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Effects of Nitrogen Fertilization and Soil Water Content on Seed and Oil Yield in Perennial Castor in a Mediterranean Environment

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Abstract: Castor (*Ricinus communis* L.) is an oilseed species that can be grown as a semi-perennial in Mediterranean environments, including the coastal areas of Sicily. The present study investigated the optimization of cultivation techniques for castor, with the crop being maintained over a two-year period, through the evaluation of different agronomical inputs in order to increase seed yield. The effects of irrigation (I) and nitrogen fertilization (N) on the seed and oil yield and their components were assessed in castor cultivated in a typical semi-arid environment. Four levels of irrigation (I0, I30, I60, and I100: 0, 30, 60, and 100% of crop evapotranspiration—ETm restoration, respectively) as the main plot and three levels of nitrogen fertilization (N) (0, 60, and 120 kg N ha^{-1}) as the sub-plot were considered. Irrigation mostly affected the number of racemes per plant, the number of capsules per raceme, and the seed weight. The oil content was, on average, 39.2% and 45.6% for the first and second year, respectively. The highest seed yield was obtained by I100N120 treatment (4154.0 kg ha^{-1}); however, the combination of a high soil nitrogen level (N120) and medium water availability (I60) resulted in satisfactory seed and oil yields. The reduction in the irrigation water to an intermediate level could be also an environmentally friendly strategy not significantly affecting yields.

Keywords: *Ricinus communis* L.; seeds yield; oil yield; Mediterranean environment

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1. Introduction

Castor (*Ricinus communis* L.) is a non-food, drought-resistant energy crop that has been used since antiquity because of the distinctive properties of its oil, with evidence of its use dating back to ancient Egypt [1,2]. Castor is a member of the Euphorbiaceae family that is found across all the tropical and semi-tropical regions of the world [3]. Ethiopia is considered to be the most probable site of origin because of the presence of high diversity [4–6]. The castor crop, due to its ease of cultivation, drought and salinity tolerance, and adaptability to a variety of growing conditions, is one of the most important non-food crops grown in arid and semi-arid areas [7,8]. The oil content of castor seed ranges between 40% and 60% and the oil consists of the following fatty acids: ricinoleic acid (91–95%), linoleic acid (4%), and palmitic and stearic acids (1%) [9]. Castor oil has a growing international market, as evidenced by over 700 applications ranging from medicines and cosmetics to the replacement of petroleum in the production of plastics, lubricants, and biodiesel [10–12].

Several studies have evidenced the adaptability of castor to European soil and the European climate [13–16]; moreover, castor was extensively grown in Europe until the 1980s, and wild types spontaneously grow in many areas of the Mediterranean region.

In the semi-arid environments of southern Italy, castor behaves as an annual spring–summer crop that requires irrigation, and its sowing is typically performed in April, when the soil temperature reaches a stable level of 16–17 °C, ensuring rapid seed germination and uniform crop establishment [17–19]. However, the Mediterranean climate of the lowlands and coastal areas of Sicily presents cool winters with infrequent light frost and peaks of annual precipitation during the autumn and winter. In these areas, castor can be grown as a semi-perennial, extending the growing season during a period of the year when rainfall is adequate for the crop, thus reducing irrigation requirements [20]. Moreover, mild temperatures in the winter extend the length of the growing season, allowing for greater vegetative development and increasing the potential yield [18,21]. Preliminary field experiments carried out in Sicily (southern Italy) and in Tunisia have proven the possibility of exploiting the perennial habit of this species [22].

The present study was conducted on a local type of castor selected from a Tunisian genotype by the Department of Agriculture, Food and Environment (Di3A) of the University of Catania (Italy). The aim of the study was the optimization of cultivation techniques in castor through an assessment of the crop's response, in terms of seed and oil yield, to different levels of irrigation and nitrogen supply, with the crop being maintained over a two-year period.

2. Materials and Methods

2.1. Field Experiment

The field experiment was conducted in two successive years (2021 and 2022) at the experimental farm of the University of Catania, Italy (10 m a.s.l., 37°25′ N lat., 15° 03′ E long.) on a typical xerofluvent soil. The soil characteristics were as follows: clay 32.3%, silt 11.8%, sand 55.9%, organic matter 1.4%, pH 7.6, total N 0.2%, available P_2O_5 46.1 mg kg^{-1} [23], and exchangeable K_2O 293.3 mg kg^{-1} [23]. The soil of the experimental area was plowed before sowing and fertilized with 70 kg ha^{-1} P_2O_5 (as single superphosphate).

The experiment was set up in a split-plot experimental design, with a 4 × 3 factorial scheme consisting of four irrigation levels (I0, I30, I60, and I100 with 0, 30, 60, and 100% of crop maximum evapotranspiration—ETm restoration, respectively), three mineral nitrogen (N) fertilization rates (N0, N60, and N120 with 0, 60, and 120 kg N ha^{-1}, respectively), and three replicates per treatment. Irrigation was assigned to the main plot, and the N fertilizer was assigned to the sub-plot. The amount of nitrogen for each N level was applied in the first year as follows: 35% before sowing (as ammonium sulphate), 45% before flowering (as ammonium nitrate), and 20% at the beginning of grain formation (as ammonium nitrate). Each plot measured 68 m^2 (8 m × 8.5 m) with 1.7 m row-to-row spacing and a 1 m plant-to-plant distance (a sowing density of 0.58 m^2) and consisted of five rows. Seeds of a local Tunisian genotype of castor selected by the Department of Agriculture, Food and Environment (Di3A) of the University of Catania (Italy), were sown manually on the 15th of April 2021 by placing three seeds per hole at 3 to 4 cm in depth. The plots were hand-thinned to one plant per hole when the plants were at the four-leaf stage. A drip irrigation system using 16 mm pipes was installed to irrigate the plants, with them supplying 2436, 1604, and 873 of water m^3 ha^{-1} in 2021 and 1624, 1070, and 582 of water m^3 ha^{-1} in 2022 to I100, I60, and I30, respectively. The plots in I0 were irrigated up to seedling establishment with a total of 237 m^3 ha^{-1} of water. The irrigation volume (V) was determined as the maximum available soil water content in the 0.6 m soil depth, at which the root system is predominantly developed. Irrigation was scheduled when the sum of the daily maximum crop evapotranspiration (ETm) corresponded to V, with rainfall events being subtracted from the calculation. Daily ETm was calculated according to the following formula:

$$ETm = E_0 \times Kp \times Kc \quad (1)$$

where ETm is the maximum daily evapotranspiration (mm); E_0 is the evaporation of a class-A pan (mm); and Kp is the pan coefficient, equal to 0.80 in a semi-arid environment. The following crop coefficients (Kc) were considered in the calculation: 0.4 from emergence to the four-leaf stage; 0.7 from the four-leaf stage to the beginning of flowering; and 1.2

from the beginning of flowering to complete capsule development of the first raceme. The irrigation volume was calculated according to the following:

$$V = 0.66 \times (FC - WP) \times \phi \times D \times 10^3 \quad (2)$$

where V = water amount (mm); 0.66 = readily available water not limiting for evapotranspiration; FC = soil water content at field capacity (27% of dry soil weight); WP = soil water content at the wilting point (11% of dry soil weight); ϕ = bulk density (1.1 g cm^{-3}); and D = rooting depth (0.6 m).

For each irrigation level, the crop water use (CWU) was determined by means of the water balance from plant emergence to the start of the rainy season (first year = *i*) and from plant regrowth up to the last irrigation (second year = *ii*)

$$CWU_{(i)(ii)} = I_{(i)(ii)} + P_{(i)(ii)} \pm \Delta C_{(i)(ii)} \quad (3)$$

where $CWU_{(i)(ii)}$ = crop water use (mm); $I_{(i)(ii)}$ = water supplied by means of irrigation (mm); $P_{(i)(ii)}$ = precipitation (mm); $\Delta C_{(i)}$ = difference between soil water content at plant emergence and soil water content after the last irrigation (mm); and $\Delta C_{(ii)}$ = the difference between soil water content at plant regrowth and soil water content after the last irrigation (mm).

Soil samples were collected to a depth of 0.6 m in each treatment, before sowing and at the anthesis stage during the first year. During the second growing season, soil samples were collected before plant regrowth and at the anthesis stage. Field moist soil samples were immediately weighted, closed in plastic zip bags, and then transferred into a ventilated oven to dry at 105 °C up to a constant weight.

Daily meteorological data and potential evapotranspiration (ET_0) were continuously measured through a weather station connected to a data logger (Delta-T, WS-GP1 Compact) and a class A evaporation pan (mm d^{-1}). In the first year (2021), during the growing season, the date of occurrence of the main phenological stages of the crop [24], seedling emergence (Ve), anthesis (A), and physiological maturation (M) were recorded, and physiological plant gas exchange (photosynthesis and transpiration), using a portable system (LCi-SD, ADC BioScientific, Great Amwell, Hertfordshire, UK), was measured at 7–10-day intervals for a total of 9 measurements. Harvest was carried out starting from the primary racemes as follows: 7 September, 25 September, 20 October, and 20 November 2021 for I100, I60, I30, and I0, respectively. The secondary racemes were harvested on 2 October, 22 October, 18 November, and 10 December of the same year in I100, I60, I30, and I0, respectively, according to the different flowering periods. In the second year (2022), harvests were performed starting from 10 June until 25 July according to the different flowering periods. At harvest, 18 plants (six plants from the three central rows) of each plot were collected. In the laboratory, the first and the secondary racemes were kept separated and weighed; the capsules were counted and manually separated from the peduncle, and the seeds were separated from their capsules to measure the number of capsules per raceme and the seed weight per raceme. Water use efficiency (WUE) was calculated as the ratio between the seed yield (kg ha^{-1}) and crop water use (CWU), considering the total of the yields and the total amount of water used, in the two years.

2.2. Meteorological Course

The weather conditions during the field experiment were those typical of a Mediterranean climate. Totals of 94 mm and 50.4 mm of rainfall were recorded before sowing (January to April 2021) and from sowing to the first harvest (April to September 2021), respectively. The cumulative rainfall from September to December 2021 was 630 mm. In the same year, the total ET_0 was 1019 mm, with an average of 3.8 mm day^{-1}, and the average temperatures were 26.2 °C (T max), 15.5 °C (T min), and 20.7 °C (T mean). During the second growing season (January–July 2022), the rainfall was 115 mm and the ET_0 was

680 mm, with an average of 3.5 mm per day. In the same year, the annual average temperatures were 21.8 °C (T max), 10.7 °C (T min), and 16.3 °C (T mean) (Figure 1).

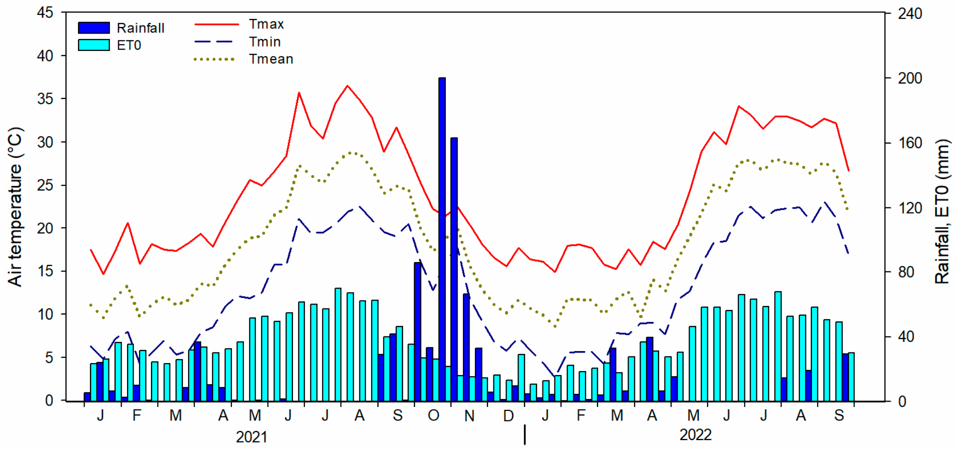

Figure 1. Meteorological course (air temperature, rainfall, and reference evapotranspiration–ET_0) recorded during the 2-year period (2021–2022) at the experimental farm of the University of Catania, Italy (10 m a.s.l., 37°25′ N lat., 15°03′ E long.).

2.3. Oil Extraction

The seeds were grinded to be subjected to oil extraction using a GM200 blade mill (Retsch GmbH, Haan, Germany). The oil content was determined according to the Randall method through the use of a quantitative solvent extractor SER 148/6 (Velp Scientifica, Usmate, Italy) [25]. Extraction was performed via immersion of the cellulose thimble containing 3 g of the sample in a boiling n-hexane solvent, followed by a rinsing phase and a recovery phase. Extraction vessels were placed in an oven at 100 °C for 30′ to eliminate any solvent residues. The analyses were performed in triplicate.

2.4. Statistical Analysis

Data on the length of phenological stages, morphological traits, seed and oil yields, and components were subjected to statistical analysis by performing the repeated measure ANOVA according to the experimental design with irrigation, fertilization, and harvested raceme type as the fixed effect and replicates as the random effect. Before conducting the ANOVA, Bartlett's test was run to verify the assumption of homogeneity of variances. LSD's post-hoc test was used for mean separation at $p \leq 0.05$. The data were statistically analyzed using CoHort Software (CoStat version 6.003, Monterey, CA, USA).

3. Results

3.1. Length of Phenological Stages

Seedling emergence occurred 15–17 days after sowing. The ANOVA showed a significant effect of irrigation and N fertilization on the time intervals of emergence–anthesis (E-A) and anthesis–seed physiological maturation of the primary racemes (A-M1). Across N levels, plants in I100 flowered first (about 68 days after sowing), while those in I0 flowered last (117 days after sowing). Anthesis started 91 and 79 days after sowing in I30 and I60, respectively. The physiological maturation of the primary racemes was completed 145 days after sowing in I100 and 219 days after sowing in I0. In I30 and I60, the plants ripened in 188 and 163 days, respectively. The length of the interval between the physiological maturation of the primary racemes and that of the secondary racemes (M1–M2) significantly changed with the level of irrigation. Secondary racemes completed maturation 25, 34, 36, and 38 days after the primary racemes in I100, I60, I30, and I0, respectively (Figure 2).

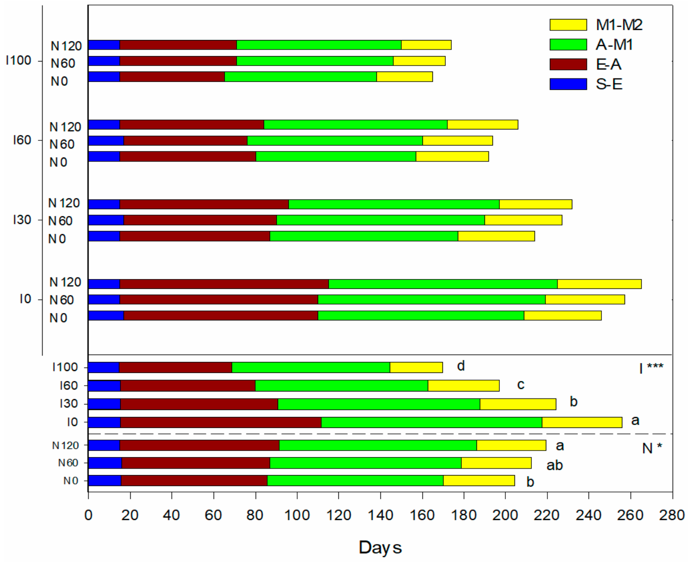

Figure 2. Length of phenological stages in castor (sowing–emergence (S-E), emergence–anthesis (E-A), anthesis–physiological maturation of the primary racemes (A-M1), and maturation of the primary racemes–maturation of secondary racemes (M1–M2)) in relation to irrigation (I0, I30, I60, and I100% = 0, 30, 60, 100% ETm restoration, respectively) and N fertilization (N0, N60, and N120 = 0, 60, and 120 kg ha^{-1} of N, respectively). The lower part shows the mean separation of the total phenological stage length, with different letters representing statistically significant means according to the LSD test ($p \leq 0.05$). The significance levels of ANOVA for irrigation (*** significant at $p \leq 0.001$) and N fertilization (* significant at $p \leq 0.05$) are shown. The interaction I × N is not significant.

Across the irrigation levels, the higher N supply (N120) led to longer phenological stages, which sped up the physiological maturation of primary and secondary racemes in comparison to that with the N0 treatment. Therefore, low levels of soil water availability led to delayed anthesis and seed ripening, as well as an increased nitrogen supply.

3.2. Morphological Traits, Yield, and Yield Components

Most of the productive traits, such as the number of capsules per raceme, the seed yield, and the seed weight, were significantly affected by the studied factors. The effects of the different irrigation and nitrogen levels on these traits are reported in Tables 1–4. The ANOVA results for productive traits are shown in Table 5.

Table 1. Number of secondary racemes in relation to irrigation (I0, I30, I60, and I00 = 0, 30, 60, and 100% ETm, respectively) and N level (N0, N60, and N120 = 0, 60, and 120 kg ha^{-1} N) of secondary racemes in 2021 and 2022 (T2 and T3, respectively). In the mean columns, the average values of all N levels (last row) and the average values of all irrigation levels (last column) followed by the same letter did not significantly differ at $p \leq 0.05$.

Number of Secondary Racemes										
	N0		**N60**		**N120**		**Mean**			
	T2	T3	T2	T3	T2	T3	N0	N60	N120	
I0	2.0	4.2	2.5	5.5	1.01	8.4	3.1	4.0	4.7	3.9 c
I30	2.0	10.7	1.5	8.5	2.0	6.0	6.4	5.0	4.0	5.1 b
I60	1.4	8.8	2.0	7.8	2.0	9.8	5.1	4.9	5.9	5.3 b
I100	3.5	9.3	2.5	10.3	4	11.8	6.4	6.4	7.9	6.9 a
Mean	2.2	8.3	2.1	8.0	2.3	9.0	5.2 b	5.1 b	5.6 a	5.3

Table 2. Number of capsules in relation to irrigation (I0, I30, I60, and I00 = 0, 30, 60, and 100% ETm, respectively) and N level (N0, N60, and N120 = 0, 60, and 120 kg ha^{-1} N) of primary and secondary racemes in 2021 and secondary racemes in 2022 (T1, T2, and T3). In the mean columns, the average values of all N levels (last row) and the average values of all irrigation levels (last column) followed by the same letter did not significantly differ at $p \leq 0.05$.

Number of Capsules													
	N0			**N60**			**N120**			**Mean**			
	T1	T2	T3	T1	T2	T3	T1	T2	T3	N0	N60	N120	
I0	21.0	29.0	10.0	45.0	32.0	27.0	36.0	36.0	22.0	20.0	34.7	31.3	28.7 b
I30	24.2	32.5	17.0	34.0	43.5	18.0	31.0	35.5	16.0	24.6	31.8	27.5	28.0 b
I60	26.0	25.5	20.0	30.0	36.0	21.0	29.5	47.0	23.0	23.8	29.0	33.2	28.7 b
I100	59.0	32.0	22.0	43.3	41.0	27.0	66.2	38.0	30.0	37.7	37.1	44.7	39.8 a
Mean	32.6	29.8	17.3	38.1	38.1	23.3	40.7	39.1	22.8	26.5 b	33.2 a	34.2 a	31.3

Table 3. Seed weight (g) in relation to irrigation (I0, I30, I60, and I00 = 0, 30, 60, and 100% ETm, respectively) and N level (N0, N60, and N120 = 0, 60, and 120 kg ha^{-1} N) of primary and secondary racemes in 2021 and secondary racemes in 2022 (T1, T2, and T3). In the mean columns, the average values of all N levels (last row) and the average values of all irrigation levels (last column) followed by the same letter did not significantly differ at $p \leq 0.05$.

Seed Weight (g)													
	N0			**N60**			**N120**			**Mean**			
	T1	T2	T3	T1	T2	T3	T1	T2	T3	N0	N60	N120	
I0	0.32	0.36	0.27	0.34	0.4	0.28	0.48	0.41	0.38	0.32	0.34	0.42	0.36 b
I30	0.24	0.38	0.29	0.42	0.37	0.35	0.44	0.4	0.36	0.30	0.38	0.40	0.36 b
I60	0.46	0.49	0.43	0.44	0.55	0.39	0.4	0.27	0.38	0.46	0.46	0.35	0.42 a
I100	0.23	0.39	0.32	0.31	0.58	0.33	0.35	0.42	0.43	0.31	0.41	0.40	0.37 b
Mean	0.31	0.41	0.33	0.38	0.48	0.34	0.42	0.38	0.39	0.35 b	0.40 a	0.39 a	0.38

Table 4. Oil content (%) in seeds of the primary and secondary racemes in relation to irrigation (I0, I30, I60, and I00 = 0, 30, 60, and 100% ETm, respectively) and N level (N0, N60, and N120 = 0, 60, and 120 kg ha^{-1} N) of primary and secondary racemes in 2021 and secondary racemes in 2022 (T1, T2, and T3). In the mean columns, the average values of all N levels (last row) and the average values of all irrigation levels (last column) followed by the same letter did not significantly differ at $p \leq 0.05$.

Oil Content (%)													
	N0			**N60**			**N120**			**Mean**			
	T1	T2	T3	T1	T2	T3	T1	T2	T3	N0	N60	N120	
I0	30.4	29.6	50.6	44	38.9	46.5	40.6	40.3	48.4	36.9	43.1	43.1	41.0 a
I30	35.2	37.2	46.2	42.1	37.1	45.8	44	38.3	43.6	39.5	41.7	42.0	41.1 a
I60	45.3	36.5	44.2	47.2	39.8	46.5	44	30.8	43.1	42.0	44.5	39.3	41.9 a
I100	35.8	45.3	43.6	37.8	46.3	46.1	34.5	41.8	42.4	41.6	43.4	39.6	41.5 a
Mean	36.7	37.2	46.2	42.8	40.5	46.2	40.8	37.8	44.4	40.0 b	43.2 a	41.0 b	41.4

The number of secondary racemes was significantly affected by irrigation and N fertilization levels. In both years, more secondary racemes were measured in plants under full irrigation (I100) and in those fertilized with the highest rate of N (N120), up to 11.8 in I100N120 in 2022. In 2021, increasing N levels induced a delay in the secondary raceme development, and as a consequence, there was a lower number of harvested racemes. In 2022, the increasing N rate was beneficial to this trait only in I0 and, to a lesser extent, in I100 (Table 1).

Table 5. ANOVA results of productive traits (I = irrigation, N = fertilization, and T = harvested raceme type).

Source of Variance	Number of Racemes	Number of Capsules	Seed Weight (g)	Seed Yield (kg ha^{-1})	Oil Content (%)	Oil Yield (kg ha^{-1})
I	***	***	***	***		***
N	****	***	**	***	**	***
T	***	***		***	***	***
I × N	***	**	***	***	*	ns
I × T	***	***	*	***	**	***
N × T	***	ns	ns	***	*	***
I × N × T	***	ns	ns	**	ns	*

*, **, *** Significant at $p \leq 0.05$, $p \leq 0.01$, and $p \leq 0.001$, respectively; ns: not significant.

The statistical analysis of the number of capsules showed a significant effect caused by the maximum irrigation level and the N fertilization applied (N60 and N120).

In 2021, the number of capsules on the primary racemes was affected by the level of water supply and N applied. Increasing N had a greater effect under I0 and I100; as a result, plants in I0N0 and I100N120 had the lowest (21.0) and the highest (66.2) number of capsules per raceme, respectively. The number of capsules on the secondary racemes in 2021 was affected by the level of N and I applied. The I60N0 and I60N120 treatments resulted in the lowest (25.5) and the highest (47.0) number of capsules per raceme, respectively.

In 2022, the number of capsules on the secondary racemes being quite lower than that measured in 2021 was observed. The effect of increasing the N level was evident in I100 and I60, but not in I30 and I0. In this year, the maximum (30) and minimum (10) number of capsules were measured in I100N120 and I0N0, respectively (Table 2).

The seed weight was significantly and positively affected by the increasing level of N fertilization; irrigation significantly affected the seed weight, with the highest seed weight value observed in the I60 treatment.

The seed weight measured based on the primary racemes in 2021 ranged between 0.23 g (I100N0) and 0.48 g (I0N120).

The seed weight in the secondary racemes was slightly higher than that measured in the primary racemes and ranged between 0.27 g (I60N120) and 0.58 g (I100N60) in 2021 and 0.27 g (I0N0) and 0.43 g (I60N0 and I100N120) in 2022 (Table 3).

Both experimental factors significantly affected seed yield ($p \leq 0.001$), as the total of the two years and all racemes (primary and secondary) progressively increased with the increase in soil water availability and the N fertilization rate. As a result, the seed yield was at its minimum in I0N0 (641.1 kg ha^{-1}) and at its maximum in I100N120 (4154.0 kg ha^{-1}) (Figure 3). The two experimental factors significantly interacted with crop productivity ($p \leq 0.001$).

Indeed, while under no irrigation, the beneficial effect of N fertilizer on seed yield was the same irrespective of the N level (60 or 120 kg ha^{-1}); thus, no further yield increase occurred in N120, and with respect to N60, in all of the irrigation treatments (from I30 to I100), the promoting effect of N was progressive from 0 to 120 kg ha^{-1}.

Indeed, while under no irrigation, the beneficial effect of N fertilizer on seed yield was the same irrespective of the N level (60 or 120 kg ha^{-1}); thus, no further yield increase occurred in N120, and with respect to N60, in all of the irrigation treatments (from I30 to I100), the promoting effect of N was progressive from 0 to 120 kg ha^{-1}.

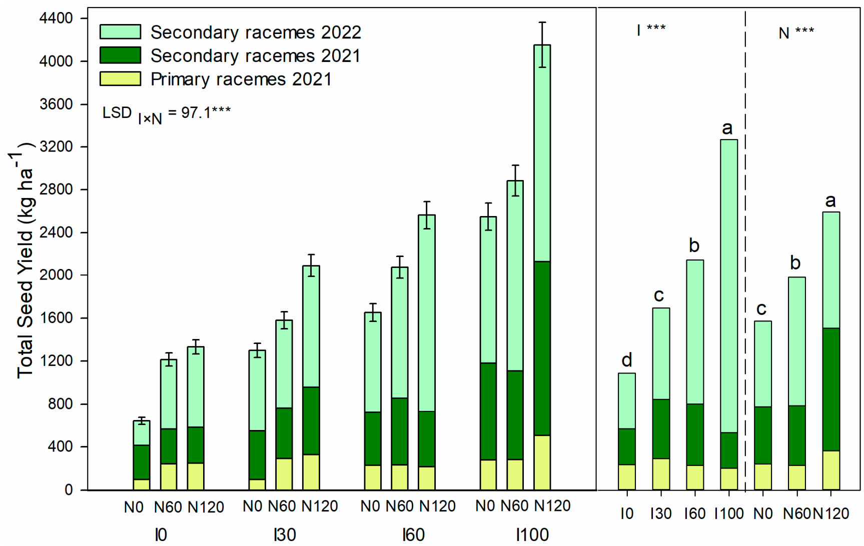

Figure 3. On the left, the total seed yield (kg ha^{-1}) (primary and secondary racemes from 2021 and 2022) in relation to irrigation (I0, I30, I60, and I00 = 0, 30, 60, and 100% ETm, respectively) and N fertilization (N0, N60, and N120 = 0, 60, and 120 kg ha^{-1} N) with error bars indicating the standard error. On the right, there is the mean separation of the total seed yield, with different letters representing statistically significant means according to the LSD test ($p \leq 0.05$). The significance levels of the ANOVA for irrigation and N fertilization (*** significant at $p \leq 0.001$) and the significant interaction ($LSD_{I \times N}$ at $p \leq 0.05$) are shown.

The seed yield of the primary raceme peaked in I100N120 (506.6 kg ha^{-1}). The lowest yield corresponded to I30N0 (95.6 kg ha^{-1}). The seed yield of the secondary racemes was 313.1 kg ha^{-1} in I0N0 and 1623.8 kg ha^{-1} in I100N120. In the second season, 2023.6 and 230.5 kg ha^{-1} were achieved under the most (I100N120) and least (I0N0) favorable soil conditions, respectively. The relative contribution of the primary and secondary racemes slightly changed within the different $I \times N$ combinations. Overall, the secondary racemes produced in the second year contributed to a greater extent to the total seed yield in comparison to the primary and secondary racemes produced in the first year. The yield increase with increasing irrigation and N fertilization levels was the result of an increased number of secondary racemes and an increased number of capsules per raceme (correlation coefficients of 0.97 and 0.82, respectively). No correlation was found between the total seed yield and the seed weight.

3.3. Oil Content and Oil Yield

No effect of irrigation was highlighted by the ANOVA. In contrast, oil content was affected by N fertilization.

In the primary raceme, the maximum content was registered in I60N60 (47.2%) and minimum content was registered in I0N0 (30.4%). In the secondary racemes, the oil content ranged between 29.6% (I0N0) and 46.3% (I100N60). In the second year, the oil content, which was slightly higher than that measured in 2021, ranged from 42.4% (I100N120) to 50.6% (I0N0).

The $I \times N$ treatments were ranked for oil yield according to their seed yield. As a result, the plants of I100 were the most productive in terms of oil yield, despite their lower seed oil content, with the maximum oil yield being achieved in I100N120 in 2021 (853.3 kg ha^{-1}) and 2022 (858.2 kg ha^{-1}) (Figure 4). I0 and I30 treatments produced the lowest oil yields, despite their high seed oil content.

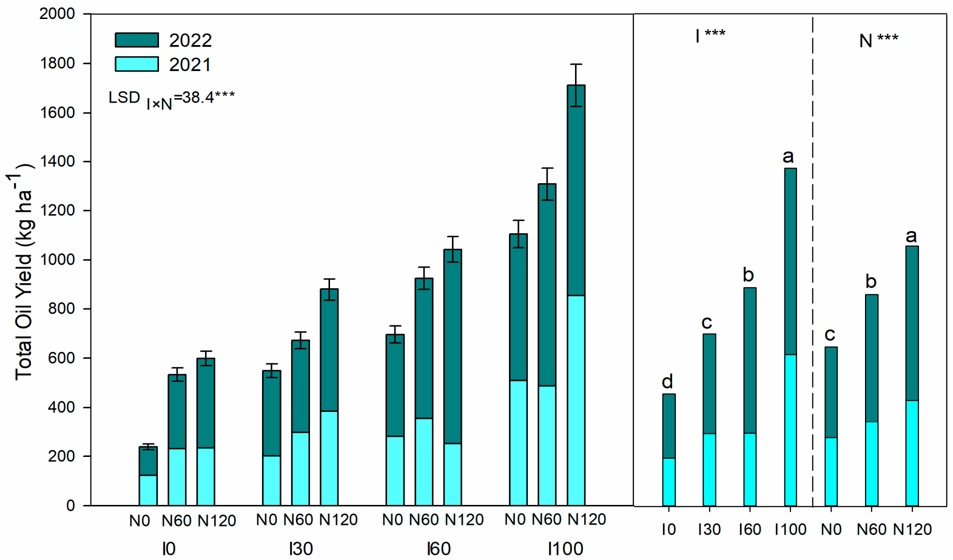

Figure 4. On the left, the total oil yield (kg ha^{-1}) of the two years (2021 and 2022) in relation to irrigation (I0, I30, I60, and I00 = 0, 30, 60, and 100% ETm, respectively) and N fertilization (N0, N60, and N120 = 0, 60, and 120 kg ha^{-1} N), with error bars indicating the standard error. On the right, there is the mean separation of the total oil yield, with different letters representing statistically significant means according to the LSD test ($p \leq 0.05$). The significance levels of the ANOVA for irrigation and N fertilization (*** significant at $p \leq 0.001$) and a significant interaction ($LSD_{I \times N}$ at $p \leq 0.05$) are shown.

3.4. Water Use Efficiency

Water use efficiency was calculated by dividing the seed yield (kg ha^{-1}), as the total amount of primary and secondary racemes obtained in the two years, by the crop water use (mm), considering the total amount of water used in the two years. The crop used the water more efficiently at high N levels and at low irrigation levels. Indeed, WUE was significantly and progressively improved with the increase in the N fertilization rate from 0.55 (N0) to 0.96 kg ha^{-1} mm (N120) (Table 6). As expected, WUE was maximized under no irrigation (1.03 kg ha^{-1} mm), with it progressively declining with irrigation, down to 0.61 kg ha^{-1} mm (I60). No further decrease in WUE occurred when the irrigation rate was increased from 60 to 100% ETm (0.66 kg ha^{-1} mm).

Table 6. Water use efficiency in relation to irrigation (I0, I30, I60, and I00 = 0, 30, 60, and 100% ETm, respectively) and N level (N0, N60, and N120 = 0, 60, and 120 kg ha^{-1} N) (year 2022). The average values of all N levels (last column) and the average values of all irrigation levels (last row) followed by the same letter did not significantly differ at $p \leq 0.05$.

	Water Use Efficiency—WUE (kg ha^{-1} mm^{-1})					
	I0	**I30**	**I60**	**I100**	**Mean**	**Significance**
N0	0.62	0.58	0.48	0.52	0.55 c	I ***
N60	1.18	0.70	0.60	0.59	0.77 b	N ***
N120	1.29	0.93	0.74	0.86	0.96 a	I × N ***
Mean	1.03 a	0.74 b	0.61 d	0.66 c		LSD I × N = 0.04

*** Significant at $p \leq 0.001$.

The significant interaction I × N was related to the lack of significant differences between I60 and I100 in the N60 treatment. However, the least variability between the highest and the lowest value was observed in the N0 treatment (22%) as compared to that in the N60 and N120 treatments (49% and 43%, respectively).

3.5. Photosynthesis and Transpiration Rates

Photosynthesis and transpiration rates were measured from June to August in the first year (2021). N fertilization did not seem to affect photosynthesis. Indeed, it did not change with the N level, with the values keeping constant along the growing season (Figure 5C). In contrast, in relation to irrigation, a tendency for photosynthesis to increase with time was observed in the plants that were well watered (I100) (Figure 5A). Interestingly, photosynthesis under moderate-deficit irrigation (I60) did not fluctuate much, whilst under moderate stress conditions (I30), it was kept constant but tended to decrease in the last measurement (the August of that year). Under no irrigation (I0), photosynthesis progressively declined from late June onwards. A similar response to N fertilization and irrigation levels was observed in leaf transpiration. This was last observed in late July, when the plants undergoing the latest treatment (those not irrigated) were approximately at the maximum growth period (Figure 5B,D). Afterward, leaf transpiration steeply declined to the initial level and remained more or less constant until late August. Overall, plants in I0 transpired less than those that were irrigated.

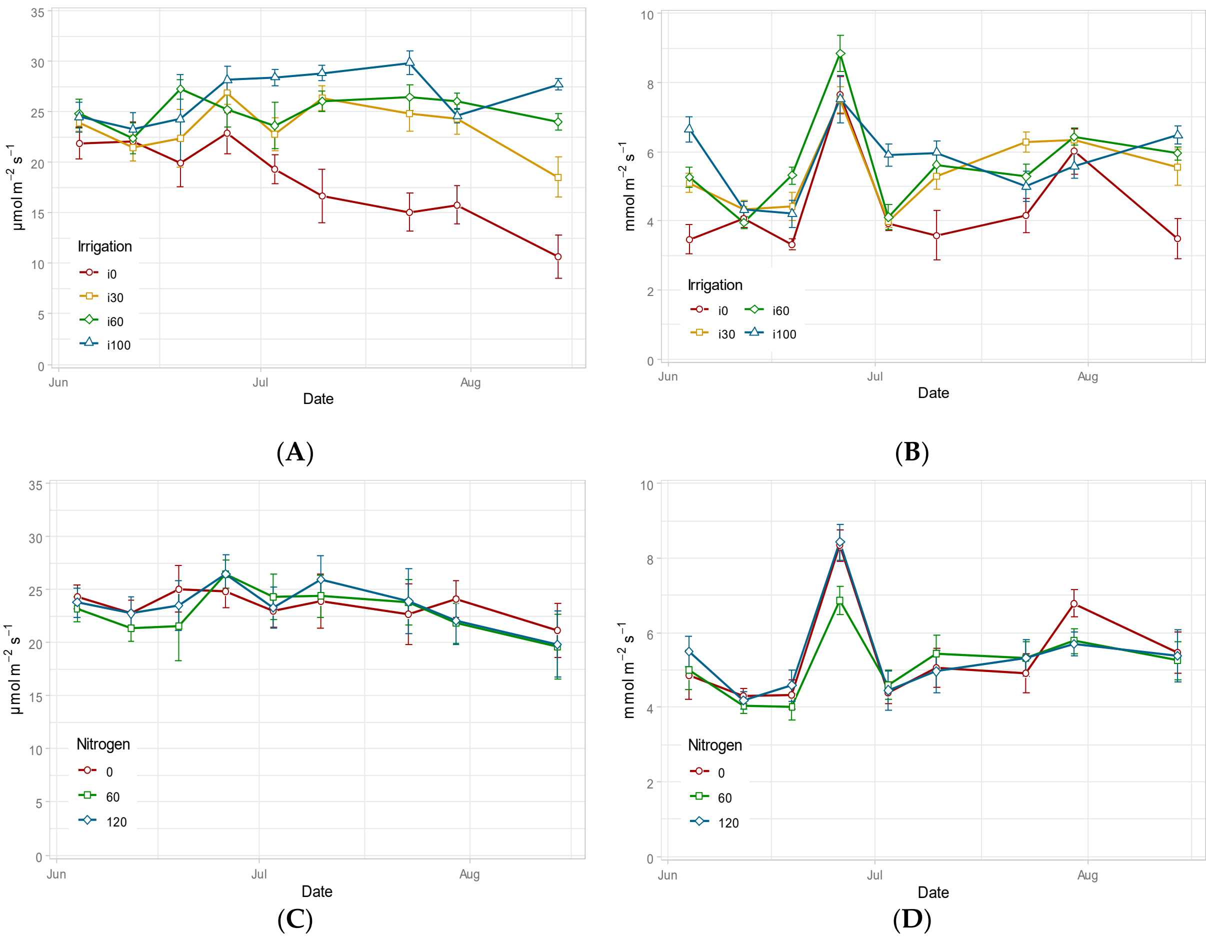

Figure 5. (**A**) Net photosynthesis (µmol CO_2 m^{-2} s^{-1}) according to the irrigation level and (**C**) nitrogen fertilization levels. (**B**) Transpiration rate (mmol H_2O m^{-2} s^{-1}) according to the irrigation level and (**D**) nitrogen fertilization levels.

4. Discussion

Irrigation was found to reduce the length of the plant life cycle, with it influencing the length of the phenological stages. Low levels of soil water availability induced a delay in anthesis and consequently seed ripening, as well as an increase in nitrogen supply.

The physiological maturation of the primary raceme was completed 219 days after sowing in plants in unirrigated plots (those of I0), while the plants that were fully watered (those of I100) reached maturity in only 145 days. These results matched those of Patanè et al. [20], who reported 240 days (with sowing in November) to 99 days (with sowing in May) occurring from sowing to maturity in castor cultivated in the coastal areas of Sicily.

The number of racemes per plant, the number of capsules per raceme, and the seed weight are the main traits that are investigated in castor breeding programs, since several studies have reported a positive correlation between these traits and the final seed yield [26,27]. The yield components were influenced by irrigation in a different way. In the first year, I0 and I30 had fewer racemes per plant, a lower number of capsules per raceme, and a low seed weight. From I60 to I100, the number of racemes per plant increased from 1.8 to 3.3 and the number of capsules per primary raceme increased from 28.5 to 56.2. Data from the second year confirmed a low number of secondary racemes and capsules per raceme and a low seed weight in I0 and I30. For the I60 to I100 treatment, the number of secondary racemes increased from 8.75 to 10.5 and the number of capsules per raceme increased from 21.3 to 26.3.

Irrigation is the main factor influencing seed yield. In fact, the data showed that the maximum number of capsules per plant (66.2 and 30.0 in the first and second years, respectively) was obtained in I100N120. Moreover, higher soil water availability induced a higher photosynthesis rate and consequently higher seed production. Nitrogen fertilization had a positive effect on the seed yield in the primary racemes but induced a delay in the development of the secondary racemes, thus causing a reduction in the mean seed yield for the secondary racemes. The average seed yield (1270.5 kg ha^{-1}) was within the range reported by Anastasi et al. [22] for Sicilian genotypes of castor. The contribution of primary and secondary racemes to the total yield was not the same in relation to nitrogen and water availability. On average, the contribution to the yield of the primary racemes was 30% and that of the secondary ones was 70%, according to a study by Severino et al. [28].

Irrigation and N fertilization influenced the number of secondary racemes per plant. High levels of water availability promoted the development of secondary racemes. High soil nitrogen levels combined with low water availability extended vegetative growth, delaying the formation of secondary racemes. In addition, in the second year, a significant increase in seed yield was obtained by increasing the water supply. The highest seed yield was obtained by I100N120 (2023.6 kg ha^{-1}) and the lowest seed yield was obtained by I0N0 (230.5 kg ha^{-1}). Regarding the average of nitrogen fertilization levels, the total seed yield decreased by 34.4%, 48.2%, and 66.8% with reductions in the water supply of 40%, 70%, and 100%, respectively, thus showing a non-proportional decrease in yield compared to the decrease in the water supply.

Indeed, this is highlighted by the increase in water use efficiency in the less irrigated treatments. Koutroubas et al. [29] reported that the seed yield of irrigated castor was significantly higher than that of the unirrigated control and concluded that irrigating castor with an equivalent amount of water between 75 and 100% of evapotranspiration was adequate to obtain a higher economic yield in the Mediterranean climate. Similar results were reported by Laureti and Marras [16]. The effect of nitrogen fertilization on total seed yield was less marked in the I0 and I30 treatments as compared to that in the treatments with higher water availability, which reached the highest seed yield. Indeed, the highest soil nitrogen content (N120) combined with high water availability (I60 and I100 treatments) was advantageous for castor productivity in terms of the number of racemes per plant, the number of capsules per raceme, and the seed weight. Regarding the average of the irrigation levels, the total seed yield was decreased by 23.5% when reducing the nitrogen fertilizer by 50% (N60) and by 39.4% without nitrogen fertilization (N0).

This result can also be ascribed to the soil nitrogen reserve. The contribution of each component to the final seed yield was not stable across the years. The highest yields for all I100 treatments in the first year were due to the higher number of capsules per raceme and the higher seed weight as compared to those with the other treatments. In the second year, despite the low seed weight, the higher number of racemes per plant determined an increase in the seed yield for all treatments. Arnaud [13] reported that the highest yield obtained by an irrigation supply was determined by an increased number of racemes and capsules per plant but not by the higher seed weight. Oil content is dependent on the genotype, environmental conditions, and their interactions [30] but is not influenced by N fertilization, irrigation, planting time, or plant spacing [27,31–34]. Oil content in castor seeds is a trait with high heritability [35].

The oil content obtained in this study was in line with that reported by Anastasi et al. [27] and Laureti et al. [36] in castor cultivated in Mediterranean environments. Seed oil content had a marginal influence on the oil yield, because it varied in a narrow range.

According to Koutroubas et al. [16], higher seed yields are usually obtained at the expense of the oil content, and there is a negative correlation between these two variables. In some studies, seed oil content has often been found to increase in late-maturing racemes [37,38]. Many irrigation-based studies on castor have revealed that the oil content of seeds is not significantly affected by different irrigation regimes. However, the oil yield increased with the maximum irrigation [39], since oil yield mainly depends on the number of racemes per plant and on seed weight.

As reported by Weiss [3], N fertilization seems to have a minor effect on the seed oil content. Some studies revealed that, as nitrogen application is increased, the percentage of oil decreases [40,41]. Higher soil water availability induced higher photosynthesis and transpiration rates, with consequential higher seed production. The soil nitrogen availability did not affect either photosynthesis or the transpiration rate.

As far as water use efficiency is concerned, the results from the present study are in agreement with several researchers who have reported that water use efficiency is generally higher under dry, rather than well-water, conditions [42–44].

5. Conclusions

Castor can grow as a semi-perennial plant in Mediterranean environments, with the growing season extending to a second year. In this way, the crop may benefit from a suitable rainfall regime in autumn–winter, thus reducing its irrigation requirements. The results obtained in both years revealed that seed yield in castor is strongly depressed under severe water-stress conditions (no irrigation or minimum irrigation, e.g., 30% ETm restoration), while under a moderate water deficit (e.g., irrigation at a 60% rate), it may achieve adequate levels. Of course, yield can be maximized with full irrigation (100% Etm restoration), when the availability of water for irrigation does not represent a limiting factor.

Irrigation is the main factor that influences the number of racemes per plant, the number of capsules per raceme, and the seed weight. A high soil nitrogen content combined with high water availability (the I60 and I100 treatments) was advantageous for castor seeds and the oil yield.

The availability of irrigation water in semi-arid environments represents a rising problem in castor cultivation. Considering the results of this study, the highest seed and oil yields were obtained with the maximum irrigation and N fertilization levels. However, a reduction in inputs to intermediate levels could be considered as an environmentally friendly strategy with minimal yield losses.

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