± 2.23 de
T5	26.3 ± 0.9 e	28.1 ± 1.5 e	42.5 ± 1.09 e	44.2 ± 0.78 e
T6	31.0 ± 1.1 f	33.0 ± 1.31 f	49.7 ± 0.85 f	51.3 ± 0.87 f
LSD	0.479	0.544	0.542	0.723

Different letters in the same column indicate statistically significant differences between the different soil types ($p < 0.05$).

In the first year, a notable increase was observed when comparing the control to amended treatments, with raises of 34.7%, 39.2%, 41.3%, 49.4%, 53.4%, and 60.4% for T1, T2, T3, T4, T5, and T6, respectively. Similarly, in the second year, branch length exhibited significant growth across the different treatments and control, with an increase of 46.2%, 48.1%, 49.4%, 50.7%, 51.8%, and 58.7% for T1, T2, T3, T4, T5, and T6, respectively.

The number of branches/plants in relation to the different treatments is presented in Table 3. Regarding the results, the number of branches per plant was higher in the T6 treatment in both growing years. In the first year, the number of branches regarding the control ranged from 4.3 ± 1.26 (first cutting) to 4.8 ± 0.96 (second cutting) and from 12.0 ± 0.82 (first cutting) to 12.8 ± 0.96 (second cutting) for T6. In the second year, the number of branches per plant for the control varied from 6.5 ± 0.58 (first cutting) to 7.0 ± 0.82 (second cutting), while for T6, it ranged from 17.3 ± 0.96 (first cutting) to 18.3 ± 0.96 (second cutting). Concerning the number of branches per plant, during the initial growth period, the increase induced by the amended treatments compared to the control ranged from 34.5% (T1) to 61.3% (T6). Additionally, in the second cultivation year, the rise varied from 38.6% (T1) to 62.0% (T6).

Table 3. Effect of the different soil types on the number of branches of plants in the 1st and 2nd years.

Treatments	1st Year (2022)		2nd Year (2023)	
	1st Cut	2nd Cut	1st Cut	2nd Cut
C	4.3 ± 1.26 a	4.8 ± 0.96 a	6.5 ± 0.58 a	7.0 ± 0.82 a
T1	6.3 ± 0.96 b	7.5 ± 1.29 b	10.8 ± 0.96 b	11.3 ± 0.5 b
T2	6.5 ± 1.29 b	8.3 ± 0.96 b	11.0 ± 1.15 b	12.0 ± 0.82 b
T3	7.0 ± 0.82 b	7.5 ± 0.58 b	12.0 ± 0.82 b	12.5 ± 1.29 b
T4	9.5 ± 1.29 c	11.0 ± 0.82 c	14.5 ± 1.29 c	15.3 ± 1.26 c
T5	9.8 ± 1.26 c	9.8 ± 1.26 c	14.5 ± 1.29 c	15.0 ± 0.82 c
T6	12.0 ± 0.82 d	12.8 ± 0.96 d	17.3 ± 0.96 d	18.3 ± 0.96 d
LSD	0.559	0.500	0.518	0.479

Different letters in the same column indicate statistically significant differences between the different soil types ($p < 0.05$).

3.2.3. Fresh/Dry Weight (g/Plant)

The fresh and dry weight in each treatment is shown in Table 4 (fresh weight) and Table 5 (dry weight). The total (first and second cut) yield of fresh weight in the first year was ordered as follows: T6 (199.4 ± 6.6 g/plant) > T5 (172.8 ± 2.18 g/plant) > T4 (164.9 ± 0.92 g/plant) > T3 (146.8 ± 1.98 g/plant) > T2 (131.5 ± 2.39 g/plant) > T1

(130.4 ± 2.13 g/plan) > C (70.2 ± 1.56 g/plant). In the second year, the fresh weight followed the same order as that in the first year. Compared to the control, the amended treatments raised the total fresh weight from 46.1% to 64.8% in 2022 and from 43.2% to 59.1% in 2023. The total dry weight was higher for the T6 treatment (48.3 ± 2.07 in the first year and 70.8 ± 1.94 g/plant in the second). The T6 pots were statistically significantly different from all the other amended treatments, with a rise between 13.9% and 42.1% and 11.5% and 33.4% in the first and second growing years, respectively. The amended treatments compared to the control plots in the first year increased the dry weight by 42.3%, 45.1%, 50.9%, 61.2%, 62.5%, and 66.6% in T1, T2, T3, T4, T5, and T6, respectively. Moreover, in the second year, the rise ranged from 47.7% (T1) to 65.2% (T6).

Table 4. Effect of the different soil types on total fresh (g) per plant in the 1st and 2nd year.

Treatments	1st Year (2022)		2nd Year (2023)	
	1st Cut	2nd Cut	1st Cut	2nd Cut
C	34.5 ± 0.77 a	35.7 ± 0.8 a	60.0 ± 1.73 a	61.9 ± 1.19 a
T1	64.0 ± 1.63 b	66.4 ± 1.87 b	105.2 ± 1.99 b	109.4 ± 0.7 b
T2	64.9 ± 1.32 b	66.7 ± 1.61 b	105.8 ± 4.47 b	109.7 ± 4.73 b
T3	72.6 ± 3.51 c	74.2 ± 2.98 c	122.3 ± 5.72 c	125.0 ± 4.25 c
T4	81.7 ± 1.56 d	83.2 ± 1.8 d	132.7 ± 3.44 d	137.8 ± 1.26 d
T5	84.9 ± 1.56 d	87.8 ± 1.23 d	136.8 ± 1.52 d	140.3 ± 1.4 d
T6	98.8 ± 5.85 e	100.6 ± 4.35 e	146.8 ± 3.82 e	151.4 ± 4.91 e
LSD	1.290	1.098	1.473	1.381

Different letters in the same column indicate statistically significant differences between the different soil types ($p < 0.05$).

Table 5. Effect of the different soil types on dry weight (g) per plant in the 1st and 2nd year.

Treatments	1st Year (2022)		2nd Year (2023)	
	1st Cut	2nd Cut	1st Cut	2nd Cut
C	7.8 ± 0.7 a	8.4 ± 0.62 a	11.9 ± 0.81 a	12.8 ± 0.75 a
T1	13.0 ± 0.74 b	14.9 ± 0.58 b	22.8 ± 0.95 b	24.3 ± 0.16 b
T2	14.1 ± 0.6 bc	15.2 ± 0.27 b	23.6 ± 1.66 b	25.1 ± 0.99 b
T3	15.5 ± 1.12 c	17.4 ± 1.02 c	24.0 ± 1.14 b	26.1 ± 2.05 b
T4	19.8 ± 1.15 d	21.8 ± 0.29 d	27.1 ± 1.22 c	30.7 ± 2.25 c
T5	20.1 ± 1.25 d	22.9 ± 1.4 d	29.3 ± 2.23 d	33.3 ± 1.56 d
T6	23.0 ± 1.45 e	25.3 ± 0.87 e	33.0 ± 1.15 e	37.8 ± 1.32e
LSD	0.494	0.387	0.680	0.702

Different letters in the same column indicate statistically significant differences between the different soil types ($p < 0.05$).

4. Discussion

The outcomes of our investigation affirm that the incorporation of mussel shells as a soil amendment resulted in notable enhancements in both the agronomic characteristics and productivity of rosemary. In a study conducted by Mwithiga et al. [27], they explored the cultivation of Rosmarinus officinalis using cow manure as a singular soil improvement agent or in combination with additional fertilizers. Strikingly, their findings regarding plant height and the number of branches per plant align closely with our observations, particularly with comparable pH levels. Moreover, Singh et al. [28] reported a decline in plant height during the second year of their study, contrasting with our results, where in the second growing year, we noted an increase in plant height. Our findings underscore the positive impact of mussel shell amendments on plant height, with treatment T6 consistently outperforming the other soil treatments. This divergence might be attributed to the synergistic effects of biological fertilizer used in conjunction with mussel shells [29,30]. Furthermore, the results of La Bella et al. [31] examining the impact of peat, compost, perlite, and their combinations on the agronomic properties of rosemary revealed consistent findings with our study, particularly concerning plant height, branch length, and the number of branches per plant, especially at pH values ranging from 7.19 to 7.23. However, discrepancies emerged regarding fresh and dry weights, where our results diverged from those reported by other researchers [32,33]. Interestingly, our study showcased that mussel shells surpassed the productivity achieved with alternative soil amendments such as bentonite [32] and vermicompost [33].

The positive impact of mussel shells on rosemary growth and productivity observed in our study aligns with the potential described by Mwithiga et al. [25], signifying mussel shells as a promising soil amendment. The variability in plant height observed in the second growing year underscores the multifaceted nature of the interactions, implicating both mussel shells and biological fertilizer. This dynamic relationship could be a key factor contributing to the observed rise in plant height during the second year, in contrast to the findings reported by Singh et al. [26].

Furthermore, our results stand in agreement with those of La Bella et al. [29] regarding the positive influence of certain soil amendments on rosemary's agronomic properties. The compatibility of our findings with their results at specific pH levels adds depth to our understanding of the relationship between soil amendments and plant performance.

However, discrepancies in fresh and dry weights compared to other studies prompt a closer examination of the specific conditions and compositions of the soil amendments used. Our study suggests that mussel shells, as a soil improvement agent, outperformed bentonite and vermicompost in enhancing rosemary productivity. This emphasizes the importance of evaluating the unique contributions of different soil amendments to plant growth under specific environmental conditions. The observed variations in plant height during the second growing year, in comparison with other studies, emphasize the complexity of factors influencing plant development. This study paves the way for further investigations, particularly those incorporating detailed chemical analyses, to unravel the intricate mechanisms underlying the positive effects of mussel shells on rosemary productivity.

In the existing literature, many studies have investigated different aquaculture by-products like oyster shells, fish waste, seaweed, and sea urchins [12,22,34,35]. These studies collectively illuminate the diverse applications and versatility inherent in these aquatic resources. They provide an understanding of how aquaculture by-products serve pivotal roles in both environmental sustainability and economic domains. In a study conducted by Lee et al. [22], the investigation into the utilization of oyster shells in cabbage cultivation revealed compelling outcomes. Their research demonstrated a significant increase in productivity with the application of 8 Mg ha^{-1} of oyster shells as a soil improvement amendment. This highlights the positive impact of oyster shells as a beneficial addition in enhancing crop yield, showcasing their potential as an effective aquaculture amendment. Further insights into the positive effects of aquaculture by-products emerge from the work of Fernandez-Calvino et al. [34]. Their study focused on crushed mussel shells and their influence on *Lolium perenne*. Notably, they observed an increase in plant length and biomass with the application of 6 and 24 g of mussel shells per kg of soil. This emphasizes the beneficial impact of mussel shells in promoting plant growth and soil health. Additionally, the study by Liu et al. [35] explored the application of ground purple sea urchin (*Paracentrotus lividus*) at a 3% rate. Their findings revealed a significant positive impact on bean growth, underscoring the potential of sea urchins as a valuable amendment for enhancing crop development. Importantly, this study noted that the wheat yield remained unaffected, showcasing the selective influence of sea urchins on different crops. Examining the synergistic effects of oyster shells and organic fertilizers, Liu et al. [12] investigated their combined impact on soil nutrients and tea yield. The results demonstrated that the incorporation of shells with organic fertilization not only improved productivity but also contributed to a reduction in the availability of heavy metal content in the soil. This dual benefit underscores the potential of integrating aquaculture by-products with organic fertilizers for sustainable and environmentally friendly agricultural practices.

Despite these notable findings, a comprehensive review of the literature reveals a scarcity of information regarding the influence of aquaculture by-products on pH regulation in acidic soils and their impact on soil fertility, particularly concerning medicinal and aromatic plants. Addressing this knowledge gap could pave the way for more tailored and effective utilization of aquaculture by-products in diverse agricultural contexts, offering insights into sustainable practices for enhancing both plant health and soil conditions.

5. Conclusions

In this research, the cultivation of *Rosmarinus officinalis* under different soil pHs was studied, using mussel shells as soil pH amendment. According to the results, the increase in soil pH provoked a rise in agronomic characteristics and the productivity of rosemary. In particular, the increase in pH to 7.19 and 7.23 ameliorated the growth and yield of the plants. The optimal amount for neutralizing soil pH has been determined to a ratio of 300 g of mussel shells per 10 kg of soil; however, the ratio of 600 g of mussel shells was found to be more effective as far as productivity and agronomic characteristics are concerned. This study has proved that mussel shells can positively affect the cultivation of rosemary when they are used for soil improvement.

We believe that this study will motivate the scientific community to investigate the important role of mussel shells as well as other fish by-products that can be recycled and used in sustainable agricultural sections for soil improvement. Particularly, there is a lack of research, and our study underscores the efficacy of mussel shells as a valuable soil improvement in rosemary cultivation, highlighting the contribution of this study in the field.

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