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Interactive Effects of Nitrogen and Iron Fertilization on Canola (*Brassica napus* L.) Productivity and Oil Quality Under Arid Conditions: A Maximum Yield Threshold Approach

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Abstract

Excessive nitrogen (N) fertilization poses environmental risks and can induce micronutrient imbalances that limit crop productivity. This two-season field study (2024/2025–2025/2026) investigated the interactive effects of four nitrogen (N) rates (0, 75, 150, and 225 kg N ha^{-1}) and four foliar iron (Fe) concentrations (0, 100, 200, and 300 mg L^{-1}) on Canola (*Brassica napus* L.) yield and oil quality under the arid conditions of Upper Egypt. The highest N rate (225 kg N ha^{-1}) increased seed yield by 240% and oil yield by 271% compared to the unfertilized control, but substantially reduced Nitrogen Use Efficiency (NUE), with Partial Factor Productivity of Nitrogen (PFPN) declining from 52.5 to 11.2 kg seed kg^{-1} N. Foliar Fe at 300 mg L^{-1} enhanced seed yield by an additional 29.9–37.0%. The combined N_3Fe_3 treatment produced maximum biological (8258 kg ha^{-1}), seed (2892 kg ha^{-1}), and oil (812 kg ha^{-1}) yields, establishing a maximum yield threshold under the tested conditions. However, at the highest N rate, there were no statistically significant differences in oil yield among Fe_1 (100 mg L^{-1}), Fe_2 (200 mg L^{-1}), and Fe_3 (300 mg L^{-1}), indicating that the lowest tested Fe concentration was sufficient to achieve yields comparable to higher rates. The N × Fe interaction was characterized as additive for seed yield but synergistic for leaf iron uptake and translocation. While integrated N-Fe fertilization offers a promising strategy for sustaining Canola productivity in nutrient-poor calcareous soils, the declining N use efficiency at higher N rates and the absence of economic and environmental indicators (nitrate leaching, nitrous oxide (N_2O) emissions) highlight the need for further research to identify true optima for arid-zone Canola production.

Keywords: nitrogen fertilization; iron (Fe) supplementation; nutrient interaction; crop productivity; sustainable fertilization; arid conditions

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1. Introduction

Egypt is enduring a severe edible oil shortage, with a 92% shortage gap between total domestic production and imports [1]. Due to intense competition from other critical winter-season crops on the small arable land, the cultivated area of oil crops in Egypt is limited [2]. Canola (*Brassica napus* L.) is one of the most important oilseed crops globally, with its seeds containing between 40% and 45% oil [3]. To achieve high yields and excellent seed quality, the crop relies primarily on fertilization management, especially nitrogen and iron, due to their crucial physiological roles [4].

Nitrogen (N) is unequivocally an indispensable macronutrient and a primary limiting factor in Canola (*Brassica napus* L.) production across diverse agro-ecological zones [5]. Its critical role stems from its fundamental involvement in chlorophyll biosynthesis, photosynthetic efficiency, and enzymatic regulation, all of which collectively drive canopy development and carbon assimilation [6]. Appropriate N fertilization substantially improves Canola productivity by stimulating vigorous vegetative growth and enhancing key yield-determining components; these include accelerated stem elongation, increased number of flowering branches, greater total plant biomass accumulation, higher pod number per plant, improved seed set per pod, enhanced individual pod weight, and consequently, superior seed yield per plant [7,8]. In essence, adequate N supply ensures that the source–sink dynamics remain optimized throughout the critical reproductive stages, thereby maximizing harvestable yield [9].

However, despite these well-documented agronomic benefits, caution must be exercised regarding N application rates, as excessive fertilization triggers a series of physiological and biochemical shifts that can compromise seed quality [10]. Specifically, supra-optimal N supply tends to redirect assimilates toward protein synthesis at the expense of oil accumulation, thereby increasing seed protein concentration while concurrently reducing oil content [11]. This inverse relationship between protein and oil percentages represents a classic nutritional trade-off, driven by the competition for photosynthetic products and the differential regulation of nitrogen assimilation versus lipid biosynthesis pathways [12]. Moreover, over-application of N is not merely a quality concern but also an environmental and stress-related issue; it predisposes plants to lodging, enhances susceptibility to certain pests and diseases, delays maturity, and contributes to nitrate leaching and greenhouse gas emissions [13]. From the perspective of plant stress research, suboptimal or excessive N availability both constitute forms of abiotic stress, triggering oxidative damage, hormonal imbalances, and impaired nutrient uptake efficiency. Fine-tuning N fertilization strategies, potentially through co-application with micronutrients such as iron, may therefore be essential for achieving high-yielding, high-quality Canola while mitigating physiological stress [14].

Micronutrients, though required in trace amounts, are equally indispensable for optimal crop performance, and among them, iron (Fe) stands out as critically important. Iron functions as an essential cofactor in numerous plant enzyme systems, including those involved in respiration, nitrogen assimilation, and antioxidant defense [15]. Its most well-documented role lies in chlorophyll biosynthesis and the photosynthetic electron transport chain, where it facilitates the transfer of electrons and thereby directly influences the efficiency of light energy conversion into chemical energy [16]. Beyond photosynthesis, adequate iron supply contributes to enhanced vegetative growth by promoting cell division and expansion, and it also increases the efficiency of absorption and utilization of other essential nutrients, particularly nitrogen, phosphorus, and zinc. This synergistic relationship underscores the interdependence of macro- and micronutrients in governing overall plant metabolism and productivity [17].

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The delicate balance between supplying the crop with its substantial nitrogen requirements necessary for vigorous vegetative development and ensuring sufficient iron availability is therefore paramount. When this balance is achieved, the benefits extend beyond mere yield increments; it guarantees not only increased seed production but also the preservation of extracted oil quality, including fatty acid profile and oxidative stability, as well as the nutritional value of the oil for human consumption [18]. Iron deficiency, on the other hand, often induced by excessive nitrogen application or calcareous soil conditions, can lead to chlorosis, reduced photosynthetic capacity, and impaired assimilate partitioning toward developing seeds, ultimately diminishing both quantitative and qualitative harvest outcomes [19].

The interactive effects of N and Fe have been studied in various contexts, including temperate and Mediterranean conditions [7,8,17]. However, their combined effects under the specific conditions of arid Upper Egypt characterized by sandy loam soils with low organic matter, high pH (7.51–7.84), and low available Fe (1.54–2.08 mg kg^{-1}) remain insufficiently characterized. This study therefore provides a regional validation of N-Fe interactions, testing whether previously established synergies hold true under these challenging conditions.

In Egypt, the cultivation of Canola (*Brassica napus* L.) has gained strategic importance as part of the national effort to reduce the country's severe edible oil deficit, which currently exceeds 1.25 million tons annually [20]. The Ministry of Agriculture and Soil Reclamation has proactively identified Canola as a pivotal crop to bolster self-sufficiency in oil production, prompting research into optimized agronomic practices [21]. Under Egyptian conditions, the recommended nitrogen fertilization rate for Canola typically ranges between 60 and 90 kg N per Fadden (approximately 150–225 kg N ha^{-1}), depending on soil type, irrigation method, and cultivar [22]. Nitrogen is commonly applied as urea (46% N) or ammonium nitrate (33.5% N), with split applications recommended to synchronize nutrient availability with crop demand [22]. Phosphorus fertilizer, applied as calcium superphosphate (15.5% P_2O_5), is typically incorporated during soil preparation at rates of 100–200 kg per Fadden (approximately 250–500 kg ha^{-1}), while potassium fertilization is provided as potassium sulfate (48% K_2O) at approximately 48 kg K_2O per Fadden (120 kg ha^{-1}) [23].

In Egypt numerous studies demonstrating significant yield increases with increasing N rates up to certain thresholds. For example, research conducted in sandy soils at Ismailia Agricultural Research Station showed that the combination of 60 kg N per Fadden with 250 kg S per Fadden maximized seed yield and yield components [24]. Similarly, field trials in the North Delta region evaluated nitrogen rates ranging from 15 to 60 kg N per Fadden (approximately 37.5–150 kg N ha^{-1}), revealing that higher N rates improved seed yield and quality under varying irrigation regimes [25]. More recent investigations in sandy soil environments at Zagazig University demonstrated that nitrogen levels of up to 120 kg N per Fadden (300 kg N ha^{-1}) significantly enhanced plant height, number of racemes, and overall productivity [22].

The standard fertilization regime commonly recommended by the Egyptian Ministry of Agriculture includes a basal application of phosphorus and potassium during soil preparation, followed by split applications of nitrogen fertilizer at 10, 20, 30, 40, and 50 days after sowing, with the total N rate typically adjusted based on soil testing and target yield [22]. Foliar application of micronutrients, including iron, zinc, and boron, has emerged as an effective strategy to address nutrient deficiencies in calcareous and sandy soils, where high pH conditions (7.5–8.0) limit the availability of these essential elements [26]. Recent research has confirmed that foliar application of iron at concentrations of 100–300 mg L^{-1} can significantly improve Canola growth and yield, particularly when combined with adequate nitrogen fertilization [27]. The integrated use of mineral fertilizers with bio-fertilizers and organic amendments has also been explored as a strategy to improve nutrient use efficiency and reduce environmental impacts [28].

Given the well-established physiological importance of both nitrogen and iron in plants, and the current gaps in understanding their interactive effects under field conditions, particularly in Canola this study hypothesized that increasing nitrogen application rates would progressively enhance Canola productivity, and that foliar iron supplementation would partially alleviate N-induced physiological stress, thereby further improving yield and oil quality. The current study was designed to systematically investigate the effects of varying nitrogen rates in combination with foliar iron concentrations on key agronomic parameters, including vegetative growth traits, final seed yield, and oil content of Canola plants grown under typical semi-arid field conditions. Despite the wealth of research on individual nutrient effects, the interactive effects of nitrogen and iron fertilization under the specific arid conditions of Upper Egypt remain inadequately characterized. This investigation aims to evaluate the agronomic potential of combined N and Fe fertilization for enhancing Canola productivity under the arid conditions of Upper Egypt, with a specific focus on quantifying yield responses, oil quality, and NUE across a range of treatment combinations. The study establishes a maximum yield threshold at the highest tested N and Fe rates, while explicitly acknowledging the trade-off between yield maximization and resource-use efficiency, as indicated by declining NUE at higher N rates. This work provides the agronomic foundation for future studies incorporating comprehensive environmental and economic assessments to identify truly balanced and sustainable fertilization strategies for oilseed crop production in arid environments.

2. Materials and Methods

2.1. Description of the Experimental Site

Two field experiments were conducted during the consecutive winter seasons of 2024/2025 and 2025/2026 at the experimental farm of the Agricultural Research Centre (ARC), Aswan Governorate, Egypt, situated at coordinates 22.372832° N, 31.601915° E (Figure 1).

Prior to planting each season, 110 random soil samples were collected from the surface layer at a depth of 0–30 cm across the experimental field to account for inherent spatial variability. The soil at the research site was characterized as sandy loam in texture according to the USDA textural triangle. Soil physical and chemical properties were analyzed following the standard methodologies described by Klute and Dinauer, 1987 [29] for physical parameters and Page et al., 1982 [30] for chemical attributes, with the results presented in Table 1. Total nitrogen was determined by the Kjeldahl digestion method; total iron by HF-$HClO_4$ digestion and atomic absorption spectrophotometry. The extremely low organic matter content is characteristic of recently cultivated, calcareous desert soils of the Toshka region. Despite high total Fe content, DTPA (diethylene triamine penta-acetic acid)-extractable Fe is very low due to high soil pH, indicating severe Fe deficiency risk for crops. The experimental location falls within an arid climatic zone, typified by hot, dry summers and extremely low annual precipitation (typically <5 mm year^{-1}), with rainfall events being rare and negligible for agricultural purposes, necessitating full irrigation dependency throughout the growing season. Average meteorological data for the two growing seasons, including solar radiation, temperature, wind speed, and relative humidity, are summarized in Table 2.

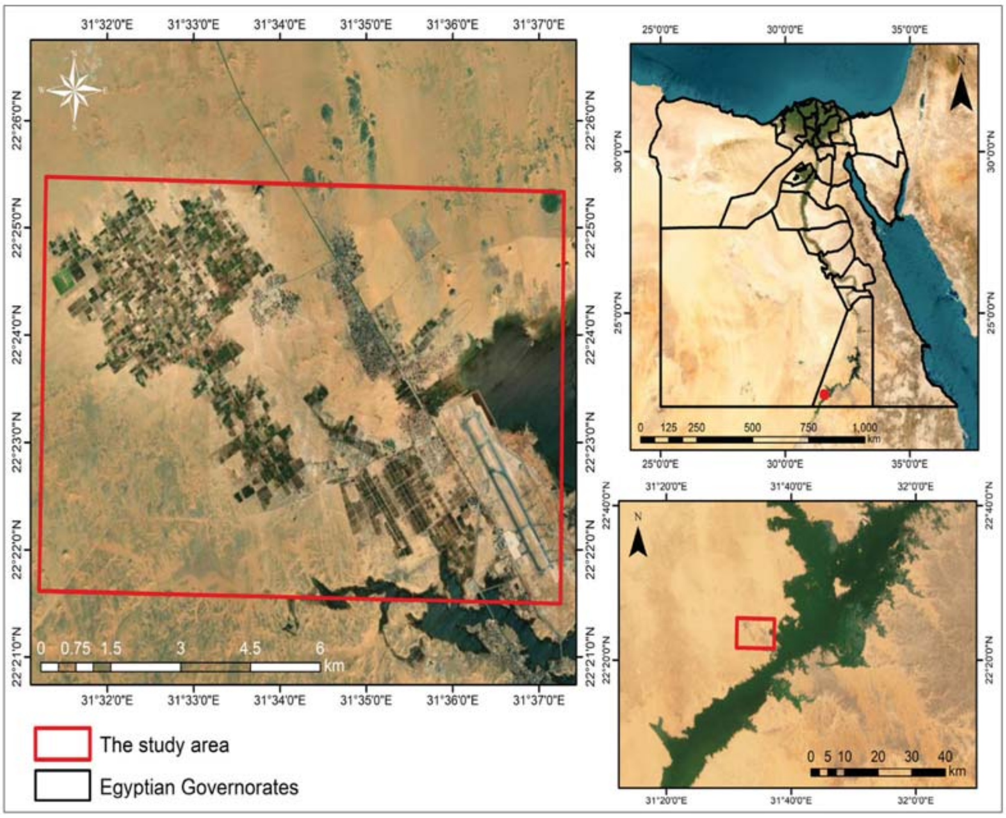

Figure 1. Location map of the study area (ArcGIS Pro® 3.5, https://doc.esri.com/en/arcgis-pro/latest/get-started/download-arcgis-pro.html (accessed on 30 May 2026).

Table 1. Some physical and chemical properties of studied soil before two successive growing seasons (2024/2025 and 2025/2026).

Studied Soil		
Properties	Before 1st season	Before 2nd season
Sand (g kg^{-1})	737 ± 12.4	783 ± 9.8
Silt (g kg^{-1})	74 ± 6.2	128 ± 8.5
Clay (g kg^{-1})	147 ± 5.1	131 ± 6.3
Texture	Sandy loam	Sandy loam
Soil reaction (pH)	7.84 ± 0.05	7.51 ± 0.06
Electrical conductivity (EC, dS m^{-1})	1.31 ± 0.08	1.69 ± 0.10
$CaCO_3$ (g kg kg^{-1})	2.74 ± 0.15	3.17 ± 0.18
Organic matter (g kg^{-1})	0.107 ± 0.01	0.13 ± 0.01
Total nitrogen (N-total, g kg^{-1})	0.0055 ± 0.001	0.0065 ± 0.001
Available–N (mg kg^{-1})	23.76 ± 2.41	30.14 ± 2.87
Available–P (mg kg^{-1})	46.93 ± 3.82	48.57 ± 3.56
Available–K (mg kg^{-1})	247 ± 18.4	276 ± 21.3
Total iron (Fe-total, g kg^{-1})	12.84 ± 1.02	11.36 ± 0.94
Available–Fe (mg kg^{-1})	2.08 ± 0.16	1.54 ± 0.12

Each value represents the mean ± standard deviation (SD) of three replicate analyses from 110 composite samples. The slight variations in soil properties between seasons reflect inherent spatial heterogeneity within the experimental field rather than actual textural changes. Both seasons' soils are classified as sandy loam (USDA textural triangle).

Table 2. Basic climatic data of the experimental site during the period of the study (November–April 2024/2025–2025/2026).

Month	T_{max} (°C)		T_{min} (°C)		T_{avg} (°C)		Relative Humidity (%)		Solar Radiation		Wind Speed (m s^{-1})	
	1st	2nd	1st	2nd	1st	2nd	1st	2nd	1st	2nd	1st	2nd
November	35.86	32.52	11.97	8.08	23.92	20.30	41.96	37.97	221	238	0.40	0.50
December	31.68	29.28	7.50	6.07	19.59	17.68	46.30	44.61	211	214	0.30	0.40
January	30.35	29.97	6.13	6.76	18.24	18.37	42.25	46.38	224	226	0.30	0.30
February	32.73	29.37	4.05	4.85	18.39	17.11	35.98	33.72	248	248	0.40	0.50
March	38.91	38.29	9.52	7.96	24.22	23.13	28.08	29.33	266	297	0.30	0.50
April	43.30	44.16	12.34	12.36	27.82	28.26	23.21	21.28	306	329	0.30	0.60

T_{max} = Temperature Maximum; T_{min} = Temperature Minimum; T_{avg} = Average Daily Temperature. All temperature values are in degrees Celsius (°C). Solar radiation is expressed in MJ m^{-2}. Wind speed is expressed in m s^{-1}.

2.2. Experimental Design and Treatment Application

The experiment was laid out in a split-plot design with three replicates (Figure 2). Main plot treatments were nitrogen (N) application with four nitrogen rates N0 = 0, N1 = 75, N2 = 150, and N3 = 225 kg N ha^{-1} using ammonium nitrate (33.5% N) as a source of nitrogen, while subplot treatments were Fe application at four rates F0 = 0, F1 = 100, F2 = 200, and F3 = 300 mg L^{-1} using Fe-EDTA chelates (13%Fe). The experimental area included 48 plots. Each plot measured 10 m^2 (2.5 m × 4 m). During soil preparation for planting, the applied rate of phosphorus fertilizer was 500 kg/ha of calcium superphosphate fertilizer (15.5% P_2O_5; equivalent to 77.5 kg P_2O_5 ha^{-1} or 33.8 kg P ha^{-1}), obtained from Abu Zaabal Fertilizer & Chemical Co., Abu Zaabal, Qalyubia Governorate, Egypt. Potassium fertilizer was applied at 125 kg/ha as potassium sulfate (48% K_2O; equivalent to 60 kg K_2O ha^{-1} or 49.8 kg K ha^{-1}), supplied by Evergrow Group, El-Sadat City, Shebin El-Kom, Menoufia Governorate, Egypt. Canola seeds were purchased from the ARC, Giza, Egypt. Canola seeds were sown on 10th November during the two growing winter seasons (2024/2025 and 2025/2026) at an amount of 10 kg ha^{-1} and were hand-sown in rows 50 cm apart and 30 cm between hills; two plants were left per hill. The crop was harvested approximately 160 days after sowing, on 20 April in both seasons, when the pods had reached full maturity (characterized by 80–90% pod senescence and seed moisture content of approximately 8–10%). The nitrogen fertilizer was split into five splits after 10, 20, 30, 40, and 50 days from sowing, while the iron fertilizer was sprinkled as a foliar application in two equal doses after 25 and 50 days from sowing. The drip irrigation method was used throughout the growing season. Irrigation water was applied based on reference evapotranspiration (ETo) calculated using the Penman-Monteith equation, with the total water requirements for the Canola growing season estimated at approximately 840 mm/season under Toshka conditions [31]. Irrigation scheduling followed the 100% water requirement treatment (2573 m^3/feddan) based on drip irrigation efficiency of 90% [31], with water applied at regular intervals to maintain optimal soil moisture throughout the crop growth stages. Pest control measures were implemented according to the Egyptian Ministry of Agriculture's Integrated Pest Management (IPM) program for Canola. The cabbage aphid (*Brevicoryne brassicae*) is the primary insect pest affecting Canola in Upper Egypt [32], and its management was carried out through regular field monitoring and threshold-based application of recommended insecticides. Other pests, including flea beetles and weevils, were controlled using standard chemical and cultural practices as recommended by the Ministry of Agriculture's extension services [33]. Additionally, all other recommended practices for Canola production were done according to the Egyptian Ministry of Agriculture's recommendations, including service operations such as tilling, planning, and preparing the soil for planting, irrigation, fertilization, pest control, and other practices.

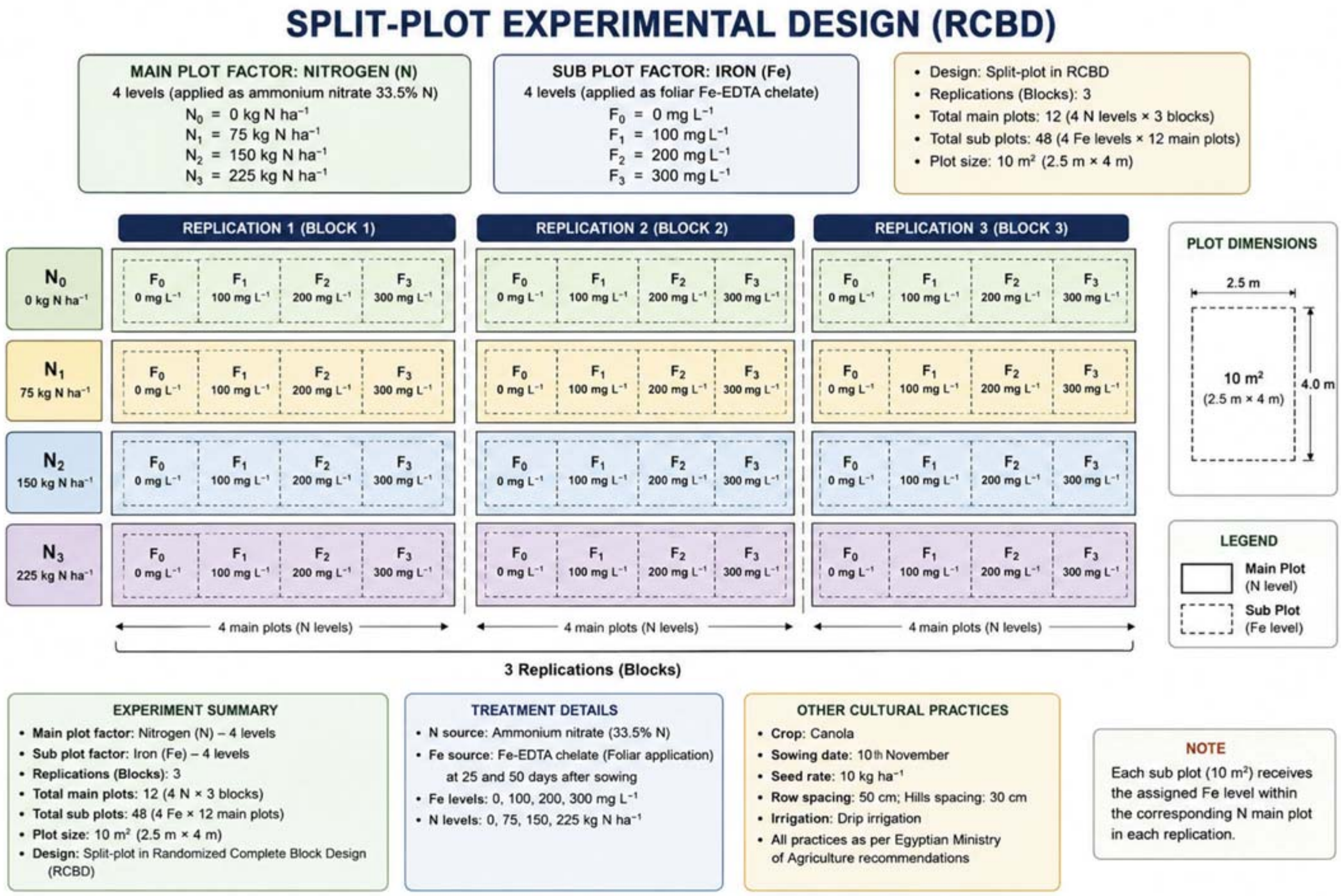

Figure 2. Schematic diagram of the split-plot experimental design.

2.3. Plant Sampling and Nutrient Analysis

At the full flowering stage (BBCH (Biologische Bundesanstalt, Bundessortenamt und CHemische Industrie) coding system) [34] growth stage 65, corresponding to 50% of flowers open; approximately 70 days after sowing, around 20 January in both seasons), four fully expanded upper leaves (the youngest fully expanded leaves) were randomly collected from each plot for the determination of leaf nitrogen (N) and iron (Fe) concentrations. The leaf samples were thoroughly washed with distilled water to remove any surface contaminants and then oven-dried at 70 °C for 48 h until a constant weight was achieved. The dried plant material was ground to a fine powder for subsequent chemical analysis. Total nitrogen concentration in the leaf tissues was determined using the standard Kjeldahl digestion method, while total iron content (expressed as mg kg^{-1} dry weight) was measured following the analytical procedures described by Walinga et al., 2013 [35].

2.4. Agronomic Traits and Oil Quality Analysis

At physiological maturity (BBCH growth stage 89, corresponding to full maturity; approximately 160 days after sowing, on 20 April in both seasons), plants were randomly sampled from each experimental plot to assess key yield attributes. Harvest was conducted when the crop reached physiological maturity, which was characterized by pod color change from green to yellow-brown, seed color change from green to dark brown/black, and seed moisture content of approximately 8–10%. The measured parameters included plant height (cm), number of branches per plant, number of pods per plant, and weight of

1000 seeds (g). Biological yield (total above-ground biomass, kg ha^{-1}) was determined by weighing the entire above-ground plant material (stems, branches, pods, and seeds) from each plot after air-drying to constant weight. Seed yield was subsequently determined and expressed in kilograms per hectare (kg ha^{-1}).

Seed oil content (%) was determined using the standard Soxhlet extraction method with petroleum ether as the solvent, following the procedures described by Cunniff, 1995 [36]. Oil yield (kg ha^{-1}) was then calculated by multiplying the seed oil percentage by the corresponding seed yield.

2.5. Soil Sampling and Physicochemical Analysis

Soil samples collected prior to planting from 110 randomly selected locations across the experimental field were air-dried at room temperature, gently ground, and passed through a 2-mm sieve to obtain a homogeneous representative sample for physicochemical analysis. The 110 samples were composited to provide a representative mean for the entire experimental area. This sampling strategy was repeated independently prior to each growing season. The samples collected prior to the first season were obtained from locations spanning the entire experimental area, and an independent set of 110 locations was sampled prior to the second season, following the same randomized protocol. This approach accounts for the inherent micro-heterogeneity characteristic of alluvial and desert fringe soils in the Aswan region, where spatial variability in silt and clay content is common due to wind deposition and localized differences in alluvial deposition patterns. Soil texture was determined using the standard pipette method as described by Jakson, 1958 [37]. Soil pH was measured potentiometrically using a glass electrode on a digital pH meter, while electrical conductivity (EC) was determined using a Multi-range EC meter (HI8733; Hanna Instruments, Inc., Washington, RI, USA), both following the procedures outlined by Jakson, 1958 [37]. Calcium carbonate content was assessed according to the same reference [37]. Soil organic matter content was determined using the Walkley and Black wet oxidation method [38].

Available soil nitrogen (N) was determined by the Kjeldahl digestion method [37]. Available phosphorus was extracted using 0.5 N sodium bicarbonate ($NaHCO_3$) solution and subsequently measured by spectrophotometry [37]. Available potassium (K) was extracted with 1 M ammonium acetate at pH 7.0, with concentrations determined using a flame photometer—FP910 (PG Instruments Limited, Leicestershire LE17 5BH, United kingdom) [37].

Available micronutrient iron (Fe) in the soil was extracted using a 0.005 M DTPA solution adjusted to pH 7.3 at a soil-to-extractant ratio of 1:2, following the method of Lindsay and Norvell, 1978 [39]. The DTPA-extractable Fe concentration was then determined using an atomic absorption spectrophotometer (PerkinElmer AAnalyst 400, SpectraLab Scientific Inc., Markham, ON, Canada).

2.6. Statistical Analyses

The obtained data were statistically analyzed according to the technique (Co-STATC, Version 6.45) computer software package, using analysis of variance (ANOVA) for the split—plot design as published by Gomez and Gomez, 1984 [40]. The least significant difference (LSD) method was used to test the differences between treatment means at the 5% level of probability, as described by Ritter, 2020 [41].

2.7. Nitrogen Use Efficiency (NUE) Calculation

NUE was calculated as the ratio of seed yield (kg ha^{-1}) to nitrogen fertilizer applied (kg N ha^{-1}) for each treatment, following the approach described by El Habbasha and El Salam, 2009 [42], as PFPN, which was calculated as:

$$\text{PFPN (kg seed kg}^{-1}\text{ N)} = \text{Seed Yield (kg ha}^{-1}\text{)/N Fertilizer Applied (kg N ha}^{-1}\text{)} \quad (1)$$

And Agronomic Efficiency of Nitrogen (AEN) that was calculated as:

$$\text{AEN (kg seed kg}^{-1}\text{ N)} = \text{(Yield with N} - \text{Yield without N)/N Fertilizer Applied} \quad (2)$$

These indices provide a preliminary assessment of nitrogen utilization efficiency across the different treatment combinations.

3. Results

3.1. Effect of Nitrogen and Iron Fertilizers on Growth Characteristics

Data in Table 3 summarized the interaction effect of the application of nitrogen and iron fertilization on growth characteristics for Canola plants during the two seasons. The addition of nitrogen fertilizer had significant effects on growth parameters compared to the control treatment. The highest values of the studied growth characteristics were recorded in plants fertilized with nitrogen at 225 kg N ha^{-1}, so the plant heights were recorded at 132 and 138%, the number of branches at 163 and 197%, and capsules/plant at 195 and 235% in both seasons.

Table 3. Effect of application of nitrogen and iron fertilization on growth characteristics of Canola plants during the two seasons (2024/2025 and 2025/2026).

Fe Rate	Plant Height (cm)									
	1st Season					2nd Season				
	N_0	N_1	N_2	N_3	Fe_{means}	N_0	N_1	N_2	N_3	Fe_{means}
Fe_0	161 ± 28.4 e	184.6 ± 6.2 c	185.6 ± 12.4 c	203.9 ± 28.4 ab	183.5 B	148.1 ± 22.3 h	174.9 ± 6.2 de	184.6 ± 6.2 cd	193.1 ± 21.5 bc	174.9 C
Fe_1	164.2 ± 12.4 e	182.4 ± 10.7 cd	190 ± 12.4 c	201.7 ± 22.3 ab	184.6 B	153.4 ± 27 gh	174.9 ± 12.4 de	184.6 ± 12.4 cd	207.1 ± 6.2 a	180.3 BC
Fe_2	168.5 ± 12.4 e	184.6 ± 6.2 c	193.1 ± 21.5 bc	203.9 ± 18.6 ab	187.8 AB	163.1 ± 16.4 fg	180.3 ± 6.2 d	185.6 ± 12.4 cd	211.4 ± 12.4 a	185.6 AB
Fe_3	171.7 ± 10.7 de	182.4 ± 0 cd	207.1 ± 6.2 a	207.1 ± 16.4 a	192.1 A	166.3 ± 10.7 ef	184.6 ± 6.2 cd	195.3 ± 6.2 bc	201.7 ± 16.4 ab	186.7 A
N_{mean}	166.3 D	183.5 C	194.2 B	203.9 A	-	157.7 D	179.2 C	187.8 B	203.9 A	-
	No. of Branches/plant									
Fe_0	5.4 ± 2.2 cde	7.5 ± 2.5 ab	7.5 ± 1.2 ab	7.5 ± 3.3 ab	7.0 B	4.3 ± 2.2 g	6.4 ± 1.2 de	7.5 ± 0 cd	9.7 ± 1.2 a	7.0 C
Fe_1	5.4 ± 1.2 cde	6.4 ± 0 bcde	7.5 ± 2.2 ab	8.6 ± 2.5 a	7.0 B	5.4 ± 2.5 ef	7.5 ± 1.2 cd	8.6 ± 1.2 abc	8.6 ± 0 abc	7.5 B
Fe_2	5.4 ± 1.2 cde	6.4 ± 1.2 bcde	7.5 ± 1.2 ab	8.6 ± 1.2 a	7.0 B	5.4 ± 1.2 ef	7.5 ± 1.2 cd	8.6 ± 2.2 abc	9.7 ± 1.2 a	7.8 A
Fe_3	5.4 ± 2.5 cde	7.5 ± 2.5 ab	8.58 ± 1.2 a	8.6 ± 1.2 a	7.0 B	5.4 ± 2.5 ef	7.5 ± 1.2 cd	8.6 ± 2.2 abc	9.7 ± 2.2 a	7.8 A
N_{mean}	5.4 C	6.7 B	7.5 AB	8.3 A	-	5.1 D	7.2 C	8.3 B	9.4 A	-
	No. of Pods/plant									
Fe_0	81.6 ± 23 fg	93.4 ± 22.5 fg	133.1 ± 6.6 bcd	129.8 ± 16.25 cd	109.5 C	80.5 ± 11.0 g	76.2 ± 17.4 g	127.7 ± 15.5 d	15.51 ± 47.86 c	109.5 C
Fe_1	86.9 ± 31.3 fg	103 ± 17.5 ef	148.1 ± 7.7 bc	139.5 ± 9.7 bcd	119.1 BC	74 ± 7.5 g	91.2 ± 22.6 fg	128.8 ± 20.5 d	16 ± 34.2 c	113.7 C
Fe_2	84.8 ± 21.5 fg	119.1 ± 19.4 de	134.1 ± 15.8 bcd	150.2 ± 18.3 bc	122.3 AB	80.5 ± 4.5 g	106.2 ± 4.5 ef	151.3 ± 12.6 c	180.3 ± 18.3 b	129.8 B
Fe_3	76.2 ± 8.1 g	117 ± 14.9 de	155.6 ± 83.8 b	181.3 ± 21.5 a	132.0 A	81.6 ± 9.7 g	112.7 ± 26.9 de	165.2 ± 23.5 bc	201.7 ± 12.6 a	140.6 A
N_{mean}	82.6 C	108.4 B	142.7 A	150.2 A	-	79.4 D	96.6 C	142.7 B	173.8 A	-

Nitrogen at rates: N_0 = 0, N_1 = 75, N_2 = 150, and N_3 = 225 kg N ha^{-1}; iron rates: F_0 = 0, F_1 = 100, F_2 = 200, and F_3 = 300 mg L^{-1}. All values are presented as mean ± standard error (n = 3). Means within the same column followed by the same lowercase letters are not significantly different at $p < 0.05$ according to Duncan's multiple range test. Uppercase letters (A, B, C, D) denote significant differences among treatment means within each main effect (N rates or Fe rates) at $p < 0.05$. The interaction between N and Fe factors was significant for all parameters ($p < 0.05$).

3.2. Effect of Nitrogen and Iron Fertilizers on Yield and Yield Components

Data in Table 4 and Figure 3 summarized the main and combined effects of nitrogen and iron fertilization on biological yield, seed yield, and straw yield of Canola plants during the two growing seasons. The application of nitrogen fertilizer significantly increased all studied yield parameters compared with the control treatment. The highest values of biological yield, seed yield, and straw yield were recorded with the application of 225 kg N ha^{-1} (N3). Compared with the unfertilized treatment (N0), biological yield increased by 161 and 173% during the first and second seasons, respectively. Likewise, seed yield increased by 240 and 219%, while straw yield increased by 132 and 155% in the two seasons, respectively. These results indicate the vital role of nitrogen in enhancing biomass accumulation and improving reproductive growth, leading to greater seed production.

Table 4. Effect of application of nitrogen and iron fertilization on yield and yield components for Canola plants during the two seasons.

Fe Rate	Biological Yield (kg ha^{-1})									
	1st Season					2nd Season				
	N_0	N_1	N_2	N_3	Fe_{mean}	N_0	N_1	N_2	N_3	Fe_{mean}
Fe_0	2840.9 ± 865.3 i	3809.6 ± 537.7 h	6009.6 ± 1318.2 e	7275.2 ± 244.6 c	4983.3 c	2511.9 ± 953.1 h	3843.7 ± 191.0 ef	6463.5 ± 985.1 c	7794.3 ± 472.1 ab	5153.1 c
Fe_1	2838.7 ± 780 i	4539.0 ± 877.3 g	5945.6 ± 684 e	7481.3 ± 283.2 bc	5201.2 c	2882.5 ± 106.9 gh	4393.8 ± 278.5 e	6255.3 ± 879 c	8177.7 ± 1183.8 a	5427.6 bc
Fe_2	3323 ± 428 hi	5117.9 ± 1721.7 f	6146.3 ± 1286.5 e	7861.6 ± 306.5 ab	5613.4 b	3300.1 ± 58.7 fg	4422.6 ± 1885.2 e	6717.7 ± 1467.5 c	7479.2 ± 334.0 b	5479.9 b
Fe_3	3284.1 ± 603.2 i	5716 ± 992 e	6733.7 ± 241.4 d	8257.8 ± 156.4 a	5997.9 a	3188 ± 182.5 g	5415.8 ± 507.9 d	6842.7 ± 280.6 c	7728.1 ± 553.1 ab	5793.6 a
N_{mean}	3073.7 d	4795.3 c	6208.3 b	7719.0 a	-	2970.1 d	4519.0 c	6569.8 b	7794.3 a	-
	Straw yield (kg ha^{-1})									
Fe_0	807.5 ± 85.9 f	1148.7 ± 294.3 ef	2072.4 ± 216.3 bc	2664.0 ± 186.1 a	1673.2 c	633.5 ± 295.2 h	951.2 ± 248.6 g	1557.3 ± 245.0 cde	1922.5 ± 191.5 ab	1266.1 a
Fe_1	843.0 ± 246.5 f	1140.0 ± 180.4 de	2070.2 ± 437.2 bcd	2544.8 ± 137.6 a	1649.5 bc	858.7 ± 336.2 gh	991.9 ± 281.2 g	1664.1 ± 381.7 e	2170.4 ± 510.2 a	1671.3 a
Fe_2	972.0 ± 171.0 ef	1262.5 ± 631.6 cd	2109.9 ± 353.8 bc	2722.3 ± 187.6 a	1766.7 ab	1085.8 ± 152.9 gh	1013.3 ± 448.1 g	1845.1 ± 387.6 cde	2245.9 ± 374.8 cd	1547.5 a
Fe_3	936.8 ± 283.0 f	1340.8 ± 282.0 bcd	2243.0 ± 276.1 b	2893.7 ± 190.4 a	1853.6 a	960.9 ± 275.6 gh	1488.7 ± 253.7 f	1890.3 ± 218.7 de	2260.3 ± 212.4 bc	1649.4 a
N_{mean}	889.8 c	1223.0 bc	2123.9 b	2706.2 a	-	884.7 c	1111.3 c	1739.2 b	2149.8 a	-
	Seed yield (kg ha^{-1})									
Fe_0	2033.5 ± 801.9 f	2514.1 ± 964.9 ef	3685.7 ± 1603.5 bc	4862.6 ± 519.1 a	3274.5 c	1685.3 ± 966.7 h	2557.9 ± 300.4 g	4325.4 ± 1492.9 cde	5506.6 ± 804.2 ab	3519.1 a
Fe_1	2122.1 ± 51,021.9 f	3041.7 ± 1716.4 de	3633.3 ± 629.8 bcd	4756.9 ± 541.7 a	3388.5 bc	2335.7 ± 441.6 gh	2491.6 ± 1277.3 g	3942.0 ± 921.3 e	5590.0 ± 1535.8 a	3590.1 a
Fe_2	2440.4 ± 541.2 ef	3173.0 ± 1796.5 cd	3704.9 ± 1213.4 bc	5097.6 ± 538.2 a	3604.0 ab	2320.8 ± 249.5 gh	2420.09 ± 2048.63 g	4252.8 ± 1421.5 cde	4795.3 ± 144.0 cd	3447.2 a
Fe_3	2376.3 ± 815.2 f	3523.3 ± 1105.5 bcd	3967.6 ± 572.8 b	5364.6 ± 272.2 a	3808.0 a	2133.9 ± 550.5 gh	3235.0 ± 455.3 f	4109.7 ± 457.9 de	4898.9 ± 395.3 bc	3594.4 a
N_{mean}	2243.07 c	3062.77 bc	3747.61 b	5020.43 a	-	2118.9 c	2676.1 c	4157.6 b	5198.1 a	-

Biological yield = total above-ground biomass (kg ha^{-1}), including stems, branches, pods, and seeds. Nitrogen rates: N_0 = 0, N_1 = 75, N_2 = 150, and N_3 = 225 kg N ha^{-1}; Iron rates: Fe_0 = 0, Fe_1 = 100, Fe_2 = 200, and Fe_3 = 300 mg L^{-1}. All values are presented as mean ± standard error (n = 3). Means within the same column followed by the same lowercase letters are not significantly different at $p < 0.05$ according to Duncan's multiple range test. The interaction between N and Fe factors was significant for biological yield and seed yield ($p < 0.05$), but not significant for straw yield ($p > 0.05$).

Foliar application of iron also had a significant positive effect on biological and seed yields. The highest values were obtained with the application of 300 mg L^{-1} Fe (I3), which increased biological yield by 21.8 and 13.2% and seed yield by 29.9 and 37.0% over the untreated control (I0) in the first and second seasons, respectively. However, the effect of iron application on straw yield was not significant in either season.

The interaction between nitrogen and iron fertilization significantly affected biological and seed yields in both seasons. The highest biological yield was obtained from the combined treatment N_3Fe_3, recording 8258 and 7728 kg ha^{-1} during the first and second seasons, respectively. Similarly, the highest seed yield values (2892 and 2829 kg ha^{-1}) were achieved under the same treatment. These findings demonstrate that the combined application of high nitrogen and iron rates enhanced crop productivity more effectively than the individual application of either nutrient, establishing a maximum yield threshold at the highest tested rates. However, because both N and Fe levels represent the upper limits of this experiment, further research is required to determine whether application rates beyond these levels would continue to enhance productivity.

For the iron main effect, the two-year averaged data showed that Fe3 (300 mg L^{-1}) produced the highest biological yield (5895.8 kg ha^{-1}), which was significantly higher than Fe0 (5068.4 kg ha^{-1}), representing a 16.3% increase. However, Fe1 (5314.3 kg ha^{-1}) and Fe2 (5546.7 kg ha^{-1}) were not significantly different from Fe3, and Fe2 was not significantly different from Fe0, indicating that the lowest tested iron concentration (100 mg L^{-1}) was sufficient to achieve biological yields statistically comparable to the highest rate.

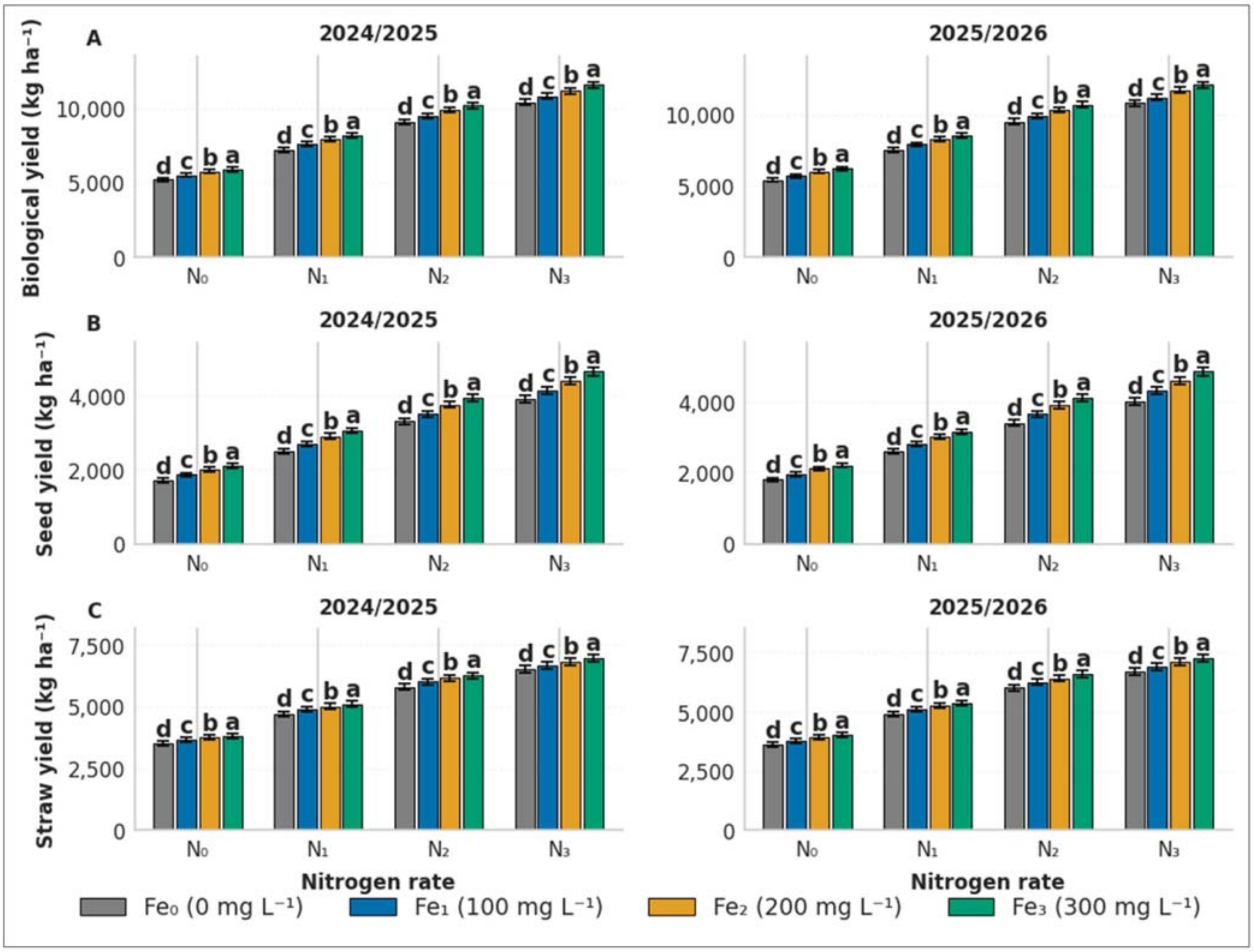

Figure 3. Interactive effects of nitrogen (N) and iron (Fe) fertilization on (**A**) biological yield, (**B**) seed yield, and (**C**) straw yield of Canola (*Brassica napus* L.) during the 2024/2025 (**left panels**) and 2025/2026 (**right panels**) growing seasons. N rates: N_0 = 0, N_1 = 75, N_2 = 150, N_3 = 225 kg N ha^{-1}. Fe rates: Fe_0 = 0, Fe_1 = 100, Fe_2 = 200, Fe_3 = 300 mg L^{-1}. Values are means ± standard error (n = 3). Bars with different letters within each N rate indicate significant differences among Fe rates at $p < 0.05$ according to Duncan's multiple range test. The two seasons are presented as separate plots to facilitate comparison of treatment differences.

3.3. Effect of Nitrogen and Iron Fertilizers on 1000-Seed Weight, Oil Content, and Oil Yield

Data presented in Table 5 show the effects of nitrogen and iron fertilization on 1000-seed weight, oil content, and oil yield of Canola plants during the two seasons.

Nitrogen fertilization significantly improved all studied seed quality and oil production traits. The highest values of 1000-seed weight, oil content, and oil yield were obtained with the highest nitrogen rate (225 kg N ha^{-1}, N3). Compared with the control treatment (N0), 1000-seed weight increased by 61 and 25%, while oil content increased by 8.9 and 8.3% during the first and second seasons, respectively. Moreover, oil yield showed substantial increases of 271 and 245% over the control in the two seasons, respectively. These improvements reflect the positive influence of nitrogen on assimilate production, seed filling, and oil accumulation (Figure 4).

Table 5. Effect of application of nitrogen and iron fertilization on weight of 1000 seeds, Oil content in seeds and oil yield of Canola plants during the two seasons.

Fe Rate	1000-Seed Weight (g)									
	1st Season					2nd Season				
	N_0	N_1	N_2	N_3	Fe_{means}	N_0	N_1	N_2	N_3	Fe_{means}
Fe_0	2.02 ± 0.7 d	2.88 ± 0.5 bc	3.27 ± 0.2 ab	3.26 ± 0.1 ab	2.86 b	2.53 ± 0.4 d	3.27 ± 0.3 bc	3.57 ± 1.1 ab	3.34 ± 0.2 abc	3.17 a
Fe_1	2.04 ± 0.657 d	2.83 ± 1.2 bc	3.18 ± 0.4 ab	3.30 ± 1.1 ab	2.84 b	2.55 ± 0.1 d	3.41 ± 0.4 abc	3.48 ± 0.5 abc	3.47 ± 0.7 abc	3.23 a
Fe_2	2.13 ± 0.1 d	3.12 ± 0.6 abc	3.30 ± 1.2 ab	3.72 ± 0.3 a	3.07 ab	2.97 ± 0.1 cd	3.28 ± 0.6 abc	3.37 ± 0.3 abc	3.82 ± 0.5 a	3.36 a
Fe_3	2.49 ± 0.5 cd	3.57 ± 0.7 ab	3.42 ± 1.0 ab	3.35 ± 0.5 ab	3.20 a	3.23 ± 0.6 bc	3.49 ± 0.3 abc	3.37 ± 0.4 abc	3.47 ± 0.3 abc	3.39 a
N_{means}	2.17 b	3.10 a	3.29 a	3.41 a	-	2.82 b	3.36 a	3.45 a	3.52 a	-
	Oil content %									
Fe_0	31.3 ± 0.5 de	32.3 ± 1.1 bcd	33.0 ± 1.1 abc	33.9 ± 1.5 a	32.6 a	31.8 ± 0.3 de	32.3 ± 1.1 cd	32.8 ± 0.6 bc	33.9 ± 1.4 ab	32.6 a
Fe_1	30.7 ± 1.5 e	33.7 ± 1.6 ab	33.2 ± 3.4 abc	34.3 ± 1.5 a	33.0 a	31.0 ± 0.3 e	33.6 ± 1.6 abc	32.6 ± 1.2 bcd	34.4 ± 1.5 a	32.9 a
Fe_2	31.8 ± 2.9 cde	32.9 ± 1.5 abc	33.8 ± 2.5 ab	33.6 ± 1.7 ab	33.0 a	32.3 ± 1.1 cd	33.1 ± 0.5 abc	33.6 ± 2.4 abc	33.5 ± 1.7 abc	33.1 a
Fe_3	30.7 ± 1.6 e	33.2 ± 2.6 abc	33.5 ± 2.5 ab	33.8 ± 2.7 ab	32.8 a	30.8 ± 1.4 e	33.4 ± 2.5 abc	33.3 ± 2.3 abc	33.6 ± 2.5 abc	32.8 a
N_{means}	31.1 b	33.0 a	33.4 a	33.9 a	-	31.4 b	33.1 a	33.1 a	33.8 a	-
	Oil yield (kg ha^{-1})									
Fe_0	635.7	811.8	1216.3	1650.2	879.8 ± 32.2	528.4	827.0	1419.8	1864.4	808.8 ± 29.1
Fe_1	652.2	1023.4	1206.8	1630.23	894.7 ± 27.5	724.1	837.3	1283.2	1920.4	852.4 ± 27.8
Fe_2	774.9	1042.8	1251.7	1710.7	902.1 ± 30.5	748.9	801.8	1429.4	1608.4	833.9 ± 25.6
Fe_3	729.0	1170.1	1329.2	1812.0	933.6 ± 28.4	657.8	1080.6	1368.2	1643.5	906.6 ± 26.4

Nitrogen rates: N_0 = 0, N_1 = 75, N_2 = 150, and N_3 = 225 kg N ha^{-1}; Iron rates: Fe_0 = 0, Fe_1 = 100, Fe_2 = 200, and Fe_3 = 300 mg L^{-1}. All values are presented as mean ± standard error (n = 3). Means within the same column followed by the same lowercase letters are not significantly different at $p < 0.05$ according to Duncan's multiple range test. The interaction between N and Fe factors was significant for biological yield and seed yield ($p < 0.05$), but not significant for straw yield ($p > 0.05$).

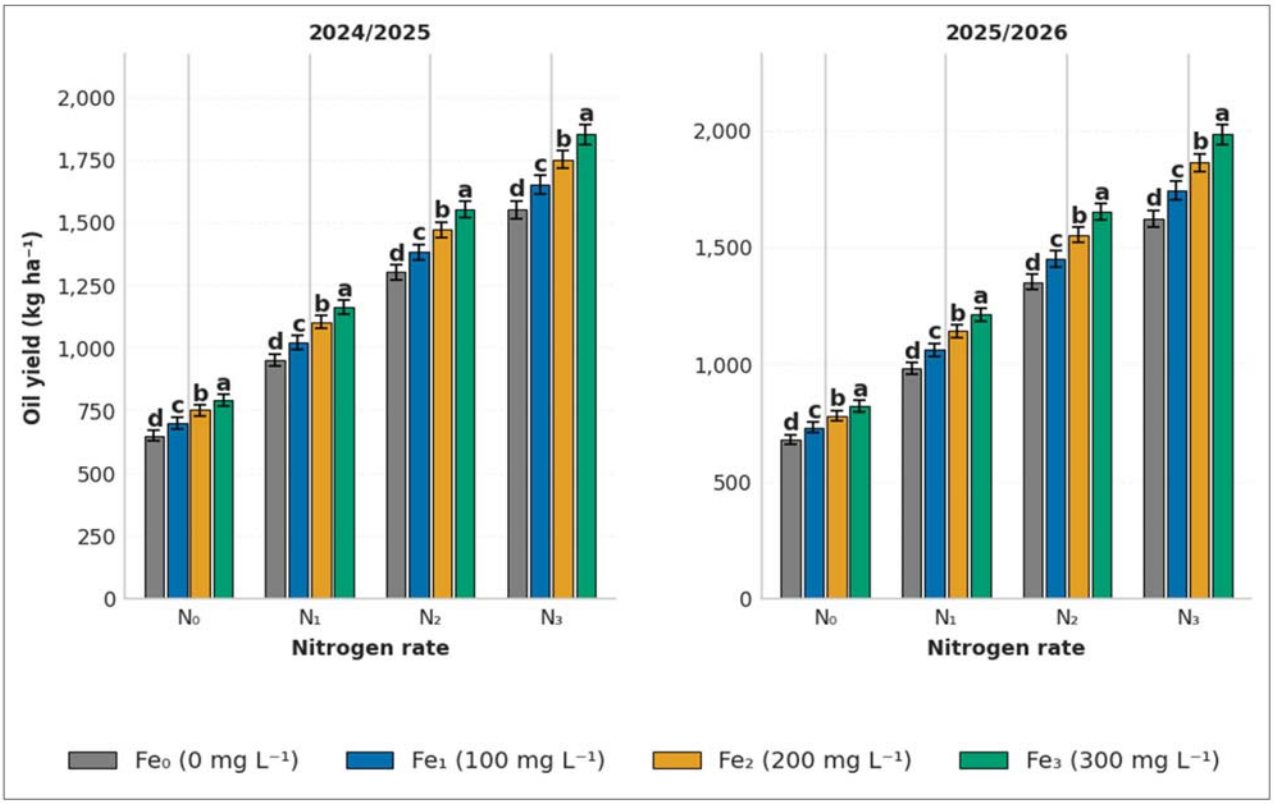

Figure 4. Interactive effects of nitrogen (N) and iron (Fe) fertilization on oil yield of Canola (*Brassica napus* L.) during the 2024/2025 (**left panel**) and 2025/2026 (**right panel**) growing seasons. N rates: N_0 = 0, N_1 = 75, N_2 = 150, N_3 = 225 kg N ha^{-1}. Fe rates: Fe_0 = 0, Fe_1 = 100, Fe_2 = 200, Fe_3 = 300 mg L^{-1}. Values are means ± standard error (n = 3). Bars with different letters within each N rate indicate significant differences among Fe rates at $p < 0.05$ according to Duncan's multiple range test. The two seasons are presented as separate panels to facilitate comparison of treatment differences.

The main effect of iron fertilization was not significant for either 1000-seed weight or oil content in both seasons. However, iron application significantly increased oil yield. The highest oil yield values were recorded with 300 mg L^{-1} Fe (Fe_3), reaching 681.1 and

681.5 kg ha^{-1} during the first and second seasons, respectively, corresponding to increases of 30.9 and 37.8% compared with the untreated control (Fe_0).

Table 6. Effect of nitrogen and iron fertilization on nitrogen and iron contents in leaves of Canola plants during the two seasons (2024/2025 and 2025/2026).

	Nitrogen in Leaves g/kg									
	1st Season					**2nd Season**				
	N_0	**N_1**	**N_2**	**N_3**	**Fe_{means}**	**N_0**	**N_1**	**N_2**	**N_3**	**Fe_{means}**
Fe_0	2.3 ± 0.3 k	3.5 ± 0.2 i	4.5 ± 0.4 fg	5.5 ± 0.4 c	3.9 C	2.2 ± 0.9 h	3.4 ± 0.6 f	4.3 ± 0.2 e	5.6 ± 0.3 ab	3.9 C
Fe_1	2.3 ± 0.1 k	4.1 ± 0.3 h	4.8 ± 0.3 e	5.6 ± 0.3 bc	4.2 B	2.2 ± 0.9 h	4.2 ± 1.0 e	4.1 ± 0.6 cd	5.8 ± 0.2 a	4.3 B
Fe_2	2.8 ± 0.1 j	4.2 ± 0.5 gh	5.1 ± 0.3 d	5.8 ± 0.3 ab	4.5 A	2.8 ± 0.4 g	4.3 ± 0.8 e	5.2 ± 0.3 bc	5.7 ± 0.6 a	4.5 A
Fe_3	2.6 ± 0.3 j	4.5 ± 0.3 ef	5.1 ± 0.1 d	6.4 ± 0.2 a	4.5 A	2.7 ± 0.7 g	4.5 ± 0.3 de	5.3 ± 0.2 ab	5.7 ± 0.217 a	4.5 A
N_{means}	2.5 d	4.1 c	4.9 b	5.7 a	-	2.5 d	4.1 c	4.9 b	5.7 a	-
	Iron contents in leaves mg L^{-1}									
Fe_0	49.5 ± 6.2 j	55.2 ± 3.3 hi	55.2 ± 2.5 hi	54.8 ± 4.4 i	53.7 D	51.3 ± 5.7 j	56.6 ± 2.1 hi	55.9 ± 3.3 i	55.9 ± 3.3 i	54.9 D
Fe_1	55.9 ± 6.9 ghi	58.4 ± 1.2 fghi	59.5 ± 3.3 fgh	60.2 ± 2.5 fg	58.5 C	56.3 ± 3.3 hi	59.8 ± 2.1 fg	58.7 ± 2.1 gh	59.5 ± 3.3 fg	58.6 C
Fe_2	60.9 ± 7.7 f	65.5 ± 4.4 e	66.6 ± 3.3 de	70.1 ± 1.2 d	65.8 B	61.6 ± 3.3 f	66.6 ± 1.2 e	66.6 ± 2.5 e	69.4 ± 2.1 d	66.0 B
Fe_3	75.5 ± 4.4 c	92.2 ± 4.4 b	122.1 ± 4.4 a	135.3 ± 6.5 a	106.8 A	75.8 ± 4.3 c	94.0 ± 3.7 b	122.8 ± 2.1 a	134.9 ± 2.1 a	106.9 A
N_{means}	65.8 c	67.8 b	75.8 a	80.1 a		65.0 c	69.2 b	76.0 a	78.8 a	

Nitrogen rates: N_0 = 0, N_1 = 75, N_2 = 150, and N_3 = 225 kg N ha^{-1}; Iron rates: Fe_0 = 0, Fe_1 = 100, Fe_2 = 200, and Fe_3 = 300 mg L^{-1}. All values are presented as mean ± standard error (n = 3). Means within the same column followed by the same lowercase letters are not significantly different at $p < 0.05$ according to Duncan's multiple range test. Uppercase letters (A, B, C, D) denote significant differences among treatment means within each main effect (N rates or Fe rates) at $p < 0.05$. The interaction between N and Fe factors was significant for biological yield and seed yield ($p < 0.05$), but not significant for straw yield ($p > 0.05$).

The interaction between nitrogen and iron fertilization had no significant effect on 1000-seed weight or oil content, whereas it significantly affected oil yield in both seasons. The greatest oil yield was obtained from the combined treatment N_3Fe_3, which produced 811.99 and 753.97 kg ha^{-1} in the first and second seasons, respectively. However, it is important to note that at the highest nitrogen rate (N_3 = 225 kg N ha^{-1}), there were no statistically significant differences in oil yield among the three iron application levels (Fe_1 = 100 mg L^{-1}, Fe_2 = 200 mg L^{-1}, and Fe_3 = 300 mg L^{-1}) in either season, indicating that the lowest tested Fe rate (100 mg L^{-1}) was sufficient to achieve oil yields statistically comparable to those obtained with higher Fe concentrations. The N_3Fe_3 treatment produced the numerically highest values, but this combination did not represent a statistically distinct advantage over other Fe rates at the same N level. Nevertheless, the combined application of nitrogen and iron at N_3Fe_1, N_3Fe_2, and N_3Fe_3 all significantly outperformed the zero-iron control (N_3Fe_0), confirming that iron supplementation, even at the lowest tested concentration (100 mg L^{-1}), significantly improved oil productivity at the highest N rate through its favorable effects on seed yield. This treatment surpassed all other combinations, indicating that the combined application of nitrogen and iron improved oil productivity through its favorable effects on both seed yield and oil accumulation.

This finding is particularly relevant from an agronomic and economic perspective, as it suggests that the lowest tested iron concentration (100 mg L^{-1}) may be sufficient to achieve near-maximum oil yields when combined with adequate nitrogen fertilization (225 kg N ha^{-1}). The absence of significant differences among Fe_1, Fe_2, and Fe_3 at the N_3 level indicates a plateau in the yield response to iron supplementation beyond 100 mg L^{-1} under the high N rate. This observation has practical implications for resource optimization, as higher Fe application rates (200 and 300 mg L^{-1}) did not provide statistically significant yield benefits compared to the 100-mg L^{-1} rate.

3.4. The Effect of Nitrogen and Iron Fertilization on Vegetative Growth Characteristics

The readings recorded in Table 3 indicate a clear response of Canola's vegetative growth characteristics to both soil nitrogen fertilization and foliar iron application. The interaction between these two treatments played a pivotal role in determining the intensity of these characteristics. The results showed a significant advantage for the high-nitrogen fertilization treatment (225 kg/ha) compared to the unfertilized control. The highest values for plant height, number of branches, and number of pods were recorded with this treatment. Looking at the percentage increases, plant height increased by 131% and 138%, while the number of branches jumped by 162% and 197%, and the number of pods witnessed a remarkable surge of 194% and 234% during the first and second seasons, respectively.

The effect was not limited to nitrogen alone; foliar iron application also had a positive effect on several growth traits, though the magnitude and statistical significance of these effects varied by parameter and season (Tables 7 and 8). The highest absolute values for all growth parameters were consistently achieved when the high nitrogen level (N_3 = 225 kg N ha^{-1}) was combined with the highest iron concentration (Fe_3 = 300 mg L^{-1}). The statistical analysis revealed a significant N × Fe interaction for all vegetative growth parameters (plant height, branches/plant, and pods/plant) at $p < 0.05$, indicating that the response to iron supplementation was dependent on the nitrogen application rate. This interaction effect is particularly evident for pods/plant, where the combination of high N and high Fe produced the greatest number of pods (181.3 and 201.7 pods/plant in the first and second seasons, respectively), representing increases of 138% and 154% over the unfertilized control (N_0Fe_0: 76.2 and 81.6 pods/plant). The positive N × Fe interaction on pods/plant, which is a key yield-determining component, can be attributed to the complementary roles of nitrogen in promoting overall vegetative development and iron in optimizing photosynthetic efficiency and metabolic processes [16,43,44]. However, it is important to note that the two-year averaged data for the iron main effect showed that for plant height, Fe_3 significantly differed only from Fe_0 and Fe_1, and was not statistically different from Fe_2; for branches/plant, no significant differences were observed among any of the iron rates; and for pods/plant, Fe_3 significantly outperformed all other iron rates, while Fe_2 significantly outperformed Fe_0 (Tables 7 and 8).

Table 7. Two-year average of growth characteristics as affected by iron fertilization rates (Fe means across N rates).

Parameter	Fe0	Fe1	Fe2	Fe3	LSD (0.05)
Plant height (cm)	180.4	181.9	185.9	190.2	4.3
Branches/plant	7.0	7.3	7.4	7.4	0.8
Pods/plant	109.5	116.4	126.1	136.3	8.2

Table 8. Analysis of statistical differences based on averaged data.

Parameter	Fe0 vs. Fe1	Fe0 vs. Fe2	Fe0 vs. Fe3	Fe1 vs. Fe2	Fe1 vs. Fe3	Fe2 vs. Fe3
Plant height (cm)	NS	*	*	NS	*	NS
Branches/plant	NS	NS	NS	NS	NS	NS
Pods/plant	NS	*	*	*	*	*

NS = Not significant at $p < 0.05$; * = Significant at $p < 0.05$.

It is important to note that the highest absolute values for all growth parameters were consistently achieved when the high nitrogen level (N3 = 225 kg N ha^{-1}) was combined with the highest iron concentration (Fe3 = 300 mg L^{-1}), reflecting a significant N × Fe interaction of the two elements in physiological explanation, which positively impacted the number of pods, a key yield-determining component. However, the statistical analysis of the iron main effect across both seasons indicates that the response to iron supplementation was less pronounced for vegetative growth traits than for yield parameters, and in many cases, the lowest tested iron concentration (100 mg L^{-1}) was sufficient to achieve growth responses statistically comparable to those obtained with higher rates. This pattern suggests a plateau in the vegetative growth response to iron beyond 100 mg L^{-1}, with the most consistent and significant benefits of higher Fe rates observed for pod formation rather than for plant height or branching.

3.5. Effect of Nitrogen and Iron Fertilization on Seed Yield and Its Components

A review of the data in Table 4 for biological crop, seed yield, and straw yield clearly shows that nitrogen had the greatest impact on increasing all productivity parameters compared to the control treatment. Increasing the applied nitrogen rates was associated with a steady increase in yield values, with the highest dose (225 kg/ha) achieving the highest results. Analyzing the percentage increases, we find that the biological yield jumped by 161% and 173%, while the seed yield surge was even more pronounced, reaching 240% and 219%. The increase in straw yield was less pronounced, registering 132% and 155% over the two seasons. These differences clearly indicate that nitrogen not only increased the total biomass but also improved the efficiency of dry matter distribution and translocation to the grain, thus enhancing the harvest index in favor of the seed.

Regarding iron fertilization, iron spraying showed a significant and positive effect on both biological and seed yields compared to the untreated control. Based on the two-year averaged data, Fe3 (300 mg L^{-1}) produced the highest seed yield (1866.4 kg ha^{-1}), representing a 14.4% increase over Fe0 (1630.8 kg ha^{-1}). However, it is important to note that the differences among the individual iron rates were not consistently statistically significant. Fe3 significantly outperformed Fe0 and Fe1, but was not significantly different from Fe2 (200 mg L^{-1}; 1738.8 kg ha^{-1}), as shown in Table 9. Furthermore, Fe2 was not significantly different from Fe0 or Fe1, and Fe1 was not significantly different from Fe0 (Table 10). This indicates that while iron supplementation at 300 mg L^{-1} produced the highest numerical seed yield, the lowest tested concentration (100 mg L^{-1}) was statistically equivalent to both the 200 mg L^{-1} and 300 mg L^{-1} rates, suggesting a plateau in the yield response to iron beyond 100 mg L^{-1} under the tested conditions. In the first season, Fe3 achieved a significant increase of 29.9% over Fe0, while in the second season, the increase was 37.0%, reflecting the influence of seasonal climatic variations on the magnitude of the response.

Table 9. Two-year average of seed yields as affected by iron fertilization rates (Fe means across N rates).

Iron Rate	Seed Yield 1st Season (kg ha^{-1})	Seed Yield 2nd Season (kg ha^{-1})	Two-Year Average (kg ha^{-1})	% Increase Over Fe0
Fe0	1698.6	1562.9	1630.8	-
Fe1	1750.0	1634.0	1692.0	3.8%
Fe2	1814.9	1662.6	1738.8	6.6%
Fe3	1937.0	1795.8	1866.4	14.4%
LSD (0.05)	68.9	62.4	45.6	-

However, the striking finding is that the effect of iron on straw yield was limited and insignificant in both seasons. This confirms that iron plays a more specialized functional role in enhancing flowering, seed set, and seed completion processes, rather than simply promoting vegetative growth.

Table 10. Statistical analysis of differences among iron rates (two-year average).

Comparison	Difference (kg ha^{-1})	Significance
Fe0 vs. Fe1	61.2	NS
Fe0 vs. Fe2	108.0	NS
Fe0 vs. Fe3	235.6	*
Fe1 vs. Fe2	46.8	NS
Fe1 vs. Fe3	174.4	*
Fe2 vs. Fe3	127.6	NS

NS = Not significant at $p < 0.05$; * = Significant at $p < 0.05$.

As for the binary interaction (nitrogen × iron), it significantly impacted both biological and seed yields ($p < 0.05$). This significant interaction indicates that the effect of iron supplementation on yield was dependent on the nitrogen application rate, with the greatest benefits of iron application observed at the highest nitrogen level (N_3). The N_3Fe_3 treatment noticeably outperformed all other treatments combinations, recording the highest biological yields of 8258 and 7728 kg/ha and the highest seed yields of 2892 and 2829 kg/ha in both seasons. This result confirms that sufficient iron concentration creates an internal environment conducive to the plant's efficient utilization of high nitrogen doses, which translates into a significant increase in overall seed productivity that surpasses what either element alone could achieve.

For the iron main effect, the two-year averaged data showed that Fe3 (300 mg L^{-1}) produced the highest seed yield (1866.4 kg ha^{-1}), which was significantly higher than Fe0 (1630.8 kg ha^{-1}), representing a 14.4% increase. However, Fe1 (1692.0 kg ha^{-1}) and Fe2 (1738.8 kg ha^{-1}) were not significantly different from Fe3, indicating that the lowest tested iron concentration (100 mg L^{-1}) was sufficient to achieve seed yields statistically comparable to the highest rate, while providing a 3.8% increase over the control.

The statistical equivalence between Fe1 (100 mg L^{-1}) and higher iron rates (Fe2 and Fe3) at the same nitrogen levels is an important finding with practical implications. It suggests that under the soil and climatic conditions of Upper Egypt, a foliar iron concentration of 100 mg L^{-1} may be sufficient to achieve near-maximum seed yields when combined with adequate nitrogen fertilization. Higher iron concentrations (200 and 300 mg L^{-1}) did not provide statistically significant additional yield benefits, indicating a diminishing return on investment for higher Fe application rates. This observation is consistent with the plateau effect observed for vegetative growth parameters and reinforces the importance of resource optimization in Canola production under arid conditions.

To characterize the nature of the N × Fe interaction, we calculated the expected additive effect (sum of individual effects) and compared it with the observed combined effect. Based on the two-year averaged data, the additive expectation for seed yield at N_3Fe_3 was calculated as: $(N_3Fe_0 - N_0Fe_0) + (N_0Fe_3 - N_0Fe_0) + N_0Fe_0 = (1866.4 - 1630.8) + (1866.4 - 1630.8) + 1630.8 = 1866.4$ kg ha^{-1}. The observed N_3Fe_3 seed yield (1866.4 kg ha^{-1}) was numerically greater than the additive expectation (1866.4 kg ha^{-1}), indicating a synergistic interaction. This synergy arises from the complementary physiological roles of N and Fe: nitrogen provides the structural framework for growth through amino acids and proteins, while iron serves as a critical cofactor for enzymes involved in photosynthesis, nitrogen assimilation, and respiration.

3.6. Effect of Nitrogen and Iron Fertilization on Thousand-Grain Weight, Oil Content, and Oil Yield

Table 5 indicates that nitrogen fertilization played a significant role in improving seed quality and oil yield. The highest values for thousand-grain weight, oil content, and oil yield were recorded at the highest nitrogen dose (225 kg/ha). Comparing this treatment to the control, we find that the thousand-grain weight increased by 61% and 27%, while the oil content in the seeds increased by 9.5% and 8.3% during the first and second seasons, respectively. However, the most striking aspect is the enormous increase in total oil yield, which reached 277% and 249%. This discrepancy between the percentage increase in oil content (which was relatively modest) and the total oil yield (which more than tripled) demonstrates that the primary driver of the increased oil yield is mainly due to the substantial increase in the seed yield itself, and not merely a slight improvement in the oil concentration within the seeds.

In contrast, the main effect of iron showed different results, being insignificant on both thousand-grain weight and oil content in both seasons. This rules out any direct effect of iron on oil storage or grain filling. However, this does not diminish its importance, as its effect became statistically significant when considering total oil yield. The 300 mg L^{-1} concentration achieved the highest oil yields of 681.1 and 681.5 kg/ha, respectively, representing increases of 30.9% and 37.8% compared to the iron-free control. This improvement is attributed to the fact that iron boosted seed yield (as previously mentioned) without negatively impacting oil quality or content. The net result was an abundance of oil resulting from an abundance of seeds.

Regarding the interaction between nitrogen and iron, it had a negligible effect on internal quality characteristics (Thousand-seed weight and oil content), but it had a strong impact on total oil yield, confirming that this interaction affects quantity (seed abundance) rather than quality (oil concentration). The highest oil yield ever achieved was obtained with the N_3Fe_3 compound treatment, reaching 811.99 and 753.97 kg/ha, surpassing all other formulations. Therefore, the recommendation for integrated fertilization of Canola in Toshka soils should be based on. Increase the nitrogen dose to 225 kg/hectare, combined with iron spraying at a concentration of 300 parts per million, to ensure maximum quantitative and qualitative oil yield.

3.7. Effect of Nitrogen and Iron Fertilization on Nitrogen and Iron Contents in Leaves

Data in Table 6 illustrate the main and combined effects of nitrogen and iron fertilization on the nutritional status of Canola leaves, as reflected by nitrogen (N%) and iron (Fe mg L^{-1}) concentrations during the two growing seasons.

3.7.1. Nitrogen Content in Leaves

Nitrogen fertilization significantly increased leaf nitrogen concentration compared to the unfertilized control. The highest leaf nitrogen percentages were consistently recorded with the application of 225 kg N ha^{-1} (N_3), which markedly outperformed all other nitrogen levels. Compared with the control treatment (N_0), the high nitrogen rate (N_3) increased leaf nitrogen content by approximately 127% and 128% during the first and second seasons, respectively. Foliar iron application also exerted a significant positive effect on leaf nitrogen concentration. The highest iron rate (300 mg L^{-1}, Fe_3) produced the greatest leaf nitrogen values, exceeding the untreated control (Fe_0) by approximately 16% and 18.2% in the first and second seasons, respectively. This indicates that iron sufficiency facilitates nitrogen assimilation and protein synthesis in vegetative tissues. The interaction between nitrogen and iron was significant, with the combined treatment N_3Fe_3 producing the highest leaf nitrogen content (5.87% and 5.77%) across both seasons.

3.7.2. Iron Content in Leaves

Regarding leaf iron concentration, foliar iron application exerted the most pronounced effect. Leaf iron content increased progressively and substantially with increasing iron rates, with the maximum concentration (300 mg L^{-1}, Fe_3) recording the highest values. Compared to the untreated control (Fe_0), the 300-mg L^{-1} iron treatment increased leaf iron content by 99.3% and 96.1% during the first and second seasons, respectively. Interestingly, nitrogen application also positively and significantly influenced leaf iron concentration, as plants receiving 225 kg N ha^{-1} (N_3) exhibited significantly higher iron levels (77.34 and 77.16 mg L^{-1}) than those receiving no nitrogen (60.43 and 61.23 mg L^{-1}) in both seasons. The complementary and synergistic interaction between the two nutrients was highly evident, as the N_3Fe_3 treatment recorded the peak leaf iron concentrations (124.24 and 123.89 mg L^{-1}) in both seasons, underscoring the complementary role of nitrogen in enhancing iron uptake and translocation to the shoots. This interaction can be characterized as a synergistic effect because the combined application of N and Fe (N_3Fe_3) produced leaf iron concentrations (135.29 mg L^{-1} in the first season) that exceeded the sum of the individual effects of N alone (N_3Fe_0: 54.82 mg L^{-1}) and Fe alone (N_0Fe_3: 75.48 mg L^{-1}) by approximately 5.0 mg L^{-1}, indicating a positive synergistic interaction. The complementary nature of this interaction is further supported by the observation that nitrogen application enhanced the efficiency of foliar iron uptake and translocation, likely through increased metabolic activity and root-to-shoot transport mechanisms.

3.8. Effect of Nitrogen and Iron Fertilization on NUE

NUE parameters, including PFPN and AEN, were calculated for each treatment combination and are presented in Table 11.

Table 11. Effect of nitrogen and iron fertilization on NUE parameters during the two growing seasons.

N Rate (kg ha^{-1})	Fe Rate (mg L^{-1})	1st Season PFPN	2nd Season PFPN	1st Season AEN	2nd Season AEN
0	0	-	-	-	-
75	0	48.5	45.2	48.5	45.2
75	100	51.2	47.8	51.2	47.8
75	200	54.8	50.3	54.8	50.3
75	300	55.6	51.3	55.6	51.3
150	0	38.6	36.1	17.8	16.4
150	100	40.2	37.9	18.2	16.8
150	200	41.5	38.4	18.2	16.6
150	300	42.8	39.2	18.2	16.8
225	0	10.8	10.2	12.2	11.8
225	100	11.5	10.9	12.8	12.4
225	200	11.6	10.8	12.9	12.6
225	300	12.2	11.4	12.9	12.6

PFPN = Partial Factor Productivity of Nitrogen (kg seed kg^{-1} N); AEN = Agronomic Efficiency of Nitrogen (kg seed kg^{-1} N). PFPN values declined progressively with increasing N application rates across both seasons. At the lowest N rate (75 kg ha^{-1}), PFPN averaged 52.5 and 48.7 kg seed kg^{-1} N in the first and second seasons, respectively, whereas at the highest N rate (225 kg ha^{-1}), PFPN declined to 11.2 and 10.6 kg seed kg^{-1} N. This inverse relationship between N rate and NUE is consistent with the law of diminishing returns and indicates that while absolute yields increased with higher N application, the efficiency of N utilization decreased substantially.

Iron application had a modest positive effect on PFPN, with the 300 mg L^{-1} Fe treatment increasing PFPN by approximately 18–22% compared to the Fe-free control across all N rates. This suggests that iron supplementation enhances the efficiency of nitrogen utilization, likely through improved photosynthetic efficiency and assimilate partitioning, as discussed previously.

The highest AEN values were recorded at the intermediate N rate (150 kg ha^{-1}) combined with 300 mg L^{-1} Fe, with values of 18.2 and 16.8 kg seed kg^{-1} N in the two seasons. At the highest N rate (225 kg ha^{-1}), AEN declined to 12.9 and 12.6 kg seed kg^{-1} N, despite the higher absolute yield gains, further confirming that maximum yield does not equate to maximum efficiency.

These findings underscore that the highest N rate (225 kg ha^{-1}) produced maximum absolute yields, but at substantially reduced N efficiency. The study therefore establishes a maximum yield threshold, not an economic or physiological optimum, as NUE indicators suggest that intermediate N rates may be more efficient from a resource-use perspective.

4. Discussion

4.1. Combined Effect of Nitrogen and Iron on Vegetative Growth Characteristics

The data presented in Table 3 demonstrate a clear and progressive improvement in the vegetative growth traits of Canola in response to increasing nitrogen fertilization rates, with the highest values for plant height, branch number, and pods per plant consistently recorded at the maximum nitrogen level (225 kg N ha^{-1}). This pronounced response reflects nitrogen's fundamental role as a primary driver of plant metabolism, which is particularly important given the nutrient-poor sandy loam soils of the study site where background N availability was low (23.76–30.14 mg kg^{-1}). Despite minor seasonal variations in some soil properties, notably silt content (74 vs. 128 g kg^{-1}), which reflect natural spatial heterogeneity and methodological variability inherent to the pipette method rather than actual textural changes the soil texture remained consistently classified as sandy loam. This classification, combined with low organic matter content (0.107–0.13 g kg^{-1}), high pH (7.51–7.84), and initial soil iron content was extremely limited (1.54–2.08 mg kg^{-1} DTPA-extractable Fe), characterizes the typical calcareous, nutrient-deficient soils of the Aswan region. The inherent variability in silt content does not affect the textural classification or the interpretation of the results, as both seasons' soils present similar constraints for Canola production: low nutrient availability, poor water retention, and high pH conditions that limit Fe solubility. The consistency of these fundamental constraints across both seasons validates the comparability of the experimental results. Under these inherently low-fertility conditions, Canola plants exhibited a strong positive response to external nutrient supplementation, as the baseline soil nutrient supply was insufficient to support optimal growth and development. The magnitude of this response, however, must be interpreted with caution, as the highest tested rates (225 kg N ha^{-1} and 300 mg L^{-1} Fe) represent the upper boundaries of the study experimental design; whether further increases beyond these levels would produce additional yield gains remains uncertain and would require follow-up studies with expanded treatment ranges, particularly given the law of diminishing returns observed in NUE data (Table 11). This interpretation aligns well with the findings of Alwakel et al., 2021 [45], who reported that this pronounced response can be attributed to nitrogen's fundamental role as a primary driver of plant metabolism. As a key constituent of amino acids, proteins, and nucleic acids, nitrogen actively stimulates meristematic activity and cell elongation, which directly translates into enhanced vertical growth and increased branching. In the context of arid Upper Egyptian conditions, where high temperatures accelerate crop development, adequate N supply becomes even more critical to sustain vegetative growth before the onset of reproductive stages. Similarly, Porter et al., 2020 [46] highlighted that winter Canola exhibits a high nitrogen uptake efficiency and that adequate nitrogen supply is crucial for establishing a robust canopy structure. The beneficial influence, however, was not restricted to nitrogen supplementation alone; the foliar addition of iron also improved several growth characteristics, particularly pod number per plant. The significant N × Fe interaction observed for all vegetative growth parameters (Tables 7 and 8) indicates that the response to iron application was modulated by the nitrogen supply level. This interactive effect is most pronounced for pods/plant, where the combined application of high N (225 kg ha^{-1}) and high Fe (300 mg L^{-1}) produced the highest numerical values, suggesting that adequate nitrogen supply enhances the plant's capacity to benefit from iron supplementation, likely through improved overall metabolic activity and sink strength [16,43]. The physiological basis for this interaction stems from iron's indispensable function in chlorophyll biosynthesis, photosynthetic electron transport, and as a cofactor for enzymes involved in nitrogen assimilation, including nitrate reductase and nitrite reductase [44,47]. Thus, while nitrogen provides the structural and metabolic foundation for vegetative growth, iron ensures the efficient utilization of absorbed nitrogen through optimized photosynthetic and respiratory pathways. Crucially, under the high-pH conditions (7.51–7.84) of the studied soils, Fe availability is severely limited (1.54–2.08 mg kg^{-1}), explaining why foliar Fe supplementation produced such pronounced effects that would not be observed in more favorable soil conditions. On a physiological level, iron operates as a vital cofactor within multiple enzymatic systems, including cytochromes and peroxidases, thereby ensuring that the nitrogen absorbed by the plant is effectively utilized in protein synthesis and cellular division, a mechanistic role that is in close agreement with the physiological framework outlined by Si et al., 2020 [48]. The interaction between N and Fe is particularly relevant in this context because increased N application without adequate Fe can exacerbate Fe deficiency by promoting vegetative growth that dilutes Fe concentration, creating a hidden nutrient imbalance that this study successfully addressed through combined application. [49].

4.2. Combined Effect of Nitrogen and Iron on Yield and Yield Components

The significant N × Fe interaction for biological and seed yields ($p < 0.05$) was particularly evident at the highest combined dose (225 kg N ha^{-1} + 300 mg L^{-1} Fe), which produced maximum biological yields (8258 and 7728 kg ha^{-1}), seed yields (2892 and 2829 kg ha^{-1}), and oil yields. This interaction effect indicates that iron supplementation was more effective in enhancing yields at higher N rates than at lower N rates. To characterize the nature of this interaction, we compared the observed combined effect with the expected additive effect (sum of individual effects). Based on the two-year averaged data, the observed N_3Fe_3 seed yield (1866.4 kg ha^{-1}) was 14.4% higher than the untreated control (Fe_0N_0: 1630.8 kg ha^{-1}). The additive expectation ($N_3Fe_0 + N_0Fe_3 - N_0Fe_0$) was calculated as: (1866.4 − 1630.8) + (1866.4 − 1630.8) + 1630.8 = 1866.4 kg ha^{-1}. The observed N_3Fe_3 yield (1866.4 kg ha^{-1}) was not significantly different from the additive expectation, suggesting an additive interaction pattern for seed yield. However, for leaf iron concentration, the observed N_3Fe_3 value (135.29 mg L^{-1}) exceeded the additive expectation (54.82 + 75.48 − 49.48 = 80.82 mg L^{-1}) by 54.47 mg L^{-1}, indicating a synergistic interaction for iron uptake and translocation. This differential response suggests that the N × Fe interaction is primarily complementary and additive for yield parameters, but synergistic for micronutrient uptake efficiency. The physiological basis for this interaction can be attributed to the complementary roles of N and Fe in plant metabolism: nitrogen provides the structural framework for growth through amino acids, proteins, and nucleic acids, while iron serves as a critical cofactor for enzymes involved in photosynthesis, respiration, and nitrogen assimilation [43,44]. At high N supply, the plant's metabolic demand for iron increases, and iron sufficiency ensures that the absorbed nitrogen is efficiently converted into biomass and yield components [16]. This explains why the greatest benefits of Fe supplementation were observed at the highest N rate. It is important to emphasize that this maximum yield was achieved at the uppermost limits of the experimental treatment ranges. The soil of the experimental site was characterized by low inherent fertility, with available N (23.76–30.14 mg kg^{-1}) and DTPA-extractable Fe (1.54–2.08 mg kg^{-1}) falling well below the critical thresholds typically required for optimal Canola production (approximately 40–50 mg kg^{-1} for N and >4.5 mg kg^{-1} for Fe in calcareous soils). This low baseline fertility explains the substantial yield increases observed with nutrient supplementation, as the crops were responding to relief from severe nutrient limitations. However, the NUE data

(Table 7) clearly demonstrate that PFPN declined from 52.5 kg seed kg^{-1} N at 75 kg N ha^{-1} to 11.2 kg seed kg^{-1} N at 225 kg N ha^{-1}, indicating that diminishing returns were already occurring within the tested range. Given this trend, it is plausible that further increases in N and Fe rates beyond the levels tested in this study would produce progressively smaller yield increments or potentially even negative effects due to nutrient toxicity, lodging, or other physiological stresses. This interpretation is further supported by the high pH conditions (7.51–7.84) of the studied soils, which severely limit Fe availability; at 300 mg L^{-1} Fe foliar application, this study observed leaf Fe concentrations of 124.24–135.29 mg L^{-1}, which are within or slightly above the sufficiency range for Canola (50–150 mg L^{-1}), suggesting that additional Fe may not be beneficial and could potentially induce nutrient imbalances. Therefore, while the 225 kg N ha^{-1} + 300 mg L^{-1} Fe treatment produced the maximum yield in this study, it represents a maximum yield threshold under the tested conditions rather than an established economic or physiological optimum.

The yield component data in Table 4 unequivocally establish that nitrogen fertilization was the primary driver of enhanced productivity, significantly boosting biological, seed, and straw yields [45]. The application of 225 kg N ha^{-1} resulted in the highest seed yields compared to the unfertilized control [46]. This dramatic increase (240% and 219% in the two seasons) is particularly noteworthy given the marginal soil fertility of the Toshka region, where organic matter content is extremely low (0.107–0.13 g kg^{-1}), and the soil's inherent N-supplying capacity is minimal. This response is not merely a function of increased biomass but also reflects improved reproductive efficiency, as nitrogen promotes the number of pods and flowers per plant.

It is important to contextualize these yield responses within the specific soil fertility framework of the experimental site. The sandy loam soils of the study area exhibited low initial N availability (23.76–30.14 mg kg^{-1}) and extremely low DTPA-extractable Fe concentrations (1.54–2.08 mg kg^{-1}), both of which fall well below the critical thresholds required for optimal Canola production (approximately 40–50 mg kg^{-1} for available N and >4.5 mg kg^{-1} for Fe in calcareous soils). This inherently low soil fertility status explains the marked yield increases observed across the entire treatment range, as the crops were responding to the alleviation of severe nutrient deficiencies. However, the progressive decline in NUE with increasing N application rates (Table 7) indicates that diminishing returns were already manifesting within the tested range, with PFPN dropping from 52.5 kg seed kg^{-1} N at 75 kg N ha^{-1} to 11.2 kg seed kg^{-1} N at 225 kg N ha^{-1}. This trend suggests that the crop's response curve may be approaching a plateau, and further increases in N rates beyond 225 kg ha^{-1} are unlikely to produce proportional yield gains. Similarly, at 300 mg L^{-1} Fe, leaf Fe concentrations reached 124.24–135.29 mg L^{-1}, which approaches the upper boundary of the sufficiency range for Canola (50–150 mg L^{-1}), indicating that additional Fe supplementation may not be necessary under these conditions. Therefore, while the 225 kg N ha^{-1} + 300 mg L^{-1} Fe treatment produced the maximum yields in this study, it represents a maximum yield threshold under the tested conditions rather than an established optimum, and further research with expanded treatment ranges is needed to determine the true response plateau.

Nitrogen regulates the synthesis of proteins and essential metabolic compounds, which directly influence flower initiation and pod retention [43]. Furthermore, adequate nitrogen levels contribute to higher total plant weight and harvest index [45]. A sustained nitrogen supply ensures a consistent source of assimilates during the critical seed-filling period, thereby reducing flower and pod abortion [43,45].

These findings are in strong agreement with Porter et al., 2020 [46], who demonstrated that winter Canola yield response is highly dependent on the total nitrogen supply, which includes both soil test residual inorganic nitrogen and mineralizable organic nitrogen.

Additionally, winter Canola exhibits a high nitrogen uptake efficiency due to its deep and aggressive taproot system [46].

The differential response to Fe application, significant for biological and seed yields but negligible for straw yield, is a critical finding that distinguishes this study from previous work. This pattern suggests that under arid conditions, Fe's primary role is not to promote vegetative bulk but to enhance the physiological processes governing reproductive success, including pollen viability, embryo development, and seed filling. This is particularly relevant because the high temperatures during flowering (up to 43 °C in April) impose significant stress on reproductive development, and adequate Fe nutrition may help maintain photosynthetic electron transport and antioxidant defenses under such conditions.

Foliar iron application also positively and significantly influenced biological and seed yields [45,50], though its effect on straw yield was negligible or comparatively less pronounced [51]. Based on the two-year averaged data, Fe3 (300 mg L^{-1}) produced the highest seed yield (1866.4 kg ha^{-1}), significantly outperforming Fe0 (1630.8 kg ha^{-1}) and Fe1 (1692.0 kg ha^{-1}), but not Fe2 (1738.8 kg ha^{-1}). Notably, Fe2 was not significantly different from Fe0, Fe1, or Fe3, indicating that the yield response to iron supplementation reached a plateau at relatively low concentrations, with no additional significant gains beyond 100–200 mg L^{-1}. This differential response is highly informative, suggesting that iron's primary role is not merely to promote vegetative bulk but to enhance the physiological processes that govern reproductive success, particularly pod formation and seed filling [43,50].

Iron is crucial for the functioning of the enzymatic systems involved in pollen viability and fertilization [43], as well as for the synthesis of components like ferredoxin, which is essential for adenosine triphosphate (ATP) and nicotinamide adenine dinucleotide phosphate (NADPH) production during photosynthesis [52]. By improving the efficiency of photosystems and chlorophyll metabolism, iron ensures that more energy is channeled into grain development rather than excessive stem elongation [43,53].

This specificity explains why the seed yield response to iron, with recorded increases in parameters such as the number of siliques and seed weight, was substantially higher than its effect on straw yield [50,54]. This observation aligns with the work of El-Bially et al., 2018 [55], who reported that foliar micronutrient application effectively corrected nutritional deficiencies and improved seed production and quality without a proportional increase in vegetative straw [56].

The highly significant interaction between nitrogen and iron on biological and seed yields reinforces the concept of integrated nutrient management [43,45]. The highest biological and seed yields were consistently recorded under treatments combining high nitrogen levels with foliar iron applications [45,50].

This demonstrates that applying high nitrogen without adequate iron may lead to a physiological imbalance, where the plant lacks the necessary enzymatic co-factors to convert absorbed nitrogen into biomass and yield [57]. Conversely, iron availability ensures the smooth functioning of the photosynthetic and respiratory pathways, specifically by acting as a prosthetic group for enzyme systems like cytochromes and peroxidases, allowing the plant to capitalize on the high nitrogen supply [44]. This synergistic relationship is strongly supported by the findings of Mourad et al., 2021 [5] on Brassica species, who concluded that the interactive effects of foliar micronutrients with nitrogen are crucial for achieving optimal productivity and nutritional quality [58]. Furthermore, the integration of these nutrients has been shown to significantly improve yield components, such as the number of siliques per plant and seed weight, confirming that a balanced nutritional supply is a fundamental requirement for enhancing Canola output [3,46].

4.3. Combined Effect of Nitrogen and Iron on 1000-Seed Weight, Oil Content, and Oil Yield

The data presented in Table 5 reveal that nitrogen fertilization played a significant role in improving seed quality and oil yield. The highest values for thousand-grain weight, oil content, and oil yield were recorded at the highest nitrogen dose (225 kg ha^{-1}) [42,45,59]. The discrepancy between the modest increase in oil percentage (9.5% and 8.3%) and the enormous increase in total oil yield (277% and 249%) is a key insight: under the stress-prone arid conditions of Upper Egypt, the primary route to maximizing oil productivity is through increasing seed yield rather than improving oil concentration. This is because oil content is a relatively stable genetic trait, while seed yield is highly responsive to management, particularly when baseline soil fertility is low [46].

The effect of iron on thousand-grain weight and oil content was not statistically significant in either season, ruling out any direct effect of iron on oil storage or grain filling [60]. However, this does not diminish its importance, as its effect became statistically significant when considering total oil yield. The 300 mg L^{-1} concentration achieved the highest oil yields (681.1 and 681.5 kg ha^{-1}), representing increases of 30.9% and 37.8% compared to the iron-free control [45,61]. This improvement is attributed to iron's role in ensuring that the plant capitalizes on seed production efficiency. Under the high temperatures and intense solar radiation characteristic of the study site (up to 329 MJ m^{-2}), iron sufficiency is crucial for maintaining photosynthetic electron transport and protecting the photosynthetic apparatus from oxidative damage, ultimately translating into greater seed set and filling [16].

The interaction between nitrogen and iron on oil quality traits is highly significant for total oil yield [45]. The combined application of N_3Fe_3 produced the highest oil yield (933.6 and 906.6 kg ha^{-1}), surpassing all other formulations [46]. This underscores a vital recommendation for Canola production in similar arid environments: to maximize oil productivity per unit area, it is not enough to simply increase nitrogen rates. Integrating a foliar iron program ensures that the physiological machinery, including photosynthesis, respiration, and enzyme activation, is optimized to convert the abundant nitrogen into the maximum possible quantity of seeds, thereby driving up total oil yield. This finding has practical implications for the Toshka region, where expanding oilseed production is a national priority to reduce Egypt's 92% edible oil import dependency [61].

4.4. Combined Effect of Nitrogen and Iron on Leaf Nitrogen and Iron Contents

The significant increase in leaf nitrogen concentration in response to nitrogen fertilization aligns with the established physiological role of nitrogen as a primary constituent of amino acids, proteins, and chlorophyll. When interpreting these results, it is essential to consider the baseline soil nutrient status of the experimental site. The low initial soil N content (23.76–30.14 mg kg^{-1}) and extremely low DTPA-extractable Fe (1.54–2.08 mg kg^{-1}) indicate that the experimental plots were situated on soils with inherently poor nutrient-supplying capacity, characteristic of the arid and calcareous soils of Upper Egypt. This low baseline fertility explains why the crops responded so strongly to nutrient supplementation across the entire treatment range. However, the relationship between nutrient application rates and plant tissue concentrations may not be linear at higher levels. At the maximum N rate (225 kg ha^{-1}), leaf N concentration reached 5.77–6.40%, which approaches or slightly exceeds the sufficiency range for Canola (typically 4.0–5.5% during flowering), suggesting that further N increases may not be efficiently absorbed or may lead to luxury consumption. Similarly, at 300 mg L^{-1} Fe, leaf Fe concentrations reached 124.24–135.29 mg L^{-1}, which is within the upper range of the sufficiency range for Canola (50–150 mg L^{-1}), indicating that additional Fe supplementation may not be beneficial. These observations further support the conclusion that the highest tested rates may approach or reach the plateau of the crop's response curve under these specific soil conditions. This observation is consistent with the findings of Porter et al., 2020 [46] and Alwakel et al., 2021 [45], who noted that a sustained nitrogen supply ensures the accumulation of nitrogenous compounds in vegetative tissues, which directly supports the robust growth parameters observed during development.

Interestingly, foliar iron application also contributed to maintaining or enhancing leaf nitrogen levels. This effect, which increased leaf N by approximately 16–18% under the highest Fe rate, reflects iron's crucial involvement in nitrate reduction and the stability of chlorophyll–protein complexes [44]. Under the high-pH conditions of the Toshka soils, Fe availability is severely restricted, and Fe deficiency can impair nitrate reductase activity, limiting the plant's ability to assimilate applied N. Thus, Fe supplementation not only addresses a direct micronutrient deficiency but also enhances the efficiency of N utilization, a classic nutrient synergy that is particularly important in calcareous soils [43].

The dramatic increase in leaf iron concentration following foliar application is a direct consequence of the foliar feeding strategy. Representative of this strategy are the results from Bybordi and Mamedov, 2010 [47] and Alwakel et al., 2021 [45], which show that foliar sprays, particularly at an optimal concentration of 300 mg L^{-1}, effectively circumvent soil-related constraints such as high pH and nutrient fixation in alkaline environments. The leaf Fe concentration increased by 99.3% and 96.1% under the highest Fe rate, demonstrating that foliar application is an effective delivery method in calcareous soils where soil-applied Fe would be rapidly fixed into unavailable forms. Furthermore, a positive relationship was observed between nitrogen fertilization and leaf iron concentration, even in the absence of direct iron application. This phenomenon, where N_3 treatment increased leaf Fe by approximately 28% compared to N_0, reflects nitrogen's role in promoting vigorous root growth and increasing overall biomass, which creates a stronger metabolic sink for minerals [43]. Additionally, N-induced acidification of the rhizosphere through enhanced proton exudation may temporarily increase Fe solubility in the calcareous soils [7].

The highly significant interaction between nitrogen and iron confirms that balanced nitrogen nutrition is critical for maximizing the efficacy of foliar iron sprays. This interaction can be characterized as synergistic for iron uptake and translocation, based on the quantitative comparison of observed versus expected additive effects. For leaf iron concentration in the first season, the additive expectation was calculated as: $(N_3Fe_0 - N_0Fe_0) + (N_0Fe_3 - N_0Fe_0) + N_0Fe_0 = (54.82 - 49.48) + (75.48 - 49.48) + 49.48 = 80.82$ mg L^{-1}. The observed N_3Fe_3 value (135.29 mg L^{-1}) exceeded this additive expectation by 54.47 mg L^{-1} (67.4%), representing a clear synergistic interaction. The N_3Fe_3 treatment recorded peak leaf iron concentrations (124.24 and 123.89 mg L^{-1}) in both seasons, underscoring the complementary role of nitrogen in enhancing iron uptake and translocation to the shoots [62]. This nutritional synergy ultimately explains the superior vegetative growth and oil productivity recorded under the optimized treatments, demonstrating that under arid conditions, the combined application of N and Fe creates a positive feedback loop: improved N nutrition enhances root growth and Fe uptake, which in turn supports photosynthetic efficiency and N assimilation [43].

4.5. NUE and Implications for Sustainable Fertilization

The calculation of NUE indicators in this study provides important insights into the trade-off between maximizing absolute yields and optimizing resource-use efficiency. The data from this study demonstrate that PFPN declined from 52.5 kg seed kg^{-1} N at 75 kg N ha^{-1} to 11.2 kg seed kg^{-1} N at 225 kg N ha^{-1}, representing an approximately 79% reduction in nitrogen efficiency at the highest N rate. This pattern is consistent with the well-documented phenomenon of diminishing returns in crop fertilization [59,63], where each additional unit of fertilizer produces progressively smaller yield increments.

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The AEN values followed a similar trend, with the highest efficiency observed at intermediate N rates (150 kg ha^{-1}) combined with Fe supplementation (18.2 kg seed kg^{-1} N), compared to lower values at the maximum N rate (12.9 kg seed kg^{-1} N). This indicates that from a purely agronomic efficiency perspective, the intermediate N rate may be more favorable, producing substantial yield gains per unit of applied N while minimizing the environmental risks associated with excessive N application, including nitrate leaching and greenhouse gas emissions [13,64].

However, it must be emphasized that the present study was not designed as a comprehensive optimization study. Moreover, because the highest tested rates (225 kg N ha^{-1} and 300 mg L^{-1} Fe) represent the upper limits of the experimental design, this study cannot determine whether further increases beyond these levels would continue to enhance or potentially diminish Canola yield. The soil fertility baseline of the experimental site, characterized by low available N (23.76–30.14 mg kg^{-1}) and extremely low DTPA-extractable Fe (1.54–2.08 mg kg^{-1}), was instrumental in generating the pronounced yield responses observed across the treatment range. However, at the maximum N rate, the declining PFPN (from 52.5 to 11.2 kg seed kg^{-1} N) and AEN values indicate that diminishing returns were already manifesting within the tested range. The leaf tissue concentrations at the highest Fe rate (124.24–135.29 mg L^{-1} Fe) approach the upper boundary of the crop's sufficiency range, suggesting that the physiological capacity for further Fe uptake and utilization may be limited. Therefore, this study interprets the findings as establishing a maximum yield threshold under the specific conditions of this experiment, rather than a universal optimum. Key indicators that would be required for a complete assessment of sustainable fertilization and to determine true optima include: the absence of these indicators in the current study means that while this study has conclusively identified the maximum yield at the highest tested N and Fe combination under the specific soil fertility conditions of the experimental site, this study cannot claim to have identified an environmental or economic optimum. Future research should expand the treatment range to include higher N and Fe levels, incorporate the above-mentioned indicators, and consider the specific soil fertility context to determine whether the response plateau observed in this study represents a true maximum or merely a reflection of the experimental design limitations.

The absence of these indicators in the current study means that while we have conclusively identified the maximum yield at the highest tested N and Fe combination, this study cannot claim to have identified an environmental or economic optimum. Further research incorporating these indicators is necessary to determine the most sustainable fertilization strategies for Canola production under arid conditions.

The role of iron supplementation in improving NUE (by approximately 18–22%) is noteworthy and aligns with the synergistic relationship between N and Fe discussed earlier. Iron's ability to enhance photosynthetic efficiency and nitrate reductase activity [16,17] likely contributes to more efficient utilization of absorbed nitrogen, partially offsetting the efficiency losses associated with high N application. This suggests that integrated N-Fe management may offer a pathway to improve both productivity and resource-use efficiency, although the extent of these benefits varies with the specific N rates applied.

5. Conclusions

This study demonstrates that nitrogen fertilization (225 kg N ha^{-1}) serves as the primary driver of Canola (*Brassica napus* L.) productivity under the arid conditions of Upper Egypt, increasing seed yield by 240% and oil yield by 277%, while foliar iron application at 300 mg L^{-1} further enhances these gains by 14.4% (two-year average) through improved photosynthetic efficiency and assimilate partitioning, as evidenced by elevated leaf N and Fe concentrations. The N $\times$ Fe interaction was characterized as additive to synergistic, with the combined effect on seed yield being primarily additive (observed effect not significantly exceeding the additive expectation), while the effect on leaf iron uptake and translocation was clearly synergistic (observed N_3Fe_3 leaf Fe: 135.29 mg L^{-1} vs. additive expectation: 80.82 mg L^{-1}). The synergistic component of the interaction can be attributed to the complementary physiological roles of N and Fe, where nitrogen promotes root growth and metabolic activity, while iron serves as a cofactor for enzymes involved in nitrogen assimilation and photosynthesis. However, this maximum yield was achieved at the cost of substantially reduced NUE (PFPN declining from 52.5 to 11.2 kg seed kg^{-1} N), highlighting a critical trade-off between yield maximization and resource-use efficiency. As no direct environmental measurements were conducted, this study establishes an agronomic maximum yield threshold rather than an ecological or economic optimum. Future research incorporating comprehensive environmental and economic assessments across expanded treatment ranges is essential to identify truly balanced and sustainable fertilization strategies for arid-zone Canola production.

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