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Biology organic fertilizer affects the quality and yield of flax under different irrigation regumes

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laxseed (*Linum usitatissimum* L.) oil is an important crop in China, which is rich in saturated fatty acids, alpha-linolenic acid, and other essential nutrients for the human body. Here, we investigated the effects of different irrigation and fertilization conditions on flax yield and quality in semi-arid regions in northern China. Using non-weighing lysimeter fertilization versus non-fertilization, the effects of four irrigation treatments (1 500, 1 800, 2 100, and 2 400 m^3 ha^{-1}) on flax yield and quality were assessed for the flax cultivar 'Yajin7.' As the irrigation quota increased, both the aboveground fresh weight and flaxseed biomass initially increased and subsequently decreased. The flax fresh weight and seed weight increased by 74.52 and 80.70%, at irrigation quotas of 2 100 and 1 500 m^3 ha^{-1}, respectively; however, irrigation quota had no significant effect on flax quality. Fertilizer application significantly improved flax and flaxseed yields by 127 and 77%, respectively, increased mean flax protein content from 20.05 to 24.63%, and decreased the mean lipid content from 46.52 to 43.67%. However, fertilization had no effect on the content of palmitic, stearic, oleic, linoleic, and linolenic acids. Overall, our results highlight that water related benefits to flax crops decrease in response to increasing the irrigation quota and appropriate fertilizer application can significantly improve flax yield and quality. Therefore, this study provides a theoretical basis for irrigation and fertilization related to flax cultivation in northern China.
Keywords: flax; bio-organic fertilizer; irrigation; fertilization management; crop yield; crop quality.

INTRODUCTION

Flax (*Linum usitatissimum* L.), also known as linseed, was discovered by humans approximately 30 000 years ago. It is recognized by international medical and nutritional circles as an important source of nutrients which contribute to several physiological functions (Taibi *et al.*, 2019; Markovic *et al.*, 2021). For example, flax oil contains 45–65% alpha-linolenic acid, which aids in regulating blood lipids, lowering cholesterol, inhibiting thrombosis, and preventing cancer. In addition, flax seeds are rich in proteins, dietary fibers, lignans, and amino acids (Kim *et al.*, 2014; Parikh *et al.*, 2018; Dhyani *et al.*, 2019).

After a millennium of continuous cultivation and improvement, flax is now widely distributed in China, the United States, Russia, Canada, and other countries (Najmanova, 2007) and serves as a primary source of industrial vegetable and cooking oil (Soto-Cerda *et al.*, 2020). Approximately 700 000 ha of arable land is used for flax cultivation in China, mainly in arid and semi-arid regions of the Gansu Province, Inner Mongolia and Ningxia Hui Autonomous Regions. Flax crops are remarkably cold and drought resistant, with the ability to grow in barren soils (Omran *et al.*, 1968).

Drought resistant crops such as flax help to address the major challenges in global agricultural production related to water shortage and irrational fertilizer application (Ram and Irfan, 2021). China is considered one of the most water-stressed countries globally. China's water scarcity stems from a limited supply of fresh water resources, a large population

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base, and water wastage during agricultural use (Ye *et al.*, 2018). Annual agricultural water use in China accounts for >60% of the national water use, with irrigation accounting for 90%; however, the corresponding effective utilization coefficient is only 0.54 (Zhuang *et al.*, 2019). Additionally, irrational irrigation methods not only result in the wastage of valuable water resources, but also have a detrimental effect on crop quality.

Unreasonable use of chemical fertilizers is another problem in agricultural production. Notably, China's use of chemical fertilizers has been increasing at an average rate of 1.44 million tons yr^{-1} (Xiao *et al.*, 2021). Moreover, at the end of 2015, annual chemical fertilizer use in China had peaked at 60.2 million tons, ranking it among the top countries in the world in terms of fertilizer use (Liu *et al.*, 2021). Although the large-scale use of chemical fertilizers can increase crop yield, the excessive use thereof poses major threats to soil, water bodies, and the atmosphere. For example, in 2015, 6.2 million tons of nitrogen and 4.3 million tons of phosphorus were retained in the soil in China, whereas 2.4 million tons of nitrogen and 300 000 tons of phosphorus were introduced into water bodies (Ji *et al.*, 2015). This has created a series of severe environmental problems, such as excessive groundwater nitrate content in the northern drylands, an excess of nitrogen and phosphorous in the surface water of southern paddy fields, high quantities of agricultural ammonia in the atmosphere, and an overall decrease in soil productivity (Zhang *et al.*, 2006; Liu *et al.*, 2021).

Our study area was located in the pastoral farming ecotone of northern China, which contained relatively barren soils. Although flax yield can be greatly improved in the short term by fertilization, the continued use of chemical fertilizers results in the loss of soil nutrients. As organic fertilizers are primarily composed of animal and plant residues (such as livestock manure and crop straw) and consist of decomposed organic materials, they can be described as less harmful plant treatments (Akanbi, 2013). In the study area, cattle and sheep dung are commonly used as organic fertilizers.

Numerous studies have shown that the use of organic fertilizers, compared with the use of chemical fertilizers, can significantly increase the accumulation of organic carbon and nitrogen in the soil. In addition, the use of organic fertilizers can improve the physical and chemical properties of soil, the buffering capacity of soil acid and alkali, the activity of soil related enzymes, and the soil microbial community, thus improving soil permeability and carbon and nitrogen metabolism, which stabilizes the soil and allows for long-term sustainable crop growth (Tang *et al.*, 2006; Chen *et al.*, 2019; Wu, 2021).

Water-fertilizer coupling refers to the effects resulting from the interplay between these two factors on plant growth and nutrient transformation—an optimal water-fertilizer ratio yields the most favorable results (Li *et al.*, 2017). Notably, flax research has long focused on the selective breeding of flax varieties, mainly examining their adaptability to drought and the effects of agricultural cultivation techniques on yield and quality (Khaled *et al.*, 2007). However, relatively few studies have been conducted on water-saving irrigation techniques. In this context, we employed non-weighing lysimeters at the National Field Scientific Observation and Research Station for Grassland Ecology and Hydrology in the northern foothills of Yinshan, Inner Mongolia to study the effects of irrigation quotas and field fertilization management methods on flax yield and quality. Our findings provide a theoretical basis and reference for flax cultivation in northern China with respect to irrigation and fertilization.

MATERIALS AND METHODS

Study site: The test site is located at the National Field Scientific Observation and Research Station for Grassland Ecology and Hydrology (41°12′10″ N, 111°13′01″ E) in the northern foothills of Yinshan, Halawusu, Damao Banner, Baotou City, Inner Mongolia Autonomous Region and China. This area is characterized by a mid-temperate, semi-arid continental monsoon climate. The zonal soil type of the test site is chestnut, and the soil texture is mostly sandy loam and light loam, with varying degrees of gravelization. With respect to nutrient content, soils are low in nitrogen and phosphorus but high in potassium. During the field study (April–September 2020), an ENVIS TrimeLog automatic weather station (German IMKO company) was used to monitor meteorological data including air temperature, air humidity, precipitation, and sunlight hours (Table 1).

The experiment was conducted using non-weighing lysimeters constructed with reinforced concrete structures, with soil backfilled in layers following construction according to the original soil distribution (Figure 1). The lysimeters were arranged in two rows of 12 (N = 24), with each unit covering an area of 9.9 m^2 (4.5 m in length, 2.2 m in width).

Table 1. Climatic data of the study site from April to October 2020.

	April	May	June	July	August	September	October
Average temperature (°C)	4.5	15.6	17.3	18.4	17.6	12.3	3.7
Minimum temperature (°C)	-3.0	4.9	13.8	16.4	12.3	7.6	-2.8
Maximum temperature (°C)	7.7	20.1	23.6	21.8	20.2	16.8	6.2
Relative humidity (%)	37.7	47.2	31.2	60.1	55.5	43.7	38.3
Rainfall (mm)	0.3	15.3	2.0	47.6	18.2	10.7	0.5

Each unit was equipped with an independent flow meter and on-off valve to accurately control the irrigation volume. To prevent the interference of natural precipitation, a rain shelter was constructed over the test site consisting of a steel frame covered with transparent panels on the roof and was equipped with roller wheels and drive units for automated deployment during rainfall.

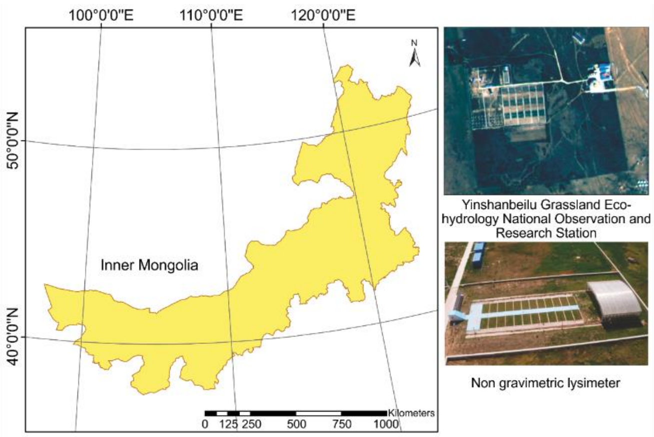

Figure 1. Study area geographic location (left); test site (top right); non-gravimetric lysimeter used in the experiment (bottom right).

Experimental design: Prior to the experiment, the soil in the lysimeters was sampled using an S-shaped sampling method at depths of 0–15 and 15–30 cm. Samples were transported to the laboratory to determine the following basic physicochemical properties: pH was measured using 0.01 mol L^{-1} $CaCl_2$ as the leaching solution, soil organic matter (SOM) was determined using the potassium dichromate oxidation-external heating method (Carter and Gregorich, 2007), soil alkali nitrogen (SAN) was measured using the Conway method (Carter and Gregorich, 2007), soil available phosphorus (SAP) was extracted using sodium bicarbonate and analyzed using Mo–Sb colorimetry (Carter and Gregorich, 2007), and soil available kalium (SAK) was extracted using NH_4OAc and analyzed using the flame photometric method (Carter and Gregorich, 2007). Undisturbed soil samples were collected using the ring knife method, while field water holding capacity (FWH) and soil bulk density (SBD) were determined using the constant head method (Carter and Gregorich, 2007) (Table 2).

"Yajin7" cultivar flax seeds were provided by the Research Institute of Pastoral Water Resources Science, Ministry of Water Resources. A two-factor design was adopted for this experiment. Fertilizer application included the following two treatments: non-fertilization and the application of basal, starter, and topdressing fertilizers, while the irrigation quota included the following four treatments: 1 500, 1 800, 2 100, and 2 400 m^3 ha^{-1} (N = 8 treatments) (Table 3).

In the field fertilization experiment, soil in the lysimeter was first leveled following deep tilling to 25 cm. As the test site was located in the interwoven area of agriculture and animal husbandry, there was an abundance of high-quality organic fertilizers (cow and sheep manure). According to the flax planting practices of local cultivators, in this experiment, 15 kg (~15 000 kg ha^{-1}) of a broken-down organic fertilizer was applied at basal level to the 12 lysimeters in the four fertilization treatments. Flaxseeds were sown by drill seeding 10 days after fertilizer application. Before sowing, 24 kg of flaxseeds were mixed with 48 g of 25% azoxystrobin wettable powder (Jiangsu Dongbao Pesticide Chemical Co., Ltd., Jiangsu, China) to prevent leaf smut. The seeds were sown at

Table 2. Soil physicochemical properties including soil organic matter (SOM), soil available phosphorous (SAP), soil available kalium (SAK), soil alkali nitrogen (SAN), field water holding capacity (FWH), and soil bulk density (SBD).

pH		SOM ($g\ kg^{-1}$)	SAP ($mg\ kg^{-1}$)	SAK ($mg\ kg^{-1}$)	SAN ($mg\ kg^{-1}$)	FWH (%)	SBD ($g\ cm^{-3}$)	Soil type
0–15 cm	8.16	14.98	0.94	153.5	58.92	16.02	1.64	Chestnut soil
15–30 cm	8.65	11.88	0.44	89.0	34.08	19.80	1.42	

Table 3. Study design for flax growth treatments.

Treatment Type	Treatment ID	Irrigation quota ($m^3\ ha^{-1}$)	Number of irrigations (treatments)	Irrigation quota ($m^3\ ha^{-1}$)
Unfertilized	HM1	150	10	1 500
	HM2	180	10	1 800
	HM3	210	10	2 100
	HM4	240	10	2 400
Fertilized	AHM1	150	10	1 500
	AHM2	180	10	1 800
	AHM3	210	10	2 100
	AHM4	240	10	2 400

a depth of 3 cm, with a row spacing of 25 cm, and 1 kg of seeds (100 kg ha^{-1}) were sown in each unit. Subsequently, 0.15 kg (150 kg ha^{-1}) of starter fertilizer diammonium phosphate (Jiangsu Dongbao Pesticide Chemical Co., Ltd.) was evenly applied to the 12 corresponding lysimeters, and the soil was mulched to retain moisture. Topdressing was carried out twice throughout the experimentation process (at seedling and bud emergence), during which 0.06 kg (60 kg ha^{-1}) of urea (Jiangsu Dongbao Pesticide Chemical Co., Ltd.) was evenly applied to the 12 lysimeters.

Irrigation was started at the time of sowing, with the four possible treatment conditions applied 10 times over the five reproductive stages—sowing-seedling emergence, seedling emergence-tillering, tillering-bud emergence, bud emergence-flowering, and grain filling-maturity (average of two applications per stage).

Testing methods: Flax was harvested 120 days after sowing, and the following indicators were measured and assayed. Five 1 m^2 flax plots were selected at random for harvesting. The fresh weight of the aboveground biomass was determined and the yield per hectare was calculated. For flax plant height and basal stem diameter, five flax plants were selected at random from the sample plots. The height was obtained using a measuring tape and the basal stem diameter using Vernier calipers. The fresh weight of flaxseeds was measured before being oven-dried at 60 °C for 12 hours. All flax seeds were peeled from the flax and their yield per 1 m^2 calculated. Flaxseed protein content was determined using the Kjeldahl method (Carter and Gregorich, 2007).

Lipid content of the flaxseeds was determined via Soxhlet extraction (Carter and Gregorich, 2007).

The content of five fatty acids (palmitic, stearic, oleic, linoleic, and alpha-linolenic acid) in the flaxseeds was determined using the hydrolysis-extraction method (Carter and Gregorich, 2007).

Statistical analysis: Graphs were plotted using Origin 2018 SR1 (OriginLab Corporation, Northampton, MA, USA), and statistical analyses were carried out using SPSS v.23.0 (SPSS Inc., Chicago, IL, USA). A one-way analysis of variance (ANOVA) was performed to test the effects of fertilizer application and irrigation quota on flax growth (aboveground fresh weight, flaxseed biomass, plant height, and basal stem diameter) and nutrient content (protein, lipid, and palmitic, stearic, oleic, linoleic, and alpha-linolenic acids). A two-way ANOVA was performed to test the effects of fertilizer application and irrigation quota on aboveground and flaxseed biomass, in addition to protein and lipid content. To compare the least significant difference (LSD) and priming effect at the significance level of p = 0.05, we performed multiple comparisons using Duncan's multiple range tests.

RESULTS

Effects of different irrigation quotas and fertilization treatments on flax growth and yield: The different fertilization treatments and irrigation quotas had varying effects on aboveground fresh weight, flaxseed biomass, plant height, and basal stem diameter of flax (Figure 2), with fertilization treatments maintaining a greater effect on aboveground fresh weight and flaxseed biomass. The average aboveground fresh weight of flax was 6791 kg ha^{-1} in the four fertilization treatments and 2 990 kg ha^{-1} in the four non-fertilization treatments (Figures 2a and b). Furthermore, the average flaxseed biomass was 1 514 kg ha^{-1} in the fertilization treatments and 854 kg ha^{-1} in the non-fertilization treatments. In contrast, fertilizer application appeared to have a negligible effect on plant height and basal stem diameter (Figures 2c and d).

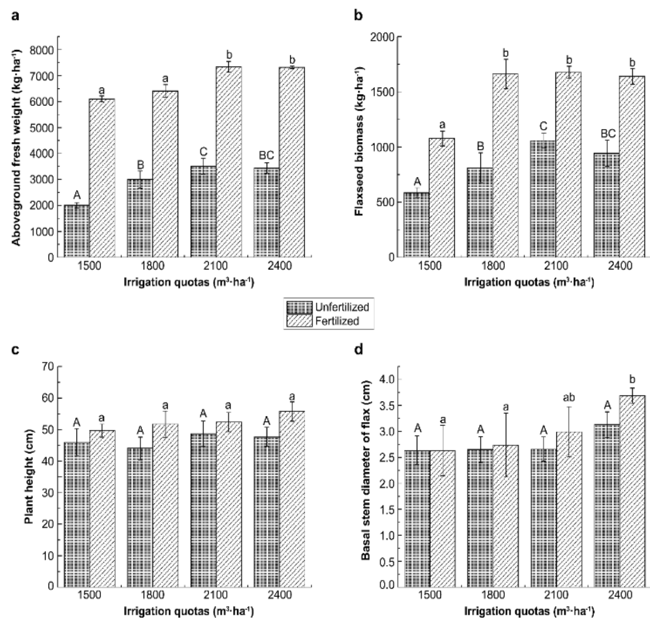

Figure 2. Effects of different irrigation quotas and fertilization treatments on flax growth and yield including (a) aboveground fresh weight, (b) flaxseed biomass, (c) plant height, and (d) basal stem diameter of flax. Uppercase letters above the bars indicate significant differences ($p < 0.05$) in flax growth between different irrigation quotas without fertilizer application, and lowercase letters above the bars indicate significant differences ($p < 0.05$) in flax growth between different irrigation quotas with fertilizer application.

When assessing the effects of different irrigation quotas on flax growth, a significant increase ($p = 0.05$) was observed in aboveground fresh weight under the non-fertilization treatments (from 2 013 to 3 513 kg ha^{-1}) and flaxseed biomass (from 587 to 1 060 kg ha^{-1}) as water quotas increased from 1 500 to 2 100· m^3 ha^{-1} (Figure 2a). In contrast, in the fertilization treatments, aboveground fresh weight increased

Table 4. Effects of different irrigation quotas and fertilization treatments on flax quality. HM1-4 refers to unfertilized treatments, while AHM1-4 refers to fertilized treatments. Lower-case letters within a column indicate significant differences ($p < 0.05$) in the nutritional indicator of flax under different treatments.

Treatment ID	Protein (%)	Lipid (%)	Fatty acid composition				
			Palmitic acid (%)	Stearic acid (%)	Oleic acid (%)	Linoleic acid (%)	Alpha-linolenic acid (%)
HMl	19.57±0.27[a]	47.08±1.23[b]	5.63±0.10[a]	4.18±0.11[a]	19.23±0.08[a]	13.61±0.34[a]	56.32±0.26[a]
HM2	20.31±0.37[a]	45.95±0.33[b]	5.68±0.01[a]	4.20±0.05[a]	19.51±0.12[a]	13.61±0.06[a]	56.19±0.04[a]
HM3	20.08±0.45[a]	46.37±0.92[b]	5.71±0.08[a]	4.21±0.06[a]	19.20±0.07[a]	13.64±0.10[a]	56.09±0.46[a]
HM4	20.23±0.85[a]	46.69±0.59[b]	5.67±0.06[a]	4.21±0.06[a]	19.34±0.09[a]	13.63±0.34[a]	56.15±0.84[a]
AHMl	24.72±0.32[b]	43.23±0.32[a]	5.71±0.38[a]	4.22±0.09[a]	19.16±0.05[a]	13.71±0.26[a]	56.11±0.16[a]
AHM2	24.47±0.93[b]	43.07±0.45[a]	5.72±0.17[a]	4.22±0.05[a]	19.15±0.01[a]	13.56±0.12[a]	56.11±0.16[a]
AHM3	24.73±0.43[b]	43.75±0.13[a]	5.65±0.13[a]	4.23±0.07[a]	19.16±0.04[a]	13.65±0.31[a]	56.07±0.21[a]
AHM4	24.59±0.08[b]	44.64±0.95[ab]	5.70±0.15[a]	4.21±0.05[a]	19.29±0.06[a]	13.64±0.18[a]	55.93±0.67[a]

Table 5. Results of a two-way ANOVA showing the effects of fertilization and irrigation quotas on flaxseed biomass, aboveground fresh weight, as well as protein and lipid content. Asterisks in the table indicate a significant difference ($p < 0.05$).

	F				P			
	Flaxseed biomass	Above ground fresh weight	Protein	Lipid	Flaxseed biomass	Aboveground fresh weight	Protein	Lipid
Fertilization (F)	304.33	1862.70	438.60	78.21	0.000*	0.000*	0.00*	0.00*
Irrigation quota (Irr.)	39.81	53.68	0.34	2.16	0.000*	0.000*	0.80	0.13
F × Irr.	3.93	2.60	0.97	1.35	0.028*	0.087	0.43	0.29

from 6103 to 7340 kg ha^{-1}, and flaxseed biomass increased from 1 077 to 1 677 kg ha^{-1} across the same irrigation range. More specifically, aboveground fresh weight showed a significant increase (p = 0.05) when the irrigation quota was increased up to 2 100 m^3 ha^{-1}, whereas flaxseed biomass showed a significant increase (p = 0.05) when the irrigation quota was increased up to 1 800 m^3 ha^{-1}. Plant height and basal stem diameter showed trends of increasing with an increased irrigation quota; however, only basal stem diameter showed a significant change (p = 0.05) at an irrigation quota of 2 400 m^3 ha^{-1}.

Effects of irrigation quota and fertilization treatment on flax quality: Flaxseed nutrient content varied depending on the irrigation quota and fertilization treatment used (Table 4). The protein content in the non-fertilization treatments was significantly lower than that in the fertilized treatment plots (p = 0.05) and the protein content decreased by approximately 4% in the untreated plots; however, the overall effect of irrigation quota on flaxseed protein content was not significant ($p > 0.05$). More specifically, the protein content in the non-fertilization treatments fluctuated within a range of 19.57–20.31% ($p > 0.05$) and varied within a range of 24.47–24.73% in fertilized treatment seeds ($p > 0.05$). Moreover, the irrigation quota did not significantly affect the lipid content in flaxseeds ($p > 0.05$). Fertilization appeared to have an inhibitory effect on the fat content of flaxseeds, showing an approximate 3% reduction compared with unfertilized treatments. Furthermore, the different irrigation quotas and fertilization treatments had virtually no effect on palmitic, stearic, oleic, linoleic, and alpha-linolenic acid content in flaxseeds.

Two-way ANOVA of irrigation quotas and fertilization treatments: The two-way ANOVA results showed that the individual or interacted fertilization and irrigation quotas showed varied effects on flaxseed yield, aboveground flax biomass, flaxseed protein content, and flaxseed fat content (Table 5). Fertilization application significantly affected flaxseed biomass, aboveground biomass, protein content, and fat content ($p < 0.05$). Similarly, when the irrigation quota acted alone, its effects on flaxseed yield and aboveground biomass were also significant ($p < 0.05$); however, no significant effects on flaxseed protein content and fat content were observed ($p > 0.05$). When fertilization and irrigation quotas interacted, the only significant effect was on flaxseed biomass ($p < 0.05$).

DISCUSSION

Water can be a limiting factor for crop growth with the majority of studies examining crop irrigation effects demonstrating that an appropriate increase in irrigation level can enhance crop quality (Sun *et al.*, 2020; Yasuor *et al.*, 2020). In our study, we showed that in the absence of fertilizer application, flax yield significantly increased by 49% when the irrigation quota increased from 1 500 to 1 800 m^3 ha^{-1}, and further increased by an additional 17% when the irrigation quota increased to 2 100 m^3 ha^{-1}. However, at an irrigation quota of 2 400 m^3 ha^{-1}, flax yield decreased by 2.3%. Thus, flax yield increased up to an inflection point with increasing irrigation quotas, which is consistent with the findings of Rebetzke et al. (2016) and Yang et al. (2022). The observed trend of flaxseed yield in response to irrigation quota was consistent with that of flax yield. Accordingly, the findings of this study suggest that during flax production, more irrigation is not always conducive, indicating that water use efficiency peaks at a certain irrigation quota and subsequently decreases. Contrary to the finding that different irrigation quotas have a significant effect on flax growth, no such significant effects were observed in the current study regarding the content of protein, fat, and the five main fatty acids in flaxseeds. Our finding indicates that changing the irrigation quota can affect flax yield but not flax quality.

Developed countries have attached great importance to the use of organic fertilizers in agricultural production. For example, manure helps to supplement soil nutrients and reduce the use of chemical fertilizers (Agegnehu *et al.,* 2017; Goenadi *et al.,* 2018). In this study, combined with the staggered planting environment of farming and grazing in northern China, cow and sheep manure fertilizer were selected as base fertilizer in the four fertilization treatments. Numerous studies have shown that the use of organic fertilizer can improve the physical and chemical properties of soil, in addition to increasing the biological richness, soil enzyme activity, and nutrients in soil; thus, providing better conditions for plant roots (Tang *et al.*, 2006; Feng, 2009; Chen *et al.*, 2013; Chen *et al.*, 2019; Wu, 2021). Furthermore, studies have been conducted examining the effects of organic fertilizer on crop yield and quality, with the vast majority demonstrating a positive correlation (Muhumed, 2014; Workneh, 2014). In coriander, the application of organic fertilizer significantly increased branch and leaf number, in addition to leaf area, and decreased the number of harvest days significantly (Ahmad, 2017). In a recent study by Wang et al. (2019), it was discovered experimentally that crop residues could be used as mulching material or organic fertilizer as an alternative to burning, subsequently improving soil organic carbon (SOC) and crop grain yield. In addition, Min et al. (2018) compared the effects of organic and chemical nitrogen (N) fertilizer on rice in China and found that organic fertilizer markedly increased soil organic matter content, promoted grain N accumulation, and improved rice production. Furthermore, organic fertilizer treatments produced a higher yield (11–13%) and higher net economic benefit (4–5%) than that of chemical N fertilizer over three years. The present study showed that the average flax yield in fertilization treatments was 6 792 kg ha^{-1}, with a yield increase of 127.1% compared with that produced under non-fertilization treatments (2 991 kg ha^{-1}). Similarly, the yield increase in flaxseeds was ≤77.9% (average flaxseed yield in fertilized and unfertilized treatments was 1 514 and 851 kg ha^{-1}, respectively), indicating that fertilization can significantly increase the yield of both flax and flaxseeds.

Notably, the use and amount of organic fertilizer should be adjusted according to local soil conditions. Specifically, fertilizer application should be adapted to local conditions, by analyzing local soil nutrient concentrations as a basis for adjusting fertilizer application. In the present study, the original soil in the test site had low levels of alkaline hydrolyzable nitrogen, available potassium, and particularly low levels of available phosphorus; therefore, two rounds of topdressing were included in the study design of the fertilization treatment.

In fertilizers, nitrogen, phosphorus, and potassium constitute the major components of plant organic matter, such as plant proteins, vitamins, and enzymes, thereby exerting direct or indirect effects on protein synthesis and lipid metabolism (Etesami and Jeong, 2020; Vicente *et al.,* 2022). For example, Williams et al. (1994) demonstrated that wheat plants treated with high concentrations of nitrogen fertilizer had less lipid accumulation compared to low nitrogen controls, whereas Dick et al. (2016) found that fertilization significantly increased total protein content in winter wheat. Results from present study showed that all fertilization treatments significantly increased protein content (~4%) and significantly decreased lipid content (~3%) compared with the non-fertilization treatments under the same irrigation quotas. Thus, we concluded that fertilization positively affects protein synthesis and lipid degradation.

Regarding the effect of the application of biological organic fertilizer and irrigation amount on crop fatty acids, Gülta *et al.,* (2020) found that increasing supplementary irrigation increased protein and oil content, volume, and fatty acids in rapeseed cultivation, with full-irrigation treatment producing the highest yields. Additionally, a study by Doost et al. (2019) reported an increase in unsaturated fatty acids (oleic acids, linoleic, linolenic and palminoleic acid) with bio-fertilizer compared to the control, while it was found vice versa in case of saturated fatty acids (palmitic and arashidic acid). Our results are consistent with these findings, which showed that fertilization increased the content of palmitic and stearic acids but decreased the content of oleic, linoleic, and alpha-linolenic acids, although the effects on palmitic, stearic, oleic, linoleic, and alpha-linolenic acids were not significant.

In our study, we investigated the cultivation of flax in the semi-arid regions of northern China with respect to the effects of variable irrigation quotas and fertilization treatments. As the irrigation quotas increased, flax yield initially increased, and then decreased; thus, the contribution of water to flax yield diminished with increasing amounts. Furthermore, increasing irrigation water volume did not significantly alter the quality of flax. Regarding the effect of fertilizer application, appropriate fertilizer application can considerably increase the yield, and significantly alter the quality of flax. The results of this study provide a theoretical basis for improving irrigation and fertilization strategies for flax cultivation in northern China. However, because the present study site was located in the semi-arid areas of northern China, the findings are restricted to specific climatic and environmental conditions, and the research results are region-specific. To further improve flax yield in northern China, future research should focus on the intercropping of flax with other crops, improvements in flax seed quality, optimization of flax irrigation methods, and meeting the nutrient and water requirements of flax in various growth stages.

Conflict of interests: The authors declare that there is no conflict of interest.

Authors' contribution statement: BC and JW designed the study; BC, LH, AB, GN, and FT performed the experiments; BC and ZHM analyzed the data and wrote the manuscript; JW and LJF provided important and valuable suggestions for designing the study and manuscript writing. All authors that commented on previous versions of the manuscript have read and approved the final manuscript.

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***Data availability statement*:** The project supporting this research is still ongoing. Therefore, the data obtained during this research are not yet available for use.

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