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Impact of Nitrogen Fertilization on Rosemary: Assessment of Physiological Traits, Vegetation Indices, and Environmental Resource Use Efficiency

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Abstract: Rosemary (*Salvia rosmarinus* L.) is a versatile and resilient plant with significant culinary, medicinal, and ecological value. This study evaluates the impact of four nitrogen (N) fertilization levels (0, 50, 100, and 150 kg N ha^{-1}) on the morphological, physiological, and agronomic traits, as well as vegetative indices, of rosemary over two growing seasons (2022 and 2023). The results indicate that plant height and leaf area index (LAI) increased with N application. Additionally, physiological characteristics such as chlorophyll content, photosynthetic efficiency, and assimilation rates (A) increased by an average of 32%, 17%, and 55%, respectively, compared to the control. Biomass production also improved with N fertilization, with yields rising by 32% in 2022 and 58% in 2023. Furthermore, both essential oil concentration and essential oil yield were enhanced by N application. Radiation use efficiency (RUE), water use efficiency (WUE), agronomic efficiency (AE), and partial factor productivity (PFP) also increased, indicating more efficient utilization of environmental resources. Moreover, higher N rates consistently enhanced vegetation indices, reflecting improved plant health, greenness, biomass, photosynthetic activity, and energy utilization. Therefore, this study highlights that the optimal N range appears to balance biomass yield and essential oil yield while maximizing the efficiency of environmental resource use.

Keywords: spectral indices; N use efficiency; productivity; essential oil content; dry matter yield

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Academic Editors: Lili Lei, Rebecca McGrail, Fumin Wang and Pete Iannetta

Received: 23 February 2025
Revised: 27 April 2025
Accepted: 29 April 2025
Published: 2 May 2025

Citation: Dordas, C.A. Impact of Nitrogen Fertilization on Rosemary: Assessment of Physiological Traits, Vegetation Indices, and Environmental Resource Use Efficiency. *Nitrogen* **2025**, *6*, 33. https://doi.org/10.3390/nitrogen6020033

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1. Introduction

Rosemary (*Salvia rosmarinus*, formerly *Rosmarinus officinalis*) is a perennial, aromatic shrub of the Lamiaceae family, native to the Mediterranean region [1,2]. It is widely cultivated and valued for its culinary, medicinal, ornamental, and aromatic properties [3]. Adapted to nutrient-poor, well-drained soils and sunny climates, rosemary is highly drought-tolerant and thrives in Mediterranean environments [1]. As a versatile and resilient plant, it holds significant culinary, medicinal, and ecological value [2,4].

Rosemary possesses several medicinal properties, including aiding digestion, enhancing memory, and alleviating muscle pain. It also exhibits anti-inflammatory and antimicrobial effects [2,5–7]. These attributes suggest that rosemary may have potential applications in managing chronic diseases and infections [2,3,8].

Nitrogen (N) is a key macronutrient that influences plant growth, yield, and essential oil composition [9–12]. Moderate N levels promote robust vegetative growth in rosemary, enhancing shoot length, leaf area, and biomass production [13,14]. Nitrogen-rich soils often result in greener, softer, and lusher foliage, making rosemary more desirable for culinary and ornamental purposes [14]. However, excessive N can compromise rosemary's natural

tolerance to drought, salinity, and nutrient-deficient soils [15–17]. Rosemary is naturally adapted to low-nitrogen environments, and excessive nitrogen levels may compromise its resilience.

Since rosemary thrives in Mediterranean climates with nutrient-poor soils, N supplementation must be carefully managed. Excessive application can contribute to soil acidification, nutrient leaching, and weed proliferation. Therefore, nitrogen management should be optimized, using specific indices to support sustainable crop production [15–17].

Although numerous vegetation indices have been developed for annual crops, their application to perennial species—particularly aromatic and medicinal plants—remains limited. However, recent advancements in hyperspectral imaging and sensing technologies have enhanced the refinement and use of spectral indices in agriculture [18–21]. These indices offer a rapid, non-invasive method for assessing plant health, chemical composition, stress levels, and growth stages through remote sensing techniques [19,22].

Among the most widely studied indices in crop science are the normalized difference vegetation index (NDVI), Modified Soil-Adjusted Vegetation Index (MSAVI2), fraction of absorbed photosynthetically active radiation (fPAR), Ratio Vegetation Index (RVI), and enhanced vegetation index (EVI2) [19,23,24]. Thus, MSAVI2, fPAR, RVI, and EVI2 have become essential tools in modern crop management, providing valuable insights into plant health, productivity, and environmental interactions. However, despite their widespread use, these indices are rarely applied to aromatic and medicinal plants. Integrating them into emerging agricultural technologies could enhance sustainable farming practices and contribute to global food security [24–26].

The objectives of this study were as follows:

1. To determine the effect of N application on various morphological, physiological, and agronomic characteristics of rosemary.
2. To evaluate different vegetation indices under varying N levels for improved N management.
3. To assess the impact of N management on environmental resource utilization in rosemary cultivation.

2. Materials and Methods

2.1. Experimental Set-Up

This study was conducted in Northern Greece at the University Farm of Aristotle University of Thessaloniki (40°48′56.55″ N, 23°29′36.5″ E) during the 2021–2022 (2022) and 2022–2023 (2023) growing seasons. Weather data were collected daily and summarized into monthly averages for temperature and monthly total rainfall across both years (Figure 1). Four nitrogen (N) application rates—control (0 kg N ha^{-1}), 50, 100, and 150 kg N ha^{-1}—were tested, with four replications in a completely randomized block design. Nitrogen applications were made in late winter (February) using ammonium nitrate (NH_4NO_3) granules (33.5-0-0 N-P-K), the most commonly used N fertilizer for aromatic and medicinal plants in the region.

At the start of the trial, the rosemary plants were in their fifth year of growth, with no fertilizers applied in previous years to ensure minimal residual soil nitrogen (N). Each experimental plot measured 10 m × 4 m and consisted of seven rows spaced 0.75 m apart, with 3–4 plants per meter of row length. The plots were arranged according to a randomized complete block design (RCBD).

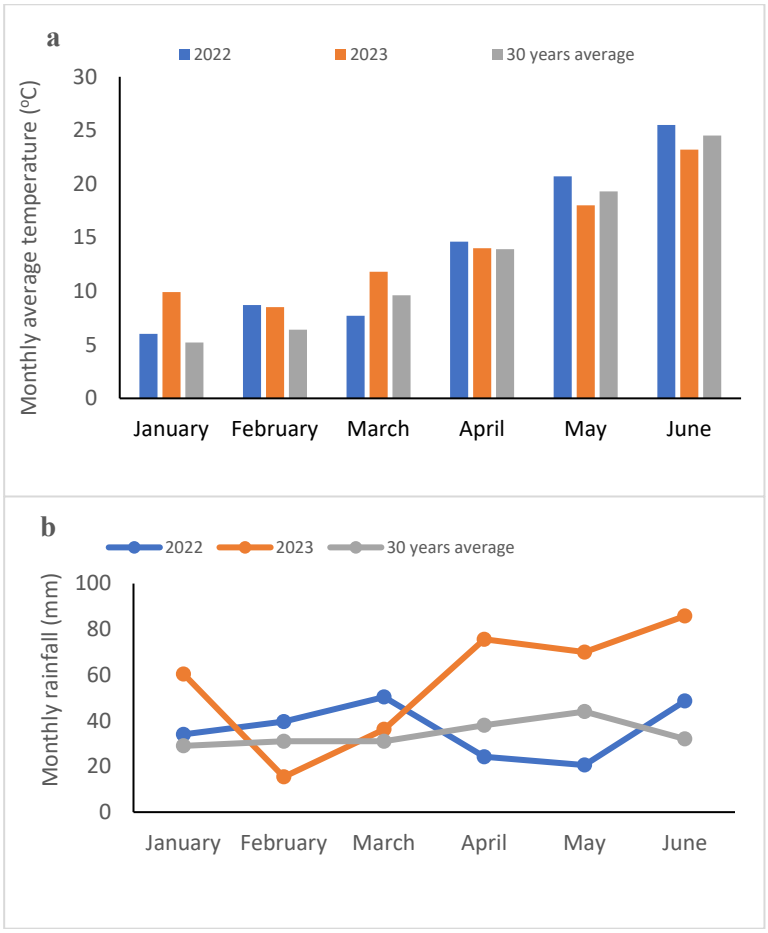

Figure 1. The main weather parameters (mean temperature (**a**) and monthly total rainfall (**b**)) for the two growing seasons of experimentation at Thermi Greece, and their comparison to the 30-year average. The weather data were recorded with an automatic weather station close to the experimental site.

2.2. Soil Sampling and Analysis

Before applying fertilizers, soil samples were collected from a depth of 0–30 cm and analyzed according to the methods outlined by Sparks et al. [27]. The soil was classified as silty clay loam and had the following properties: pH (1:2 water) of 7.9, organic matter content of 20.2 g kg^{-1}, nitrate nitrogen (N-NO_3)—14.16 mg kg^{-1}, available phosphorus (P, Olsen)—21.65 mg kg^{-1}, exchangeable potassium (K)—245 mg kg^{-1}, calcium carbonate ($CaCO_3$)—105 g kg^{-1}, and magnesium (Mg)—690 mg kg^{-1}.

2.3. Measurements

Throughout the growing season, a range of plant traits were assessed at two distinct growth stages: pre-bloom and full bloom. These measurements were taken to evaluate the impact of N fertilization on rosemary. The traits analyzed included plant height, leaf area index (LAI), chlorophyll content (SPAD readings), photosynthetic performance, the normalized difference vegetation index (NDVI), other spectral indices, dry biomass, essential oil concentration, and essential oil yield. In addition, agronomic N use efficiency, productivity factor, water use efficiency, and radiation use efficiency were determined at the different treatments.

Measurements for the first year were conducted on 17 June 2022 and 25 June 2022 for the pre-bloom and full bloom stages, respectively. For the second year, measurements

were taken on 22 June 2023, and 30 June 2023 for the pre-bloom and full bloom stages, respectively. The crop harvest occurred on 25 June 2022 and 30 June 2023.

2.4. Morphological Characteristics

2.4.1. Plant Height

Plant height was measured to determine the influence of N fertilization on rosemary growth. Measurements were performed using a measuring tape on five central plants within each plot at both pre-bloom and full bloom stages.

2.4.2. Leaf Area Index (LAI)

Leaf area index (LAI) was measured using the AccuPAR LP-80 (METER, Pullman, WA, USA), a portable device designed to measure leaf area and photosynthetically active radiation (PAR) under field conditions. The device calculates LAI by recording PAR (400–700 nm) through its array of sensors and applying specific computations. Readings were taken between 11 a.m. and 1 p.m. to ensure consistent light conditions. Three readings were recorded within the plant canopy, and the average value was calculated to represent the LAI for each plot.

2.5. Physiological Characteristics

2.5.1. Chlorophyll Content (SPAD Readings)

Chlorophyll content was measured using the SPAD-502 Plus, a handheld dual-wavelength meter designed for non-destructive chlorophyll assessment in plant tissues (Minolta Camera Co., Ltd, Osaka, Japan). The device uses chlorophyll's absorption characteristics at 460 nm (cyan) and 670 nm (red) in the visible spectrum of electromagnetic radiation (400–700 nm) to determine chlorophyll levels. In each plot, 12 fully developed, young leaves were selected for sampling before each data collection session. SPAD readings provided a reliable and non-invasive method for estimating chlorophyll content, ensuring no harm to the plants during measurements.

Relative chlorophyll meter (RCM) readings were calculated by dividing any SPAD reading by the maximal value from 200 kg N ha^{-1}. This index, ranging from 0.5 to 1, is also called the sufficiency index [28].

2.5.2. Photosynthetic Efficiency

Photosynthetic efficiency was measured using the FluorPen FP 110 (Photon Systems Instruments, Drásov, Czech Republic), a portable device manufactured by Photon Systems Instruments. This instrument evaluates photosynthetic fluorescence parameters non-destructively, providing insights into plant physiological performance [29]. In each plot, 12 individual leaf measurements were taken, and the average was calculated to represent the photosynthetic efficiency parameter.

2.5.3. Gas Exchange Parameters

Gas exchange measurements were conducted using the LCi Leaf Chamber Analysis System (ADC BioScientific Ltd., Hoddesdon, UK), which included a 6.25 cm^2 chamber for data collection. Several physiological parameters were assessed, including the rate of CO_2 assimilation (A), transpiration rate (E), and stomatal conductance to water vapor (g_s). These measurements were taken at two growth stages: pre-bloom and anthesis.

The same leaves used for chlorophyll content measurements were selected, and five readings were taken per plot. Instantaneous water use efficiency (WUE) was calculated by dividing the CO_2 assimilation rate (A) by the transpiration rate (E), as described by von Caemmerer and Farquhar [30].

2.6. Vegetation Indices

A range of vegetation indices were calculated using canopy light reflectance data obtained with the SpectroSense2$^+$ system (Skye Instruments, Ddole Enterprise Park, UK). This portable device was mounted on a handheld pole positioned 1.8 m above the canopy. Measurements were based on the ratios of incoming and reflected red and near-infrared light, as detected by the device's sensors [31]. The key indices that were determined were normalized difference vegetation index (NDVI), enhanced vegetation index (EVI2), Modified Soil-Adjusted Vegetation Index (MSAVI2), fraction of absorbed photosynthetically active radiation (fPAR), and Ratio Vegetation Index (RVI). NDVI was calculated by comparing the absorption of red light to the reflection of near-infrared light. This non-destructive metric is widely used to monitor plant health and condition [19,23,32].

2.7. Dry Biomass and Essential Oil Content

2.7.1. Dry Biomass

Dry biomass yield was measured by harvesting plants from a 1 m^2 section of each experimental plot. Fresh plant weight was recorded on-site using a precision electronic scale. The harvested samples were then air-dried at room temperature for 10 days or until they reached a constant weight. Once dried, the samples were weighed again to determine the dry weight.

The relative dry matter yield for each plot was calculated by comparing the dry matter yield at a specific N application rate to the maximum dry matter yield recorded across all N treatments [33].

2.7.2. Essential Oil Content

Essential oil content was quantified using a Clevenger apparatus (Sigma, London, UK) via water distillation. For each sample, 40 g of dried plant material was distilled for 3 h. The essential oil volume was measured and expressed as mL per 100 g of dry material, following the method outlined by Wichtl [34].

2.8. Radiation Use Efficiency (RUE)

Radiation use efficiency (RUE) was calculated as the ratio of the total biomass produced to the cumulative radiation intercepted by the plants over the growing season. This calculation was performed according to the methodology described by Elhakeem et al. [35]. RUE provides an estimate of how effectively plants convert intercepted solar radiation into biomass.

2.9. Water Use Efficiency (WUE)

Water use efficiency (WUE) was determined by dividing the dry biomass yield by the total water input, which included rainfall during the experimental period. This approach followed the method outlined by Howell [36], providing insights into the relationship between water availability and biomass production under different N treatments.

2.10. Agronomic Efficiency and Productivity

Agronomic efficiency (AE) was calculated according to the following equation:

$$AE = (\Upsilon_F - \Upsilon_C)/N$$

where Υ_F = dry matter yield of the fertilizer treatment (in kg ha^{-1}) and Y_C = dry matter yield of the control treatment (in kg ha^{-1}), and N is the fertilizer rate (in kg ha^{-1}) [10]. Therefore, AE is a key indicator of how efficiently N is utilized by the crop to produce additional yield.

The productivity was recorded as a result of N input using the partial factor productivity (PFP), expressed as kg harvested product per kg of N applied, and is calculated as the ratio of the crop yield to the amount of the nutrient applied [10].

$$PFP = Y/F$$

Therefore, this index provides a broad measure of the productivity of the applied nutrient, without accounting for diminishing returns at higher application rates. It is widely used in nutrient management to evaluate overall efficiency.

2.11. Statistical Analysis

The data collected from the two growing seasons were subjected to analysis of variance (ANOVA) using models that accounted for key factors and their interactions. A three-factor model was employed for traits measured at multiple growth stages, encompassing growing season (2 levels) × fertilizer treatment (4 levels) × growth stage (2 levels). For dry biomass and essential oil content, a two-factor model was used, considering growing season (2 levels) × fertilizer treatment (4 levels). The study followed a randomized complete block design (RCBD) with four replications. Mixed linear models were integrated within the ANOVA framework to accurately estimate standard errors and account for variability among treatment combination means [37,38]. Within the methodological framework of mixed linear models, the basic assumptions of the ANOVA method were fulfilled. The least significant difference (LSD) method was applied to compare treatment means, using a significance threshold of $\alpha = 0.05$ ($p \leq 0.05$). All statistical computations were performed with SPSS software (version 25, SPSS Inc., Chicago, IL, USA). Additionally, Pearson correlation analyses were carried out to examine relationships across data from both growing seasons, leveraging the entire dataset within SPSS.

3. Results

3.1. Morphological Characteristics

3.1.1. Plant Height

Nitrogen (N) fertilization significantly influenced rosemary plant height at both growth stages (before bloom and full bloom) and across both growing seasons (2022 and 2023) (Table 1). In the 2022 season, plant height increased significantly with rising N levels, with the tallest plants observed under the 150 kg N ha^{-1} treatment. At full bloom, these plants were 55% taller than the control. A similar trend was observed before bloom, though the percentage increase was smaller, likely due to the earlier stage of growth and lower biomass accumulation. In 2023, the positive response to N fertilization persisted, though the magnitude of the increase was less pronounced compared to 2022. On average, plant height in fertilized treatments increased by 26% and 38% in 2022 and 15% and 11% in 2023 for the before bloom and full bloom stages, respectively (Table 1).

Table 1. Plant height of rosemary plants at two growth stages (before bloom and at full bloom) at four nitrogen levels and during two growing seasons, 2022 and 2023.

Year	N Treatments	Before Bloom	Full Bloom
2022	0 N	92.08 ± 6.33 a †	94.75 ± 3.15 a
	50 N	106.69 ± 8.30 b	108.67 ± 9.01 b
	100 N	114.46 ± 5.88 b	137.92 ± 6.83 c
	150 N	127.73 ± 9.22 b	147.25 ± 7.60 c

Table 1. *Cont.*

Year	N Treatments	Before Bloom	Full Bloom
2023	0 N	108.13 ± 1.25 a	122.00 ± 0.33 a
	50 N	124.27 ± 5.23 b	134.75 ± 0.85 b
	100 N	125.81 ± 1.58 b	135.42 ± 0.25 b
	150 N	124.29 ± 2.43 b	136.58 ± 1.16 b

† Means in the same column followed by the same letter do not differ significantly for the same year according to the LSD test ($p \leq 0.05$).

3.1.2. Leaf Area Index

The leaf area index (LAI) was significantly influenced by N fertilization, with higher N levels resulting in greater LAI values compared to the control and the 50 kg N ha^{-1} treatment (Table 2). In 2022, LAI increased substantially with N application. The control treatment (0 kg N ha^{-1}) had LAI values of 1.32 before bloom and 1.69 at full bloom, while the highest N treatment (150 kg N ha^{-1}) recorded values of 2.04 and 2.82, respectively. This corresponds to a 56% increase before bloom and 48% at full bloom compared to the control. In 2023, LAI remained higher in fertilized treatments, averaging 23% and 37% higher than the control before bloom and at full bloom, respectively (Table 2). Additionally, LAI values in 2023 were higher overall than in 2022, suggesting improved plant canopy development in the second growing season.

Table 2. Leaf area index (LAI) of rosemary plants at two growth stages (before bloom and at full bloom) at the four nitrogen levels and during two growing seasons, 2022 and 2023.

		Leaf Area Index (LAI)	
Year	**N Treatments**	**Before Bloom**	**Full Bloom**
2022	0 N	1.32 ± 0.07 a †	1.69 ± 0.11 a
	50 N	1.92 ± 0.12 b	2.06 ± 0.17 b
	100 N	2.21 ± 0.28 b	2.62 ± 0.11 b
	150 N	2.04 ± 0.07 b	2.82 ± 0.15 b
2023	0 N	2.44 ± 0.013 a	3.23 ± 0.12 a
	50 N	2.92 ± 0.16 b	3.92 ± 0.10 b
	100 N	2.87 ± 0.02 b	4.75 ± 0.22 c
	150 N	3.19 ± 0.09 b	4.66 ± 0.27 c

† Means in the same column followed by the same letter do not differ significantly for the same year according to the LSD test ($p \leq 0.05$).

3.2. Physiological Characteristics

3.2.1. Chlorophyll Meter Readings (CMR)

The results in Table 3 show that N fertilization significantly increased chlorophyll content in rosemary plants, as measured by chlorophyll meter readings (CMRs) and relative chlorophyll meter readings (RCMRs) at two growth stages across both growing seasons (2022 and 2023). Higher N levels enhanced chlorophyll content, which is critical for optimizing photosynthesis and overall plant health. In 2022, the highest CMR values were observed under the 100 kg N ha^{-1} treatment, with readings of 38.18 before bloom and 41.95 at full bloom. In 2023, the trend continued, with the maximum CMR (53.48 at full bloom) recorded under the 150 kg N ha^{-1} treatment. On average, CMR values in N-treated plants were 32% and 25% higher than the control at the first and second growth stages, respectively, in 2023. In 2022, the increases were 14% and 20%, respectively (Table 3).

RCMR followed a similar trend, confirming that N fertilization not only boosts absolute chlorophyll content but also enhances its relative concentration in the leaves (Table 3).

Table 3. Chlorophyll meter readings (CMRs) and relative chlorophyll meter readings (RCMRs) of rosemary with two growth stages (before bloom and at full bloom), four nitrogen levels, and two growing seasons.

		Chlorophyll Content Meter Readings (CMRs)		Relative Chlorophyll Meter Readings (RCMRs)	
Year	**N Treatments**	**Before Bloom**	**Full Bloom**	**Before Bloom**	**Full Bloom**
2022	0 N	33.50 ± 1.10 a †	33.78 ± 1.85 a	0.87 ± 0.01 a	0.82 ± 0.01 a
	50 N	38.18 ± 1.02 b	38.76 ± 0.71 b	0.99 ± 0.02 b	0.95 ± 0.02 b
	100 N	38.18 ± 0.77 b	41.95 ± 0.98 b	0.99 ± 0.03 b	1.02 ± 0.03 b
	150 N	36.44 ± 0.44 b	40.20 ± 0.79 b	1.00 ± 0.02 b	1.00 ± 0.02 b
2023	0 N	36.65 ± 1.11 a	40.51 ± 0.79 a	0.69 ± 0.02 a	0.79 ± 0.03 a
	50 N	45.18 ± 1.04 b	48.10 ± 0.72 b	0.84 ± 0.03 b	0.93 ± 0.02 b
	100 N	46.70 ± 0.79 b	52.13 ± 1.17 b	0.87 ± 0.02 b	1.01 ± 0.03 b
	150 N	53.48 ± 1.30 c	51.55 ± 0.25 b	1.00 ± 0.01 b	1.00 ± 0.02 b

† Means in the same column followed by the same letter do not differ significantly for the same year according to the LSD test ($p \leq 0.05$).

3.2.2. Photosynthetic Efficiency

Photosynthetic efficiency, measured using a chlorophyll fluorescence meter, assessed the quantum yield efficiency of photosystem II (PSII) at both growth stages across both years (Table 4). On average, N application increased photosynthetic efficiency by 17% compared to the control in both years (Table 4). However, no significant differences were observed among the N fertilization treatments, as values remained relatively similar across treatments.

Table 4. Photosynthetic efficiency of rosemary plants during two growth stages (before bloom and at full bloom), four nitrogen levels, and two growing seasons.

		Photosynthetic Efficiency	
Year	**N Treatments**	**Before Bloom**	**Full Bloom**
2022	0 N	0.596 ± 0.016 a †	0.615 ± 0.010 a
	50 N	0.678 ± 0.015 b	0.665 ± 0.014 b
	100 N	0.681 ± 0.009 b	0.649 ± 0.013 b
	150 N	0.718 ± 0.010 b	0.662 ± 0.014 b
2023	0 N	0.600 ± 0.004 a	0.568 ± 0.041 a
	50 N	0.667 ± 0.004 b	0.680 ± 0.004 b
	100 N	0.718 ± 0.011 b	0.678 ± 0.006 b
	150 N	0.709 ± 0.013 b	0.686 ± 0.008 b

† Means in the same column followed by the same letter do not differ significantly for the same year according to the LSD test ($p \leq 0.05$).

3.2.3. Assimilation Rate and Gas Exchange Parameters

The results indicate that N fertilization significantly enhanced photosynthesis and gas exchange parameters in rosemary plants. Higher N levels increased CO_2 assimilation rates (A), intercellular CO_2 concentrations (C_i), evaporation rates (E), and stomatal conductance (g_s) (Table 5). Optimal N levels, particularly 100 and 150 kg N ha^{-1}, improved gas exchange efficiency, which is essential for maximizing photosynthetic performance.

Table 5. Gas exchange measurements and instantaneous water use efficiency (A/E) of rosemary plants during full bloom, four nitrogen levels, and two growing seasons.

Year	N Treatments	Assimilation Rate (A) (μmol m^{-2} s^{-1})	Transpiration Rate (E) (mmol m^{-2} s^{-1})	Stomatal Conductance (g_s) (mol m^{-2} s^{-1})	Instantaneous Water Use Efficiency (A/E) (μmol mmol^{-1})
2022	0 N	2.46 ± 0.13 a †	0.63 ± 0.036 a	0.06 ± 0.003 a	4.09 ± 0.21 a
	50 N	3.57 ± 0.23 b	0.70 ± 0.034 ab	0.18 ± 0.009 b	5.13 ± 0.32 b
	100 N	4.40 ± 0.18 b	0.86 ± 0.035 b	0.13 ± 0.004 b	5.14 ±0.28 b
	150 N	4.50 ± 0.07 b	0.90 ± 0.044 b	0.11 ± 0.002 b	5.00 ± 0.33 b
2023	0 N	2.68 ± 0.41 a	0.62 ± 0.026 a	0.13 ± 0.024 a	4.26 ± 0.58 a
	50 N	5.78 ± 0.36 b	0.84 ± 0.062 b	0.28 ± 0.016 b	6.93 ± 0.64 b
	100 N	6.41 ± 0.11 b	0.98 0.068 b	0.34 ± 0.02 b	6.63 ± 0.48 b
	150 N	6.32 ± 0.46 b	1.07 0.078 b	0.31 ± 0.016 b	6.01 ± 0.49 b

† Means in the same column followed by the same letter do not differ significantly for the same year according to the LSD test ($p \leq 0.05$).

Nitrogen-treated plants exhibited a notably higher CO_2 assimilation rate, reaching 6.41 µmol m^{-2} s^{-1} under the 100 kg N ha^{-1} treatment in 2023. The intercellular CO_2 concentration (C_i) increased with higher N levels, averaging a 10% rise compared to the control. The 23% increase in evaporation rates (E) suggests that stomata remained open longer to facilitate CO_2 uptake, which is crucial for sustaining high photosynthetic rates under sufficient N supply. Stomatal conductance (g_s) increased by 26%, further supporting the role of N in enhancing gas exchange dynamics. Higher g_s values allowed greater CO_2 influx while also promoting water vapor loss through transpiration. Additionally, instantaneous water use efficiency (WUE), measured as A/E, improved with increased N supply, indicating more efficient water utilization. This trend was observed in both growing seasons, with an average increase of 38% (Table 5).

3.3. Dry Matter Yield and Essential Oil Content

The dry matter yield increased significantly with N fertilization. In 2022, yields ranged from 95.75 g m^{-2} (0 kg N ha^{-1}) to 132.25 g m^{-2} (150 kg N ha^{-1}), and in 2023, from 94.50 g m^{-2} (0 kg N ha^{-1}) to 157.25 g m^{-2} (150 kg N ha^{-1}). The average increase in dry matter yield was approximately 32% in 2022 and 58% in 2023, compared to the control (0 kg N ha^{-1}), highlighting the substantial increase in biomass production, particularly in the second year (Table 6).

Table 6. Dry matter yield, relative dry matter yield, essential oil concentration, and essential oil yield of rosemary plants during full bloom, four nitrogen levels, and two growing seasons.

Year	N Treatments	Dry Matter Yield (g m^{-2})	Relative Dry Matter Yield	Essential Oil (%)	Essential Oil Yield (mL m^{-2})
2022	0 N	95.75 ± 2.93 a †	0.74 ± 0.021 a	1.53 ± 0.09 a	1.62 ± 0.19 a
	50 N	117.25 ± 7.90 b	0.91 ± 0.023 b	2.02 ± 0.12 b	2.38 ± 0.20 b
	100 N	129.25 ± 7.50 c	1.00 ± 0.019 b	1.91 ± 0.03 b	2.47 ± 0.19 b
	150 N	132.25 ± 5.01 c	1.02 ± 0.021 b	1.98 ± 0.13 b	2.59 ± 0.21 b
2023	0 N	94.50 ± 6.67 a	0.66 ± 0.023 a	2.06 ± 0.13 a	1.89 ± 0.18 a
	50 N	143.50 ± 5.24 b	1.00 ± 0.027 b	2.78 ± 0.17 b	4.01 ± 0.28 b
	100 N	143.50 ± 2.53 b	1.00 ± 0.017 b	2.44 ± 0.15 b	3.55 ± 0.21 b
	150 N	157.25 ± 6.28 b	1.10 ± 0.024 b	2.44 ± 0.14 b	3.83 ± 0.24 b

† Means in the same column followed by the same letter do not differ significantly for the same year according to the LSD test ($p \leq 0.05$).

Relative dry matter yield was consistently higher in nitrogen-treated plots, with the highest relative yields observed at 100 kg N ha^{-1} and 150 kg N ha^{-1} during both years. This suggests a direct correlation between N application and plant growth performance (Table 6).

The essential oil concentration also responded positively to N fertilization. In 2022, it increased from 1.53% at 0 kg N ha^{-1} to 1.98% at 150 kg N ha^{-1}. In 2023, the oil concentration ranged from 2.06% at 0 kg N ha^{-1} to 2.78% at 50 kg N ha^{-1}, demonstrating that N not only enhances biomass but also improves essential oil quality (Table 6).

Similarly, the essential oil yield followed a positive trend. In 2022, it increased from 1.62 mL m^{-2} at 0 kg N ha^{-1} to 2.59 mL m^{-2} at 150 kg N ha^{-1}. In 2023, it rose from 1.89 mL m^{-2} at 0 kg N ha^{-1} to 4.01 mL m^{-2} at 50 kg N ha^{-1}. The average increase in essential oil yield was approximately 81% in 2022 and 53% in 2023, with N treatments outperforming the control (Table 6).

3.4. Radiation Use Efficiency (RUE)

This study indicated that RUE (radiation use efficiency) significantly increased with N fertilization, demonstrating that higher N application rates enhanced the conversion of intercepted global radiation into biomass. The highest recorded RUE value was 8.64 $MJ/m^2/day$ during the 150 kg N ha^{-1} treatment, which was substantially greater than the control (Table 7). This result aligns with existing literature that highlights the role of N in improving crop efficiency in utilizing solar radiation for growth. The trend of increased RUE with N application was consistent across both years of the experiment, underscoring a strong relationship between N fertilization and light utilization efficiency. This consistency emphasizes the critical role of N in optimizing biomass yield through improved photosynthetic efficiency (Table 7).

Table 7. Radiation use efficiency, water use efficiency (WUE), agronomic efficiency (AE), and partial factor productivity (PFP) of the different N treatments in rosemary.

Year	N Treatments	Radiation Use Efficiency (RUE; g MJ^{-1})	Water Use Efficiency (WUE) (kg/ha/mm)	Agronomic Efficiency (AE) (kg/kg)	Partial Factor Productivity (PFP) (kg/kg)
2022	0 N	5.24 ± 0.37 a †	4.40 ± 0.23 a	-	-
	50 N	6.41 ± 0.41 b	5.39 ± 0.28 b	4.30 ± 0.16 a	23.45 ± 1.21 a
	100 N	7.07 ± 0.67 b	5.95 ± 0.24 b	3.35 ± 0.14 b	12.93 ± 1.18 b
	150 N	7.23 ± 0.52 b	6.08 ± 0.31 b	2.43 ± 0.12 c	8.82 ± 0.87 c
2023	0 N	5.19 ± 0.41 a	2.75 ± 0.14 a	-	-
	50 N	7.88 ± 0.46 b	4.18 ± 0.21 b	9.80 ± 0.54 a	28.70 ± 2.41 a
	100 N	7.88 ± 0.53 b	4.18 ± 0.23 b	4.90 ± 0.28 b	14.35 ± 2.14 b
	150 N	8.64 ± 0.74 b	4.58 ± 0.21 b	4.18 ± 0.26 b	10.48 ± 1.87 b

† Means in the same column followed by the same letter do not differ significantly for the same year according to the LSD test ($p \leq 0.05$).

3.5. Water Use Efficiency

The data on water use efficiency (WUE) in relation to N fertilization underscore the significant impact of N application on a crop's ability to effectively utilize water for biomass production. The results indicate that WUE was significantly influenced by the different fertilization treatments, showing a notable increase with higher N application rates (Table 7). The highest WUE values were recorded at 100 kg N ha^{-1} and 150 kg N ha^{-1}, while the control and the lowest N application treatment exhibited the lowest WUE values. In 2022, WUE increased by 32% compared to the control treatment, and in 2023, this increase reached

up to 35% with N fertilization. These consistent improvements across both years highlight the role of N in optimizing water utilization, which is crucial for sustainable agricultural practices (Table 7).

3.6. Agronomic Efficiency (AE) and Productivity PFP (Partial Factor Productivity)

The agronomic efficiency (AE) of N fertilization was higher at the lowest N application rate and showed a greater increase in the 2023 growing season compared to 2022 (Table 7). AE declined as N levels increased, as there was no corresponding increase in dry matter yield (Table 7).

Similarly, partial factor productivity (PFP) was highest at the lowest N treatment and decreased with higher N levels (Table 7). This decline in PFP aligns with the trend observed in AE, as there was no linear increase in dry matter yield with increasing N application (Table 7).

3.7. Vegetation Indices

The data presented in Table 8 on the use of various vegetation indices in rosemary at two growth stages (before bloom and full bloom) across four N levels and two growing seasons provide valuable insights into the effects of N fertilization on plant health and productivity.

Normalized difference vegetation index (NDVI) values were significantly higher in fertilized treatments compared to the control across both years and growth stages, indicating that N application enhances plant greenness and overall health. The increase was more pronounced during the vegetative stage (before bloom) than at full bloom (Table 8). Similarly, the enhanced vegetation index (EVI2) also increased with higher N levels, reflecting improved vegetation density and health. These values consistently rose from the vegetative stage to full bloom in both experimental years.

The Modified Soil Adjusted Vegetation Index (MSAVI2) increased with both growth stages and higher N rates, suggesting that N fertilization positively influences biomass accumulation and plant vigor. Additionally, the Fraction of Photosynthetically Active Radiation (fPAR) values increased with N application, peaking at the highest N rates, indicating better light interception and utilization for photosynthesis. The Ratio Vegetation Index (RVI) also responded positively to N fertilization, showing a notable 42% increase compared to the control treatment (Table 8).

There was notable variability between the two growing seasons. For instance, in 2023, NDVI values were generally higher across all treatments compared to 2022, suggesting that environmental conditions may have influenced plant responses to N fertilization (Table 8). The data reveal that vegetation indices were generally higher before bloom than at full bloom for most treatments, indicating that N may have a more significant impact on early growth phases than on later stages (Table 8).

3.8. Correlation Analysis of the Studied Parameters

The data presented in Table 9 outline Pearson correlation coefficients among various plant growth and yield parameters. To effectively analyze this data, it is important to interpret the relationships between the different variables, focusing particularly on significant correlations.

Essential oil content showed a very strong positive correlation with essential oil yield and NDVI, suggesting that as essential oil content increases, essential oil yield also rises significantly. The enhanced vegetation index (EVI2) had a high correlation with the Modified Soil Adjusted Vegetation Index (MSAVI2), indicating that these two indices are closely related in measuring vegetation health.

Table 8. Vegetation indices of rosemary plants during two growth stages (before bloom and at full bloom), four nitrogen levels, and two growing seasons.

		NDVI		EVI2		MSAVI2		fPAR		RVI	
Year	**Treatment**	**Before Bloom**	**Full Bloom**	**Before Bloom**	**Full Bloom**	**Before Bloom**	**Full Bloom**	**Before Bloom**	**Full Bloom**	**Before Bloom**	**Full Bloom**
2022	0 N	0.54 ± 0.018 a †	0.69 ± 0.009 a	0.15 ± 0.013 a	0.17 ± 0.019 a	0.12 ± 0.006 a	0.15 ± 0.018 a	0.50 ± 0.022 a	0.64 ± 0.019 a	3.39 ± 0.161 a	5.47 ± 0.214 a
	50 N	0.64 ± 0.022 ab	0.78 ± 0.018 b	0.21 ± 0.010 b	0.27 ± 0.012 b	0.17 ± 0.011 a	0.24 ± 0.011 b	0.62 ± 0.027 b	0.77 ± 0.044 b	4.62 ± 0.306 b	7.58 ± 0.304 b
	100 N	0.67 ± 0.014 b	0.78 ± 0.012 b	0.21 ± 0.004 b	0.24 ± 0.010 b	0.18 ± 0.020 ab	0.24 ± 0.016 b	0.66 ± 0.017 b	0.76 ± 0.021 b	5.11 ± 0.264 b	7.56 ± 0.395 b
	150 N	0.62 ± 0.018 ab	0.80 ± 0.027 b	0.24 ± 0.012 b	0.25 ± 0.016 b	0.23 ± 0.007 b	0.24 ± 0.017 b	0.60 ± 0.022 ab	0.77 ± 0.002 b	4.42 ± 0.268 b	7.61 ± 0.316 b
2023	0 N	0.77 ± 0.007 a	0.76 ± 0.004 a	0.18 ± 0.019 a	0.15 ± 0.010 a	0.16 ± 0.018 a	0.13 ± 0.009 a	0.78 ± 0.011 a	0.77 ± 0.010 a	7.58 ± 0.332 a	7.32 ± 0.281 a
	50 N	0.79 ± 0.008 a	0.77 ± 0.003 a	0.21 ± 0.027 ab	0.23 ± 0.058 b	0.18 ± 0.025 a	0.21 ± 0.055 b	0.81 ± 0.023 a	0.78 ± 0.005 a	8.66 ± 0.962 b	7.63 ± 0.148 a
	100 N	0.79 ± 0.006 a	0.80 ± 0.009 a	0.24 ± 0.022 b	0.19 ± 0.037 a	0.22 ± 0.021 b	0.17 ± 0.035 b	0.82 ± 0.013 a	0.83 ± 0.011 b	8.79 ± 0.542 b	9.24 ± 0.469 b
	150 N	0.75 ± 0.014 a	0.80 ± 0.007a	0.22 ± 0.057 b	0.21 ± 0.027 b	0.20 ± 0.057 ab	0.19 ± 0.027 b	0.77 ± 0.039 a	0.83 ± 0.008 b	7.64 ± 0.874 a	9.16 ± 0.351 b

† Means in the same column followed by the same letter do not differ significantly for the same year according to the LSD test ($p \leq 0.05$).

Table 9. Pearson correlation coefficients among some of the characteristics that were measured in this study in 2022 and 2023.

	LAI	**CMRs**	**PE**	**E**	**g_s**	**A**	**A/E**	**DMY**	**EOC**	**EOY**	**NDVI**	**EVI2**	**MSAVI2**	**PAR**	**RVI**
PH	0.596 **	0.572 **	0.408 **	0.511 **	0.099	0.464 **	0.115	0.519 **	0.292	0.481 **	0.518 **	0.243	0.298 *	0.559 **	0.453 **
LAI		0.781 **	0.263 *	0.694 **	0.274	0.731 **	−0.379 **	0.550 **	0.621 **	0.709 **	0.608 **	0.007	0.029	0.667 **	0.621 **
CMR			0.470 **	0.648 **	0.134	0.733 **	−0.328 *	0.633 **	0.572 **	0.710 **	0.658 **	0.189	0.196	0.629 **	0.615 **
PE				0.336 *	0.149	0.623 **	0.147	0.731 **	0.158	0.498 **	0.294 *	0.430 **	0.411 **	0.261 *	0.201
E					0.348 *	0.746 **	−0.406 **	0.542 **	0.546 **	0.666 **	0.778 **	0.320 *	0.365 *	0.654 **	0.639 **
g_s						0.310 *	−0.310 *	0.160	0.449 **	0.400 *	0.228	−0.033	−0.034	0.197	0.145
A							−0.307 *	0.697 **	0.572 **	0.771 **	0.634 **	0.384 **	0.382 **	0.553 **	0.528 **
A/E								−0.135	−0.527 **	−0.438 *	−0.440 **	0.140	0.112	−0.418 **	−0.380 **
DMY									0.366 *	0.790 **	0.570 **	0.311	0.341	0.411 *	0.360 *
EOC										0.844 **	0.691 **	0.091	0.140	0.630 **	0.605 **
EOY											0.771 **	0.201	0.244	0.628 **	0.582 **
NDVI												0.250 *	0.245	0.875 **	0.843 **
EVI2													0.948 **	0.339 **	0.377 **
MSAVI2														0.336 **	0.372 **
fPAR															0.934 **

* Significant at the 0.05 level of probability. ** Significant at the 0.01 level of probability. Abbreviations, PH: plant height; CMRs: chlorophyll meter readings; LAI: leaf area index; PE: photosynthetic efficiency; E: evapotranspiration; g_s: stomatal conductance; A: assimilation rate; A/E: instantaneous water use efficiency; DMY: dry matter yield; EOC: essential oil content; EOY: essential oil yield; NDVI: normalized difference vegetation index; MSAVI2: Modified Soil Adjusted Vegetation Index; fPAR: fraction of absorbed photosynthetically active radiation; RVI: Ratio Vegetation Index; EVI2: enhanced vegetation index.

The leaf area index (LAI) was strongly correlated with several other variables, including SPAD, photosynthetic efficiency, and dry matter yield, suggesting that a larger leaf area is associated with improved photosynthetic performance and increased biomass production. Photosynthetic efficiency itself was positively correlated with transpiration (E) and stomatal conductance (g_s), highlighting that efficient photosynthesis is linked to effective water use. Higher photosynthetic efficiency may support better growth and essential oil production in rosemary plants (Table 9).

Additionally, essential oil content showed high correlations with essential oil yield and several other growth parameters, such as dry matter yield. This correlation underscores that a higher oil content generally results in greater oil yield.

While most correlations were positive, there were a few negative correlations, notably between instantaneous water use efficiency (WUE) and both dry matter yield and essential oil content (Table 9). These negative correlations suggest that plants with higher WUE may not necessarily produce higher biomass or essential oil content.

4. Discussion

Nitrogen is a critical nutrient for plants, including rosemary, as it influences vegetative growth, essential oil yield, and overall productivity [11,12,39]. While moderate N levels optimize growth and improve oil quality, excessive N can reduce the plant's ability to adapt to stress and negatively affect the quality of its aromatic compounds [4,15,17]. Proper nitrogen management, tailored to rosemary's specific ecological needs, is essential for sustainable cultivation and the production of high-quality products [11,12,14,39].

4.1. Morphological Characteristics

4.1.1. Plant Height

Rosemary plants treated with nitrogen exhibited greater height compared to the untreated control (0 kg N ha^{-1}), highlighting the positive role of N in promoting vegetative growth [16,40]. This substantial growth response can be attributed to nitrogen's essential role as a macronutrient that supports cell division and elongation, driving overall plant development [11,14,41]. The reduced responsiveness observed in 2023 may be due to environmental factors such as variations in temperature and rainfall, which could have influenced nutrient uptake efficiency or growth dynamics [11,14,41]. Despite these seasonal differences, N fertilization consistently increased plant height compared to the control in both years. The observed plant height in this study was higher than in some previous research [16], possibly due to more favorable field conditions.

These findings underscore the importance of N fertilization for rosemary cultivation while also highlighting the potential influence of seasonal variability on crop responses [16,40]. Future studies could focus on identifying optimal N rates under diverse environmental conditions to maximize N use efficiency and minimize environmental impacts [14,41]

4.1.2. Leaf Area Index

The data demonstrate that higher N levels consistently lead to an increased leaf area index (LAI), highlighting N's critical role in enhancing leaf development and overall plant growth. These findings align with previous research indicating that N fertilization significantly boosts leaf expansion and canopy development in various plant species, including rosemary [14,42].

In 2023, baseline LAI values were higher across all treatments compared to 2022, even in the control group (2.44 before bloom and 3.23 at full bloom). While the increase in LAI due to fertilization was smaller than in 2022—23% before bloom and 37% at full bloom—it

still demonstrates N's positive impact on leaf area development [42]. This variation may be attributed to differences in environmental conditions, such as temperature, humidity, and soil moisture, which significantly influence nutrient uptake and growth dynamics.

The significant increases in LAI with N application have important implications for rosemary cultivation. A higher LAI enhances light interception and photosynthetic capacity, leading to increased biomass production and potentially greater essential oil yields, as observed in this study [33]. Therefore, optimizing N management strategies is essential for maximizing rosemary productivity while ensuring sustainability. These findings also emphasize the importance of carefully monitoring N levels to avoid over-fertilization, which could lead to environmental issues such as nutrient leaching and soil degradation [11,14,39].

4.2. Physiological Characteristics

4.2.1. Chlorophyll Meter Readings (CMR)

The consistent increase in chlorophyll content with N application aligns with previous studies, which indicate that N is a critical nutrient for chlorophyll synthesis and overall plant vigor [16,42–44]. N enhances the production of chlorophyll pigments, which are essential for capturing light energy during photosynthesis [45,46].

The significant increases in chlorophyll meter readings (CMRs) of 32% and 25% during the second year, at both growth stages, highlight the effectiveness of N fertilization in enhancing leaf greenness and health compared to the control group. These findings are consistent with earlier studies that reported similar improvements in chlorophyll content in response to N fertilization across various plant species [33,47,48].

The variability observed between the two growing seasons can likely be attributed to environmental factors. In 2023, baseline chlorophyll readings were higher across all treatments compared to 2022, suggesting that growing conditions were more favorable that year. Factors such as temperature, humidity, and soil moisture availability significantly affect nutrient uptake and overall plant health [12,44]. The increase in CMR and relative chlorophyll meter reading (RCMR) values in both years emphasizes the importance of optimal environmental conditions in conjunction with nutrient management to maximize chlorophyll content.

4.2.2. Photosynthetic Efficiency

The observed increase in photosynthetic efficiency, as indicated by chlorophyll fluorescence metrics, further supports the positive effects of N fertilization. On average, photosynthetic efficiency increased by 17% across both years, suggesting that N not only enhances gas exchange parameters but also optimizes the quantum yield of photosystem II (PS II), a key component of the photosynthetic process [44]. However, it is important to note that no significant differences were found among the various N treatments in this regard, indicating a potential saturation point beyond which additional N may not lead to further improvements in photosynthetic efficiency [49].

4.2.3. Assimilation Rate and Gas Exchange Parameters

The observed increase in the assimilation rate and other gas exchange parameters supports previous research highlighting N as a critical nutrient for chlorophyll synthesis and photosynthetic efficiency [16,41]. Enhanced N availability promotes the development of leaf structures that optimize light capture and CO_2 assimilation, leading to improved overall plant productivity [45,46]. This suggests that N fertilization not only boosts leaf area and chlorophyll content but also enhances the plant's capacity to maintain higher internal CO_2 concentrations, which are essential for efficient photosynthesis [45,50].

Higher stomatal conductance (g_s) facilitates greater CO_2 influx while also promoting water vapor loss through transpiration. This balance is crucial, as it reflects the plant's ability to manage water use and carbon assimilation effectively [30,45]. The improved instantaneous water use efficiency (WUE) observed under higher N conditions suggests that rosemary plants can utilize water more efficiently for photosynthesis, a particularly beneficial trait in regions with limited water availability.

4.3. Dry Matter Yield and Relative Dry Matter Yield

Dry matter yield increased significantly in response to N fertilization across both growing seasons, with an average increase of 32% in 2022 and 58% in 2023 compared to the control. This increase can be attributed to N's essential role in stimulating vegetative growth by enhancing chlorophyll production and photosynthesis, both of which are critical for biomass accumulation. As noted by Heikal and Helmy [16], N fertilization significantly enhances various growth parameters, including fresh and dry leaf weights, aligning with the observed increases in dry weight in this study.

The relative dry matter yield was also positively influenced by fertilization treatments, consistently remaining higher in N-treated plots compared to the control and the 50 kg N ha^{-1} treatment. The highest relative dry matter yield values were observed at the 100 and 150 kg N ha^{-1} treatments in both growing seasons, indicating that higher N levels positively impact dry matter production [33]. This consistent pattern suggests that N not only enhances total biomass but also improves the efficiency of biomass production relative to the control treatment. Similar findings have been reported in other studies, which noted significant increases in herb yield with higher N rates in aromatic and medicinal plants [33,51,52].

4.4. Essential Oil Concentration and Essential Oil Yield

Essential oil content increased with N fertilization, with notable differences observed between the two years of the experiment. On average, the essential oil content was higher in N-treated plants, with the highest concentration recorded in the 150 kg N ha^{-1} treatment and the lowest in the control group across both years. This increase in essential oil concentration can be attributed to enhanced metabolic activity resulting from improved nutrient availability, particularly N, which plays a crucial role in secondary metabolite production in aromatic plants like rosemary [53]. Previous studies have shown that optimal N levels can lead to increased essential oil content, while excessive N may cause dilution effects [16,51,52].

Nitrogen fertilization also had a significant effect on essential oil yield, which was more strongly influenced by the increase in dry matter yield than by essential oil concentration. The highest essential oil yield was observed in the 150 kg N ha^{-1} treatment, with incremental increases noted across the range of N treatments compared to the control. This substantial boost in oil yield can be attributed to the combined effects of increased biomass and enhanced essential oil concentration at higher N levels. Research indicates that N fertilization significantly contributes to both herbage yield and essential oil production in various aromatic plants [54]. Consistently, the highest essential oil yields were observed in the 150 kg N ha^{-1} treatment, reinforcing the critical role of adequate N supply in maximizing oil production [49].

4.5. Radiation Use Efficiency (RUE)

Radiation use efficiency (RUE) increased significantly with N fertilization, indicating that N application enhanced the conversion of intercepted global radiation into biomass. The highest RUE value (3.53 g MJ^{-1}) was recorded in the 150 kg N ha^{-1} treatment, which was significantly higher than the control. This trend was consistent across both years

of the experiment, emphasizing the critical role of N fertilization in improving light utilization efficiency and contributing to higher biomass yields [35,45,55,56]. The ability of plants to efficiently convert solar radiation into biomass is a key factor in growth and productivity [35,45,55,56]. The significant difference in RUE between the highest N treatment and the control highlights the potential benefits of optimized N management in agricultural practices. Improved RUE not only leads to higher biomass yields but also signifies more efficient use of available resources, further reinforcing the importance of effective N fertilization [35,45,55,56].

4.6. Water Use Efficiency (WUE)

The highest water use efficiency (WUE) values were observed in the 100 kg N ha^{-1} and 150 kg N ha^{-1} treatments, while the control and the lowest N application treatment exhibited the lowest WUE values. This pattern suggests that N fertilization enhances the crop's ability to convert water into biomass, thereby improving overall resource use efficiency. The consistent improvements across both years highlight the critical role of N in optimizing water utilization, a key aspect of sustainable agricultural practices.

These findings indicate that N application not only boosts biomass yield but also enhances WUE, demonstrating a synergistic effect where improved nutrient management contributes to better water management [57,58]. This is particularly relevant in regions where water resources are limited, like the Mediterranean area, and agricultural productivity needs to be maximized without compromising sustainability [57,58].

4.7. Agronomic Efficiency (AE) and Partial Factor Productivity (PFP)

This study shows that the agronomic efficiency (AE) of N fertilization was highest with the lowest N application rate, with a notable increase in AE during the 2023 growing season compared to 2022. This suggests that lower N applications may lead to more efficient N use, resulting in better crop yields relative to the amount of fertilizer applied. However, as N application rates increased, AE declined, likely due to a lack of proportional increase in dry matter yield. This phenomenon aligns with previous research indicating that excessive N can lead to diminishing returns in crop yield, a pattern observed in several studies that identified optimal N levels for achieving maximum yield without over-fertilization [10,33,59].

The partial factor productivity (PFP) was evaluated, showing a peak in the first N treatment, followed by a decrease with subsequent applications. This trend mirrors the observed pattern in agronomic efficiency (AE), where increasing N application did not result in a linear increase in dry matter yield. These findings emphasize the importance of optimizing N application rates to enhance productivity while minimizing environmental impacts. The decline in both AE and PFP with higher N levels suggests that farmers should carefully consider their fertilization strategies to avoid over-application, which could lead to nutrient runoff and other ecological concerns [9].

4.8. Vegetation Indices

The findings regarding vegetation indices (VIs) and their relationship with N fertilization are consistent with several studies. For instance, Gao et al. [20] demonstrated that vegetation indices, such as NDVI and EVI, are effective indicators of crop health and can be influenced by nutrient management practices, including N application. Their study emphasized that higher N levels correlate with improved vegetation indices, reflecting enhanced photosynthetic activity and biomass production. Furthermore, other research has shown that increased N fertilization leads to significant improvements in plant growth metrics, including NDVI, which in turn correlates with enhanced chlorophyll content and overall plant vigor.

Proper N management not only boosts crop yield but also improves physiological metrics such as NDVI and other vegetation indices across various crops. These findings collectively reinforce the conclusion that N fertilization significantly enhances vegetation indices in rosemary plants, improving their ability to utilize resources efficiently for growth and biomass production [20–23,41,56].

The vegetation indices (VIs) used in this study, such as the normalized difference vegetation index (NDVI), are particularly useful for assessing crop nitrogen (N) requirements and serve as valuable tools for monitoring N nutrition, as they strongly correlate with leaf N content. By integrating NDVI measurements with N application strategies, growers can improve nitrogen-use efficiency, reduce input costs, and minimize environmental impacts in rosemary [22,23]. Additionally, VIs can be used to assess plant health, chlorophyll content, and biomass accumulation in aromatic and medicinal plants.

Moreover, the Enhanced Vegetation Index 2 (EVI2) improves upon NDVI by reducing sensitivity to atmospheric effects and soil background noise. It is particularly useful in high-biomass conditions, where NDVI tends to saturate, allowing for more accurate assessments of nitrogen (N)-related canopy differences [20]. Additionally, the Modified Soil-Adjusted Vegetation Index 2 (MSAVI2) accounts for soil background effects, making it effective for early-season N monitoring when canopy cover is low. It helps determine N availability during early growth stages, facilitating timely fertilizer applications [20–23,41,56].

Another useful index is the Fraction of Photosynthetically Active Radiation (fPAR), which estimates the fraction of sunlight absorbed by plants for photosynthesis. This index correlates with nitrogen (N) supply and biomass production, as a lower fPAR value may indicate N stress, leading to reduced photosynthetic efficiency. Additionally, the Ratio Vegetation Index (RVI) serves as an indicator of plant chlorophyll content and biomass and can be used alongside other indices to refine N status assessments and guide precision fertilization.

All these vegetation indices can be measured using remote sensing tools such as drones, satellites, or portable spectrometers to detect N deficiencies early. This enables the targeted application of N fertilizers only where needed, improving efficiency and reducing fertilization costs.

4.9. Correlation Coefficients

In the present study, a strong positive correlation between essential oil content and essential oil yield was found, indicating that as the content of essential oil increases, the yield also significantly rises. This relationship is critical for crop production, particularly for plants valued for their essential oils, such as rosemary, lavender, and mint [33,51,52]. Previous studies have shown that higher essential oil content often correlates with increased economic yield in aromatic plants [60].

Additionally, the correlation between EVI2 and MSAVI2 suggests a strong relationship in assessing vegetation health. Both indices used to evaluate plant vigor and biomass reflect essential growth dynamics. Their high correlation implies that they can be used interchangeably in certain contexts.

A strong correlation between LAI, SPAD, photosynthetic efficiency, and dry matter yield indicates that larger leaf areas positively influence photosynthesis and biomass production. This aligns with findings that LAI is a critical determinant of light interception and photosynthetic capacity in crops [61].

The positive correlation of photosynthetic efficiency with transpiration (E) and stomatal conductance (g_s) highlights the importance of efficient water use in enhancing photosynthetic performance. Efficient photosynthesis is crucial for plant growth and can lead to better yields, especially under varying environmental conditions [30,57].

Conversely, negative correlations observed between instantaneous water use efficiency (WUE) and both dry matter yield and essential oil content suggest that excessive water use may not lead to proportional increases in yield or oil content. This could indicate a trade-off, where higher water use does not directly translate into higher productivity [58].

These findings emphasize the interrelated nature of plant traits, suggesting that improvements in one characteristic could lead to enhancements in others. This is particularly relevant for agricultural practices aimed at maximizing yield and quality, such as N fertilization. Understanding these relationships allows researchers to identify key traits for breeding or management strategies, ultimately optimizing crop performance. Furthermore, negative correlations necessitate careful management to prevent unintended reductions in yield or quality when attempting to improve other characteristics.

While N fertilization can increase crop yields and farm profitability, its environmental impacts, such as nitrate leaching, soil degradation, and contributions to climate change, must be carefully evaluated. Therefore, it is important to reduce the risks of over-fertilization and to find new tools for optimizing N use efficiency, and incorporating innovative technologies, like vegetation indices and adopting sustainable crop management practices, are essential. Although N application can lead to nitrate leaching in certain crops [9,14], rosemary cultivation in dryland areas with limited rainfall and no irrigation significantly mitigates this risk [9,14]. In addition, N over-fertilization can lead to soil degradation and reduce soil health. This can be corrected by the sustainable use of N fertilization and also meeting crop demands [11,12,14]. Moreover, the extensive use of N fertilizers increases greenhouse gas emissions as the production of N fertilizers consumes a considerable amount of fossil fuels [11,12,14].

The methodologies presented in this study can be adapted to other crop species, underscoring the importance of validating these approaches across diverse crops and environmental conditions. It is important to note that the responses of different crops to these methods may vary, and similar principles may apply under alternative treatments, particularly in the presence of additional stress factors.

Previous research has shown that other Lamiaceae species, including oregano, thyme, and chia, respond positively to N fertilization [33,50,51]. This highlights the critical role of N fertilization in the successful cultivation of emerging crop species. Even crops traditionally grown in marginal lands and low-input systems require adequate nutrient supplementation to maintain productivity [33,50,51].

Nitrogen fertilization is particularly important for sustaining high productivity in crops like rosemary. While increased N application involves additional costs, these are offset by corresponding gains in dry matter and essential oil yields, as demonstrated in this study and corroborated by earlier research [33,51,52]. These findings underscore the necessity of providing adequate N levels to achieve optimal crop performance.

5. Conclusions

These findings have significant implications for rosemary cultivation practices, highlighting the crucial role of N fertilization in enhancing both morphological and physiological traits in rosemary plants. N fertilization improves plant height, the leaf area index, and overall growth metrics. Effective N application enhances growth and productivity while reducing the environmental impacts associated with over-fertilization. N fertilization also boosts radiation use efficiency, water use efficiency, essential oil content, and biomass yield, promoting sustainable agriculture and maximizing resource utilization. Integrating these practices into the cultivation of medicinal and aromatic plants like rosemary can lead to higher yields of valuable compounds, thereby increasing farmers' income. These

findings underscore the importance of tailored N fertilization strategies in sustainable rosemary cultivation.

Funding: This research was co-financed by the European Regional Development Fund of the European Union and Greek national funds through the Operational Program Competitiveness, Entrepreneurship and Innovation, under the call RESEARCH—CREATE—INNOVATE (project code:T2EDK-01627).

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: The author declares no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

CM	Chlorophyll meter.
RCM	Relative chlorophyll meter.
LAI	Leaf area index.
E	Evapotranspiration.
g_s	Stomatal conductance.
A	Assimilation rate.
A/E	Instantaneous water use efficiency.
NDVI	Normalized difference vegetation index.
MSAVI2	Modified Soil Adjusted Vegetation Index.
fPAR	Fraction of absorbed photosynthetically active radiation.
RVI	Ratio Vegetation Index.
EVI2	Enhanced vegetation index.
WUE	Water use efficiency.
RUE	Radiation use efficiency.
AE	Agronomic efficiency.
PFP	Partial factor productivity.

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