Pak. J. Bot., 57(2): DOI: http://dx.doi.org/10.30848/PJB2025-2(3)

ALLOMETRIC VARIATIONS IN *CAMELINA SATIVA* L. IN RESPONSE TO ENVIRONMENTAL FACTORS AND NUTRIENT LEVELS

ARSHID MUNIR[1], FAYYAZ-UL-HASSAN[1*], ABDUL MANAF[1], EHSAN UL HAQ[1], MUHAMMAD KUSAR NAWAZ SHAH[2] AND TAMOOR HUSSAIN[3]

[1]Department of Agronomy, PMAS Arid Agriculture University Rawalpindi, Rawalpindi 46300, Pakistan
[2]Department of Plant Breeding and Genetics, PMAS Arid Agriculture University Rawalpindi, Rawalpindi 46300, Pakistan
[3]Barani Agricultural Research Institute, Chakwal, Pakistan
[*]Corresponding author's email: fayyaz.sahi@uaar.edu.pk

Abstract

Climate change poses challenges for plant species in less hospitable regions, yet resilient varieties like Camelina sativa may thrive. This study, conducted during the winter seasons of 2016–17 and 2017–18 across three locations in the Pothwar region, Pakistan, aimed to assess *Camelina sativa's* adaptability to varying environments and macronutrient levels. Employing five nitrogen (N) and phosphorus (P) rates alongside a constant potassium (K) rate, the experiment utilized a randomized complete block design with a split-plot arrangement. Results indicated significant effects from all factors tested (NPK levels, locations, and years). Application of NPK @ 50:30:20 kg ha^{-1}notably enhanced plant height (119.45cm), pod count per plant (804.8), seeds per pod (19.9), thousand seed weight (1.84 g), seed yield (1789 kg ha^{-1}), and biological yield (7952.7 kg ha^{-1}). Conversely, control treatments yielded minimal results. Furthermore, NARC exhibited the tallest plants (94.7cm) and highest biological yield (7708 kg ha^{-1}), while Talagang showed superior attributes such as pod count per plant (449.9), seeds per pod (14.7), thousand seed weight (1.41g), and seed yield (1437 kg ha^{-1}).Oil content decreased with rising NPK levels, while protein content displayed an inverse relationship. NPK @ 50:30:20 kg ha^{-1}resulted in lower oil content (40.8%), but higher protein content (34.1%) compared to controls. Overall, oil and protein content exhibited a negative correlation and responded significantly to NPK variations. Application of NPK fertilizers notably improved Camelina growth, yield, and quality traits across precipitation levels. NPK fertilizers (50:30:20 kg ha^{-1}) enhanced Camelina yield attributes under diverse precipitation conditions.

Key words: NPK fertilizers; Rainfall; Locations; Climate.

Introduction

Pakistan is facing a severe deficiency of edible oil where production is far lower than consumption. The native oilseed crops have lower yield potential and are susceptible to diseases and insect pest attacks with shattering and post-harvest losses such as Rapeseed, Mustard, and Canola have high water requirements and also more than 35% shattering losses. Therefore, promising alternate options as compared to existing ones are limited for the farmers. The total demand in the country was estimated to be 3.214 million tons out of which only 16.7% (0.460 million tons) was locally produced while the remaining 83.3% (2.754 million tons) was imported paying a cost of Rs. 662.657 billion (Anon., 2020). To overcome the deficiency and to meet the demand of a rapidly growing population it is an imperative approach to introduce an oil seed crop with unique and attractive features. Currently, there is an urgent need to comprehend the possible effects of catastrophic climatic occurrences on important agricultural areas. A significant issue in Pakistan is the unprecedented weather patterns, especially for the production of oilseeds (Khan *et al.*, 2021). This scenario results in several difficulties, including moisture stress, poor seed quality, pod cracking, and increased pest and disease pressure, all of which lower the potential yield of native oilseed crops (Raza, 2021). Moreover, to minimize the import bill and to fulfill the requirement of the country, an oilseed crop like Camelina with best agronomic features could be the best alternative of winter rapeseed due to its low input requirements, drought tolerant ability, and least shattering losses.

Camelina sativa is an exotic oilseed crop belonging to the family Brassicaceae, having fewer agronomic requirements (Haq *et al.*, 2022). It has a unique fatty acids profile with more alpha-linolenic acid and low erucic acid (Zubr & Matthäus, 2002). The Camelina seed comprises more than 40 % oil, out of which unsaturated fatty acids account for 90%. It also includes alpha-linolenic acid (30–40%), linoleic acid (15–25%), oleic acid and eicosenoic acid (15%), Tocopherol content (700 mg kg^{-1}) as well as lower cost vegetable oil (Waraich *et al.*, 2013). In dry land cereal-based cropping systems, Camelina has a great potential to enhance productivity and sustainability, while its fatty acid profile makes it suitable for industrial and nutritional applications (Hulbert *et al.*, 2012). Camelina is predominantly able to bear drought conditions and can be grown in most soil types (Gugel & Falk, 2006).

Apart from this, Camelina is a crop that may be planted in spring or fall and has a short growing season with a variable growth cycle ranging from 90 to 130 days (Cullere *et al.*, 2023). It exhibits resistance to drought, cold, pests, and diseases, requires little agricultural inputs, demonstrates its flexibility to a variety of climatic conditions, and even thrives on depleted and marginal soils (Vollmann *et al.*, 2007). Furthermore, it is an effective and sustainable diversification strategy for European agricultural systems to grow this crop due to its compatibility with current farm machinery and possible uses as a main crop, cover crop, or relay crop. However, compared to other Brassica crops, Camelina has lesser yield stability (Jarecki, 2021). This factor typically works as the main barrier to its successful integration and wide use within modern farming systems, along with poor agronomic expertise (Angelini *et al.*, 2020).

Fertilizers are essential components of modern farming, have played a significant role in agricultural growth and yield enhancement of different commodities. Types of fertilizers, balanced amount, time and methods of application have great importance in sustainable crop production (Haq *et al*., 2023). In arid and semi-arid environments, efficient macronutrient (NPK) management is essential for obtaining the best yields of *C. sativa.* Among these fundamental macronutrients, nitrogen (N), phosphorus (P), and potassium (K) are crucial for plant growth and yield. For instance, nitrogen stimulates the production of proteins, cell division, and chlorophyll in plants (Haq *et al.*, 2023). Improving the N-efficiency of *C. sativa* reduces the potential of environmental contamination while increases economic rewards. In terms of the environment, the crop should get optimal N dose to ensure yield development and to avoid eventual N-leaching from the soil (Barłóg, & Grzebisz, 2004). The proper usage of N-sources is also essential to maximize the economic return (Sarwar *et al.*, 2021). Phosphorus, after nitrogen, is the scarcest necessary plant macronutrient. Phosphorus is essential in numerous biological processes that occur in all living creatures. It is a necessary component of nucleic acids and cellular membranes, and it is important in photosynthesis, energy conservation, carbon metabolism, cell signaling, and as a catalyst in many biological activities (de Bang *et al.*, 2021). The application of phosphorus helps strengthen plant roots, which promotes better grain dispersion and higher crop quality (Grant & Flaten, 2019). Meanwhile, potassium has an impact on oilseed crops as well as the activation of enzymes, stomatal function, and starch production in plants (Borah, 2021).

This demonstrates that NPK fertilizers have an important role in increasing the yield of a variety of field crops, including *C. sativa*. Despite its significance, no systematic attempt has been made to establish the ideal NPK dose to guarantee the successful production of *C. sativa* under the Pothwar regions in Pakistan. Therefore, this study aimed to examine the response of *C. sativa* under different environments in low, medium, and high rainfalls of the Pothwar region and to evaluate the effects of N, P, and K on growth, yield, and quality attributes.

Material and Methods

Experimental conditions: During the winter seasons of 2016-17 and 2017-18, field experiments were conducted to assess the adaptability of *C. sativa* to diverse environments and nutrients at three distinct locations on the Pothwar plateau. These locations include the National Agricultural Research Center, Islamabad (NARC) (latitude 33.7o N; longitude 73.1o E; elevation, 504 m; annual rainfall; 1000-1200 mm), University Research Farm (URF), Chakwal Road, Rawalpindi (latitude 33.1o N; longitude 73.0o E; elevation 510 m; annual rainfall, 650-850 mm), and Talagang (latitude 33.5° N; longitude 71.8° E; elevation, 457 m; annual rainfall, 300-425 mm). Each site underwent two preparatory tillages and was left as summer fallow. The seedbed was prepared using two plows, followed by planking. The experiments were conducted using Randomized Complete Block Design (RCBD) with three replications, 1.8 m x 5 m plot size, and six rows per plot, 30 cm apart. To have easy access for sampling, a 2 m distance was maintained within the replications. The treatments were assigned as five nitrogen rates (0 kg, 10 kg, 20 kg, 40 kg & 50 kg ha^{-1}), five phosphorus rates (0 kg, 10 kg, 20 kg, 30 kg, and 40 kg ha^{-1}), and a single rate of potassium @ 20 Kg ha^{-1} in all the treatments other than control (no fertilizer application). The sources of nitrogen, phosphorous, and potassium were urea, diammonium phosphate (DAP), and potassium sulfate (SOP), respectively. The crop was planted with single row hand drill by using seed @ 4 kg ha^{-1} in 2nd week of October during both years. The crop was thinning after three weeks of emergence to maintain a 10 cm plant-to-plant distance. Two hoeing were carried out on 30th and 60th day after sowing. Harvesting was done manually at physiological maturity. The harvesting dates at NARC-Islamabad, URF-Koont, and Talagang were the 20th, 24^{th,} and 27thof March 2017, while during 2018, the crop was harvested on the 22nd, 25^{th,} and 28th of March at three locations, respectively.

Data collection: The study recorded crop data on *C. sativa* growth and yield attributes, determining plant height (PH) by randomly selecting ten plants at harvest time and quantifying the average calculations. The number of pods per plant (NPP) was assessed by counting pods from ten randomly chosen plants per plot at harvest, and the mean was calculated. Additionally, one hundred pods were randomly sampled from each plot during harvesting, and the seeds within each pod were counted to determine an average. Three sets of a thousand seeds were extracted from each plot and their weight was measured using an electrical balance to determine the average thousand seed weight. Harvesting involved collecting a two-meter central row length from each plot, followed by sun-drying the plants for several days. The biological yield (BY) was converted to kg ha^{-1} by weighing dried samples, and the seed yield (SY) was determined by measuring the weight of the seeds.

Seed quality parameters: The oil content (OC) (%) of the seed was determined using a solvent extraction technique using n-hexane (Elleuch *et al.*, 2007). The protein content (PC) (%) of the seed was calculated using the Kjeldhal (Kjel Sampler K-376) method (Bayar *et al.*, 2016).

Soil data collection: Composite soil samples from each replication were taken from 0-30 cm and 15-30 cm depths before sowing at all three locations during both years. The soil extract was prepared and the pH of the extract was recorded with a pH meter (BANTE Instrument, PHS-3BW). The electrode of the EC meter (CORNING Conductivity meter-220) was rinsed with distilled water and then inserted into the soil extract to record the EC from the instrument display. Organic matter and nitrate-N were measured as described by Keeney & Nelson (1982) with minor modifications. A spectrophotometer (PD 303S-APEL Co., Ltd., Kawaguchi, Japan) was used to record phosphorus and extractable K was measured by flame photometer (Digiflame-DV-710)as mentioned by Westerman (1990). The physicochemical properties of three experimental locations are given in Table 1.

Table 1. Soil analysis data of NARC, Koont, and Talagang during 2016-17 & 2017-18.

Location	**NARC**		**Koont**		**Talagang**	
Year	**2016-17**	**2017-18**	**2016-17**	**2017-18**	**2016-17**	**2017-18**
Depth (cm)	**0-30**	**0-30**	**0-30**	**0-30**	**0-30**	**0-30**
Sand %	72	71.3	79.1	78.4	77.2	76.2
Silt %	18.3	18.7	15	15.6	15.7	16.4
Clay %	10.6	10.9	6.76	6.86	7.97	8.27
pH	7.97	7.77	7.77	7.97	8.17	7.87
EC (ds/m^3)	0.84	0.88	0.72	0.74	0.88	0.94
O.M	0.8	0.77	0.64	0.62	0.73	0.74
Aval. P	8.27	7.97	5.75	5.65	6.36	6.26
Aval. K	231.1	237.1	230.1	223	192.7	193.7
NO_3-N	6.76	6.26	5.95	6.15	6.46	6.66

EC = Electric conductivity, OM = Organic matter

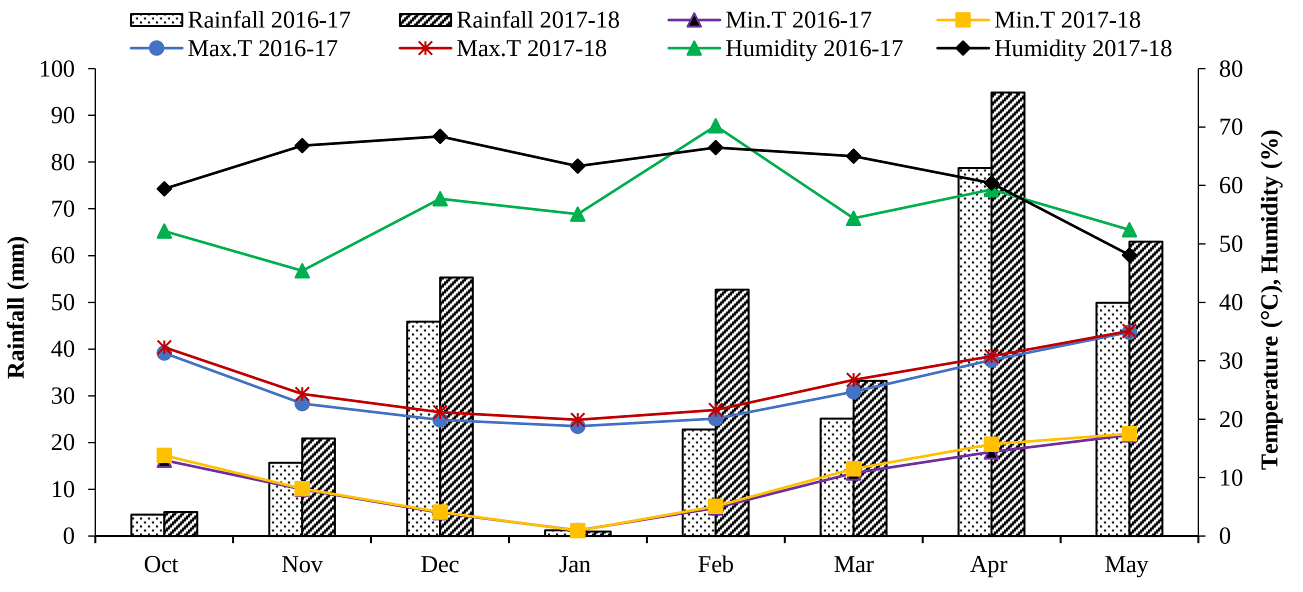

Fig. 1. Weather data of three locations during 2016-17 & 2017-18.

Climate data collection: The Pakistan Meteorological Department in Islamabad provided weather data for experimental sites from nearby observatories during both years (Fig. 1).

Statistical analysis: The statistical analysis was conducted utilizing Statistics 8.1, with the least significance test (LSD) applied at a 5% probability level to discern significant variations among treatment means. Additionally, the linear relationships between agronomic traits were assessed using Pearson's correlation coefficient. A GGE biplot analysis was performed to explore the interactions between NPK levels, location, and year on various agronomic traits of *C. sativa*. This analysis was executed using the "correlation coefficient" and "age" functions within R Studio (R Studio, 2022). Subsequently, p-values were computed to categorize the various agronomic traits of *C. sativa* in response to potential interactions among NPK levels, location, and year, respectively("R Studio" 2022).

Results

Effects of nutrients (NPK): The main effects of NPK fertilizers showed statistically significant differences among mean values of all the observed growth, yield, and quality characteristics at $p<0.05$ (Table 2). Maximum mean values were observed for plant height (112 cm), number of pods plant-1(650.29), number of seeds pod^{-1} (18.73), thousand seed weight (1.69 g), seed yield (1861.3 kg ha^{-1}), biomass yield (7952.7 kg ha^{-1}) with NPK applied @ 50: 30: 20 kg ha^{-1} while lowest mean values (68.2cm, 268.83, 9.23, 1.06g, 998kg ha^{-1} and 7261.9 kg ha^{-1}, respectively) for all the attributes were recorded in control treatments. NPK @50:30:20 kg ha^{-1} for quality variables provided minimum oil (40.8%) and protein contents (34.0%), which were significantly influenced by various NPK levels as compared to control treatment where maximum oil contents (45.0%) and minimum protein contents (30.4%) were observed with negative correlation to each other in Camelina crop, respectively.

Effects of years: The data analysis for both year means revealed that the observed parameters exhibited differential responses like plant height (92.7cm), number of pods (450.29), number of seeds per pod (14.17), thousand seed weight (1.38 g), biomass yield (7536.5 kg ha^{-1}) and finally the seed yield (1407.8 kgha^{-1}) provided statistically superior results ($p<0.01$) during second year (2017-18) (Table 2).

Table 2. Interactive effects of nutrients, environments, and years for growth, yield, and quality traits of *Camelina sativa*.

Treatments	Plant height (cm)	No. of pods / Plant	No. of seeds / Pod	1000 seed weight (g)	Seed yield (kg ha^{-1})	Biological yield (kg ha^{-1})	Seed oil content (%)	Seed protein content (%)
NPK levels	**	**	**	**	**	**	**	**
$N_0P_0K_0$	68.2 h	269 h	9.24 g	1.06 i	998.0 h	7262 def	46.6 a	32.0 ijkl
$N_{30}P_{10}K_{20}$	81.0 g	329 fg	11.7 e	1.17 gh	1127 fg	7239 ef	46.1 abc	32.5 fghij
$N_{30}P_{20}K_{20}$	89.1 ef	387 e	12.7 e	1.27 f	1264 e	7388 cde	45.3 bcde	33.1 defgh
$N_{30}P_{30}K_{20}$	92.8 de	434 d	13.8 d	1.33 e	1389 d	7491 bc	43.6 gh	33.6 bcdef
$N_{30}P_{40}K_{20}$	95.9 cd	474 c	14.8 d	1.39 d	1518 c	7538 bc	44.5 efg	33.6 bcde
$N_0P_{30}K_{20}$	78.5 g	314 g	10.6 f	1.13 h	1075 gh	7126 f	46.3 ab	32.2 ghijk
$N_{10}P_{30}K_{20}$	83.6 fg	363 ef	12.1 e	1.20 g	1195 ef	7452 bcd	45.8 abcd	32.8 efghi
$N_{20}P_{30}K_{20}$	101 bc	504 c	15.9 c	1.46 c	1608 c	7624 b	45.0 def	34.3 abc
$N_{40}P_{30}K_{20}$	105 b	561 b	17.1 b	1.57 b	1738 b	7828 a	43.0 hi	34.6 ab
$N_{50}P_{30}K_{20}$	112 a	650 a	18.8 a	1.69 a	1861 a	7953 a	42.0 ij	35.1 a
SE ±	3.3513	18.799	0.5127	0.021	49.977	99	0.1822	0.1962
Locations (L)	**	**	**	**	**	**	**	**
NARC	94.7 a	411.2 b	12.6 c	1.24 c	1312 b	7707 a	41.9 c	31.5 c
Koont	90.3 b	424.4 b	13.8 b	1.33 b	1384 a	7425 b	43.6 b	32.0 b
Talagang	87.1 b	449.9 a	14.7 a	1.41 a	1436 a	7338 b	44.4 a	32.9 a
SE ±	1.8356	10.297	0.2808	0.0115	27.374	54.225	0.1003	0.1075
Year (Y)	**	**	**	**	Ns	**	ns	**
2016-17	88.5 b	406.8 b	13.2 b	1.27 b	1347 b	7443 b	42.9 b	31.8 b
2017-18	92.9 a	450.3 a	14.2 a	1.39 a	1407 a	7536 a	43.7 a	32.5 a
SE±	1.4987	8.4072	0.2293	0.0094	22.351	44.274	0.0819	0.0877
Y × L	**	**	**	**	**	**	*	**
Y × T	**	**	**	**	NS	**	NS	**
L x T	NS	NS	NS	NS	NS	NS	NS	NS
Y x L x T	**	**	**	**	**	*	**	**

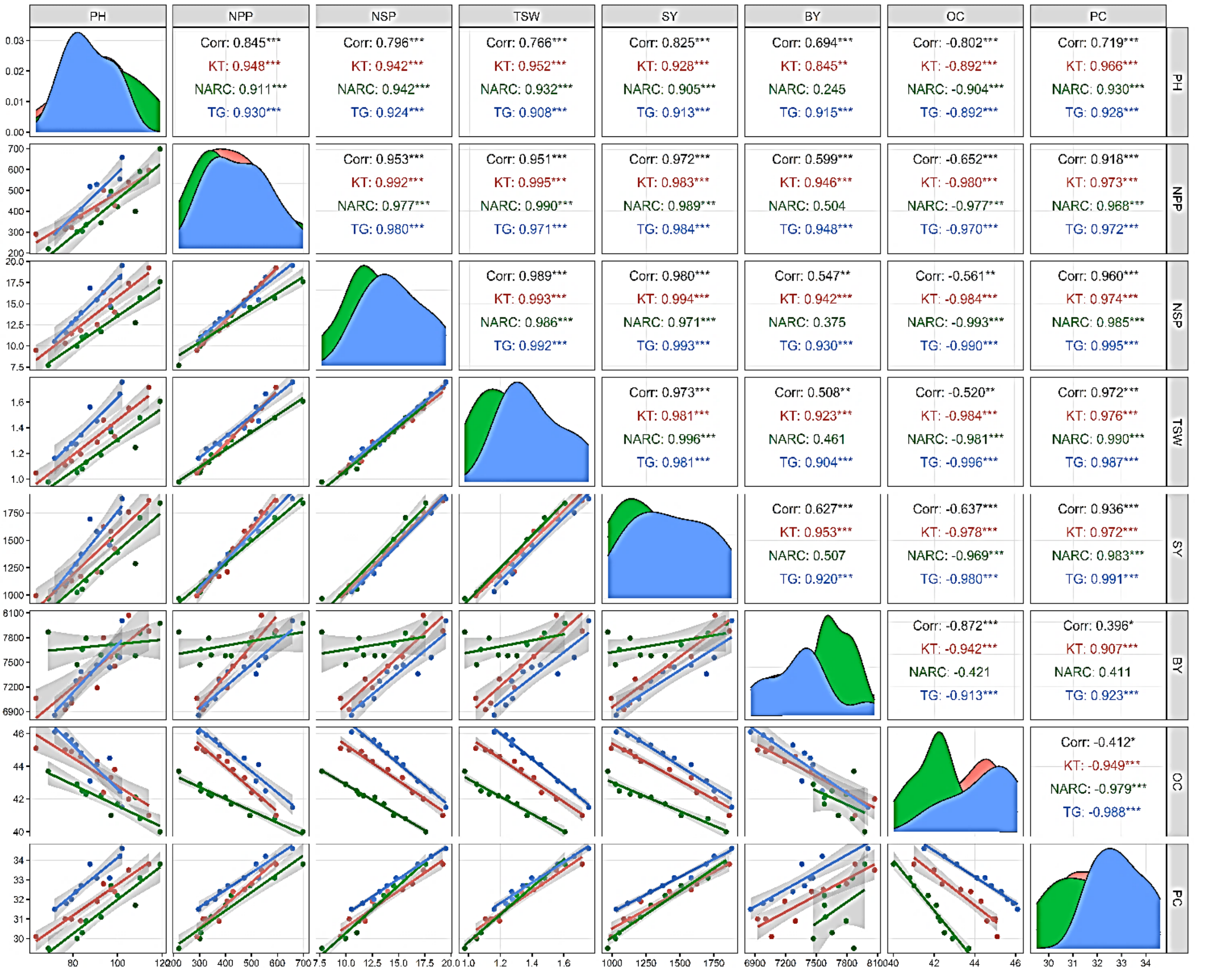

Fig. 2. Correlation among agronomic traits and seed quality traits of *C. sativa*.

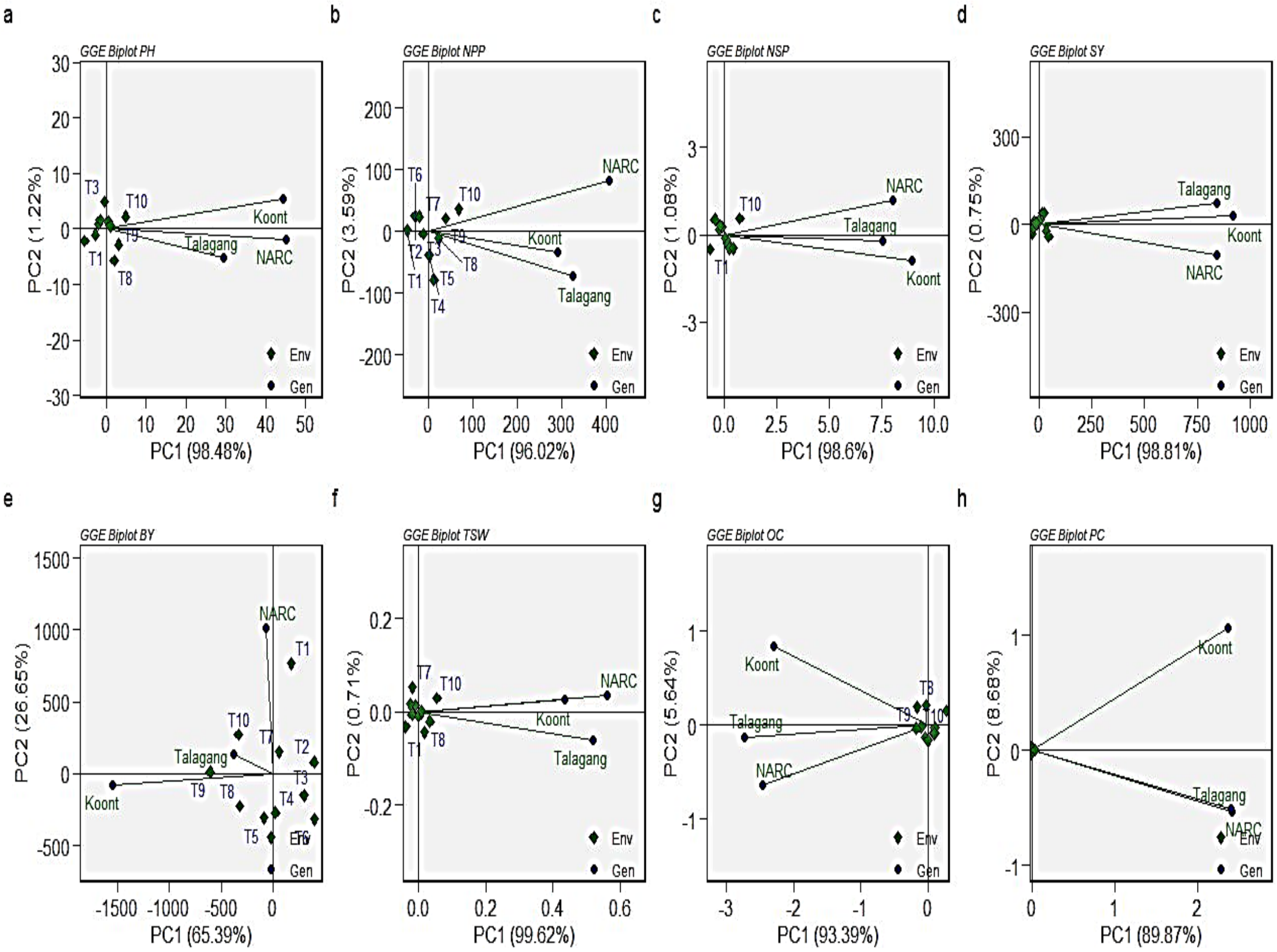

Fig. 3. Which-won-where type GGE scatter biplot analysis for the *C. sativa* studied under different environments and different treatments where PH shows: plant height (cm), NPP shows the number of pods plant^{-1}, NSP shows the number of seeds pod^{-1}, TSW shows thousand seed weight, BY shows: biomass yield (kg/ha), SY shows: seed yield (kg/ha), OC shows: oil content (%), PC shows: protein content (%).

Effects of locations: Growth, yield, and quality of *C. sativa* at all three locations showed significant response to nutrients for all the traits under observation. Similarly, location means revealed statistically significant differences ($p<0.01$) for all the studied traits (Table 2). NARC achieved the highest plant height (94.7cm) and maximum biomass yield (7708 kg ha^{-1}) while Talagang produced the maximum number of pods plant^{-1} (449.9), number of seeds pod^{-1} (14.7), thousand seed weight (1.41g) and seed yield (1437 kg ha^{-1}). URF-Koont and Talagang were statistically similar in plant height and biomass yield, but NARC had the highest results in pods and seeds number, TSW, and seed yield (1312.2 kg ha^{-1}). Talagang gained maximum oil contents (44.4%) and protein contents (32.9%) as compared to NARC (41.9%, 31.5%) and URF-Koont (43.6%, 31.9%), respectively, by showing differentially significant response for these quality traits.

Interactive effect of nutrients, years, and locations: The three-way interaction of year, location, and NPK nutrients revealed highly significant differences ($p<0.01$) for all the parameters of growth, yield, and quality traits of *Camelina sativa* (Table 2). The interactions for *C. sativa* quantitative characteristics are presented graphically by using GGE plot analysis in Fig. 2, where considerable variations were demonstrated.

Correlation among agronomic traits and seed quality traits of *C. sativa*: Seed yield and biomass yield showed significant positive correlations with plant height, pod number, seed weight, and seed weight, while negative correlations were found for OC and PC.

GGE biplot analysis: To determine which treatment performed best in the different environments, genotype and genotype by environment biplot analyses based on which-won-where patterns of treatment mean performances and stability across the three locations were utilized. Following GGE scatter biplot analysis for all variables, NPK macronutrient treatments on *C. sativa* evaluation occurred across multi-locations to find out which variables performed the best in different locations. The first two components (PC1 and PC2) of the GGE biplot contributed 99.17% of the total variability. The study examines treatments and environment interactions in mega-environments, analyzing biplots across different sectors to identify site-specific performance (Fig. 3).

The GGE comparison biplot identifies ideal locations based on representativeness and discrimination power, focusing on average tester coordinate abscissa and longest vector length for Camelina sativa crop traits. For PH, NPP, NSP, TSW, BY, SY, OC, and PC, the most favorable location was Talagang, followed by URF-Koont and NARC. URF-Koont emerged as the best location for TSW, SY, and BY, followed by Talagang and NARC (Fig. 3).

Discussion

The study confirms the hypothesis that *C. sativa* exhibits variations in morphological characteristics in response to different environments and nutrients. The implementation of balanced nutrient management practices significantly influenced the growth and yield of *C. sativa*. Our results are in close conformity with the findings of (Končius & Karčauskiene, 2010), who examined the influence of different levels of NPK fertilizers on the physio-morphological growth and yield of mustard. They reported that the maximum plant height (78.7cm) was observed at an optimum level of NPK (60-40-30 kg ha^{-1}). Our results are also in line with (Wysocki *et al.*, 2013), who studied the response of seed yield towards applied Nitrogen and Phosphorus in four cropping environments and investigated that Camelina showed less response towards applied Nitrogen at low rainfall environments while its response was more at higher rainfall environments. Similar results were recorded by (Singh *et al.*, 2019), in which they specified that plant height increased constantly with continuous additions of nitrogen up to 100 kg ha^{-1} at all growth stages and crop harvest in Canola. Nitrogen is required for growth and is a component of many organic substances, such as protein and nucleic acid, as well as protoplasm. It promotes rapid vegetative growth and modulates soil P and K nutrient utilization (Tyoakoso *et al.*, 2019). A sufficient amount of nitrogen promotes carbohydrate and protein metabolism, as well as cell division and expansion(Lau *et al.*, 2007). Nitrogen deficiency reduces crop leaf area (Yang *et al.*, 2022).

Furthermore, the vegetative growth of the plant performed well with the application of N and P fertilizers. The yield and yield-related characteristics of *C. sativa* increase with nitrogen fertilizer application. The number of pods per plant and the number of seeds per pod increased with increasing NPK levels. Increased metabolic activity at the cellular level and improved availability of crucial nutrients in the root zone led to an increase in nutrient absorption and accumulation in the vegetative portions of the plant. This larger nutrient content in the vegetative plant part, together with the better metabolism, allowed for greater transfer of these nutrients towards crop reproductive organs, which ultimately results in higher nutritional levels in the seeds and Stover. The biomass built up by a specific plant portion and its nutritional content had an impact on how much nutrients (N P and K) were absorbed. The increased buildup of nutrients was, therefore, ultimately a result of the fertilizer application's favorable effects on nutrient availability and metabolic activity. Our results are in line with (Urbaniak *et al.*, 2008, Solis *et al.*, 2013, Jiang & Caldwell, 2016). Similarly, (Manore & Yohanns, 2019) reported that *C. sativa* showed a significant increase in the number of pods per plant and seed yield towards nitrogen application as compared to the control.

The enhanced plant height and other vegetative development parameters could be attributed to the improved biological yield. Đurić, N. & Spasić (2019) reported that NPK application caused a significant increase in the biological yield of Camelina as compared to the control treatment; thus our findings are consistent with them. Biological yield steadily increased in Camelina when NPK levels were applied in the range of 100-60-25 kgha^{-1}. Hence, Camelina responded positively and significantly towards an increase in NPK levels, providing highest biological yield and grain yield. Increased N, P, and K levels may lead to increased carbohydrate and protein accumulation, enhancing growth and yield, resulting in more biomass and grain yield.

Apart from this, the highest grain yield of any crop is the result of all positive yield component interactions. Fertilizer application, particularly nitrogen, increases crop production. Our results conform with (Załuski *et al.*, 2020), who reported a 72.7% variance in seed yield to the effect of environmental conditions on the study description of spring Camelina with tengenotypes in Poland. The average seed yield was higher in a dry year and the lowest in a wet year. It might be due to its ability to be relatively drought tolerant but extremely susceptible to waterlogging in field conditions. It could also be due to the drought tolerance ability of Camelina, which is qualified to extract water from deep horizons of soil as observed by other researchers (Gesch & Cermak, 2011; Berti *et al.*, 2016). However, other researchers like (Hunsaker *et al.*, 2011) observed that the short life cycle of camellia probably performs a key role in its low water use and severe drought tolerance. The performance of the crop at Talagang with the least rainfall against the three locations is consistent with this conclusion.

Optimal environmental conditions, coupled with a balanced source-sink ratio throughout the crop cycle, have been shown to extend the days to maturity in mustard. Favorable soil and plant environments, along with adequate rainfall, have been observed to stimulate prolific flowering, thereby enhancing the development of various yield attributes in mustard crops (Boote *et al.*, 2021). The yield formation stages in brassica are notably impacted by climatic variables such as solar radiations, evapotranspiration, and daily mean temperature (Pullens *et al.*, 2021). Our research underscores the significance of suitable environmental conditions during specific growth phases, which play a pivotal role in determining the yield potential of *C. sativa*. Elevated rainfall events, especially during flower initiation and maturity, can increase the hydrothermal coefficient, but may reduce seed yield due to insufficient pollination (Pradhan *et al.*, 2014). Cool temperatures, alongside sufficient and evenly distributed precipitation during critical growth stages, have been associated with robust correlations among various productive components in mustard crops (Rajković *et al.*, 2021).

The average oil contents recorded in the present study are higher than the oil contents (32 to 33%) reported by other studies (Sintim *et al.*, 2016). Similar results were reported (Pavlista & Santra, 2016) when Camelina was grown under rain-fed conditions or little irrigation. An inverse association between oil and protein contents in Camelina seed was confirmed by previous results as in the current study (Obour *et al.*, 2017).

Besides this, the results of this study illustrated that protein contents (%) were statistically significant at all three locations, i.e., NARC, Koont, and Talagang. The study results of (Rathke *et al.*, 2005) explained that by increasing nitrogen fertilization, the formation of protein increased because the synthesis of fatty acid increased due to their carbon skeleton competition during the process of carbohydrate metabolism. Similar findings were observed in Austria on Camelina breeding lines, which determined the seed protein contents between 24.2% and 29.3%, with an average protein content of 26.7% (Załuski *et al.*, 2020). In another study on Camelina by (Krzyżaniak *et al.*, 2019), the researchers, while studying spring Camelina seed yield and its composition, cultivated tengenotypes in Central Europe with temperate climate, revealed short growth period, high rate of emergence and extensive drought resistance in Camelina plants.

An efficient statistical approach for determining and measuring Treatments x Environmental Interaction (TEI) is the GGE biplot analysis. This is accomplished by grouping treatments with the appropriate environments that support particular variables. The scores from PC1 and PC2 together form the main foundation for this arrangement. The configuration resembles blue dots among the locations, representing mega-environments, where environments with comparable performance characteristics congregate. Lines starting at the origin are split into many sections. Each area refers to the treatments that flourish in a certain setting for the relevant feature.

In the present study, the significant cumulative variance represented by the first two principal components indicates a suitable explanation for the pattern of GEI across the examined characteristics, as seen in the environment-centered principal component analysis biplot (Fig. 3). Furthermore, (Yan & Kang, 2002) support the idea that a GGE biplot accounting for 60% or more of the variance may be successful in the mega context.

Conclusions

Overall, it can be concluded that NPK @ 50:30:20 kg ha^{-1} proved the best combination for the maximum growth, yield, and quality parameters of *C. sativa*. Apart from this, the experimental site “Talagang” received less rainfall but produced the maximum yield, proving the crop's less water requirement and drought-tolerant nature. Thus, *C. sativa* might be successfully cultivated in the Pothwar region and is a promising alternative to diversifying the prevailing cropping system.

References

Angelini, L.G., L. Abou Chehade, L. Foschi and S. Tavarini. 2020. Performance and Potentiality of Camelina (*Camelina sativa* L. Crantz) genotypes in response to sowing date under mediterranean environment. *Agronomy*, 10: 1929.

Anonymous. 2020. Economic Survey of Pakistan 2019-20. Islamabad, Pakistan.

Bayar, N., M. Kriaa and R. Kammoun. 2016. Extraction and characterization of three polysaccharides extracted from *Opuntia ficus indica cladodes*. *Int. J. Biol. Macromol.*, 92: 441-450.

Barłóg, P. and W. Grzebisz. 2004. Effect of timing and nitrogen fertilizer application on winter oilseed rape (*Brassica napus* L.). II. Nitrogen uptake dynamics and fertilizer efficiency. *J. Agron. Crop Sci.*, 190(5): 314-323.

Berti, M., R. Gesch, C. Eynck, J. Anderson and S. Cermak. 2016. Camelina uses, genetics, genomics, production, and management. *Ind. Crops Prod.*, 94: 690-710.

Boote, K.J., R. Seepaul, M.J. Mulvaney, A.K. Hagan, M. Bashyal, S. George, I. Small and D.L. Wright. 2021. Adapting the CROPGRO model to simulate growth and production of *Brassica carinata*, a bio-fuel crop. *GCB Bioenergy*, 13: 1134-1148.

Borah, B. 2021. Potassic fertilizer management for sustainable groundnut productivity in India: A Review. *Agric. Rev.*,

Cullere, M., Y. Singh, E. Pellattiero, S. Berzuini, I. Galasso, C. Clemente and A. Dalle Zotte. 2023. Effect of the dietary inclusion of *Camelina sativa* cake into quail diet on live performance, carcass traits, and meat quality. *Poult. Sci.*, 102: 102650.

Đurić, N. and M. Spasić. 2019. Introduction of alternative oil plants in production on small farms. *Sustain. Agric. Rural Dev. Terms Repub. Serbia Strateg. Goals Realiz. within Danube Reg. Sustain. Multifunct.*, 605-622.

de Bang, T.C., S. Husted, K.H. Laursen, D.P. Persson and J.K. Schjoerring. 2021. The molecular–physiological functions of mineral macronutrients and their consequences for deficiency symptoms in plants. *New Phytologist*, 229(5): 2446-2469.

Elleuch, M., S. Besbes, O. Roiseux, C. Blecker and H. Attia. 2007. Quality characteristics of sesame seeds and by-products. *Food Chem.*, 103: 641-650.

Gesch, R.W. and S.C. Cermak. 2011. Sowing date and tillage effects on fall-seeded Camelina in the Northern Corn Belt. *Agron. J.*, 103: 980-987.

Grant, C.A. and D.N. Flaten. 2019. 4R management of phosphorus fertilizer in the northern Great Plains. *J. Environ. Qual.*, 48: 1356-1369.

Gugel, R.K. and K.C. Falk. 2006. Agronomic and seed quality evaluation of *Camelina sativa* in western Canada. *Can. J. Plant Sci.*, 86: 1047-1058.

Haq, E.U., F.U. Hassan, M. Iqbal, M. Ahmed, S. Ghuffar, J. Ahmed, R. Ahmed, M. Shahbaz, A.U. Rehman and A.M. Hamzah. 2022. Effects of micronutrients (Bo-ron and Zinc) as foliar application on growth and yield of *Camelina sativa* L. *Plant Cell Biotechnol. Mol. Biol*., 1-11.

Haq, E.U., F.U. Hassan, F. Zhou, X. Gong, A. Manaf, G. Shabbir, M.F. Karim, P.J.H. King, M.F. Adil and I.H. Shamsi. 2023. Nitrogen fertilization improves the agro-morphological and yield attributes of *Sinapis alba* L. *Agronomy*, 13: 1621.

Hulbert, S.H., S. Guy, W. Pan, T. Paulitz, W. Schillinger, K. Sowers and D. Wysocki. 2012. Camelina production in the dryland Pacific Northwest. Washington State University Extension.

Hunsaker, D.J., A.N. French, T.R. Clarke and D.M. El-Shikha. 2011. Water use, crop coefficients, and irrigation management criteria for camelina production in arid regions. *Irrig. Sci.*, 29: 27-43.

Jarecki, W. 2021. The reaction of winter oilseed rape to different foliar fertilization with macro- and micronutrients. *Agriculture*, 11: 515.

Jiang, Y. and C.D. Caldwell. 2016. Effect of nitrogen fertilization on camelina seed yield, yield components, and downy mildew infection. *Can. J. Plant Sci.*, 96: 17-26.

Keeney, D.R. and D.W. Nelson. 1982. Nitrogen-inorganic forms in Methods of Soil Analysis, Part 2. Chemical and Microbiological Properties, (Ed.): Page, A.L., 643-693, SSSA Book Series No 9. *Soil Sci. Soc. Am. Am. Soc. Agron. Madison, WI*.,

Khan, M.M., A. Manaf, F. Hassan, M.S. Ahmad, A. Qayyum, Z.H. Shah, H. Alsamadany, S. Yang and G. Chung. 2021. Allometric expression of sesame cultivars in response to various environments and nutrition. *Agriculture*, 11: 1095.

Končius, D. and D. Karčauskiene. 2010. The effect of nitrogen fertilisers, sowing time and seed rate on the productivity of *Camelina sativa*. *Zemdirbyste*, 97: 37-46.

Krzyżaniak, M., M.J. Stolarski, J. Tworkowski, D. Puttick, C. Eynck, D. Załuski and J. Kwiatkowski. 2019. Yield and seed composition of 10 spring camelina genotypes cultivated in the temperate climate of Central Europe. *Ind. Crops Prod.*, 138: 111443.

Lau, K.S., E.A. Partridge, A. Grigorian, C.I. Silvescu, V.N. Reinhold, M. Demetriou and J.W. Dennis. 2007. Complex n-glycan number and degree of branching cooperate to regulate cell proliferation and differentiation. *Cell*, 129: 123-134.

Manore, D. and A. Yohanns. 2019. Evaluating growth, seed yield and yield attributes of Camelina (*Camelina sativa* L.) in response to seeding rate and nitrogen fertilizer levels under irrigation condition, southern Ethiopia. *Agric. For. Fish.*, 8: 31-35.

Obour, A.K., E. Obeng, Y.A. Mohammed, I.A. Ciampitti, T.P. Durrett, J.A. Aznar-Moreno and C. Chen. 2017. Camelina seed yield and fatty acids as influenced by genotype and environment. *Agron. J.*, 109: 947-956.

Pavlista, A.D. and D.K. Santra. 2016. Planting and harvest dates, and irrigation on fenugreek in the semi-arid high plains of the USA. *Ind. Crops Prod.*, 94: 65-71.

Pradhan, S., V.K. Sehgal, D.K. Das, A.K. Jain, K.K. Bandyopadhyay, R. Singh and P.K. Sharma. 2014. Effect of weather on seed yield and radiation and water use efficiency of mustard cultivars in a semi-arid environment. *Agric. Water Manag.*, 139: 43-52.

Pullens, J.W.M., K.C. Kersebaum, U. Böttcher, H. Kage and J.E. Olesen. 2021. Model sensitivity of simulated yield of winter oilseed rape to climate change scenarios in Europe. *Eur. J. Agron.*, 129: 126341.

R Studio. 2022.

Rajković, D., A. Marjanović Jeromela, L. Pezo, B. Lončar, F. Zanetti, A. Monti and A. Kondić Špika. 2021. Yield and quality prediction of winter rapeseed—artificial neural network and random forest models. *Agronomy*, 12: 58.

Rathke, G.-W., O. Christen and W. Diepenbrock. 2005. Effects of nitrogen source and rate on productivity and quality of winter oilseed rape (*Brassica napus* L.) grown in different crop rotations. *F. Crop. Res.*, 94: 103-113.

Raza, A. 2021. Eco-physiological and biochemical responses of rapeseed (*Brassica napus* L.) to abiotic stresses: Consequences and Mitigation Strategies. *J. Plant Growth Regul.*, 40: 1368-1388.

Sarwar, N., O. Farooq, A. Wasaya, M. Hussain, A.M. El-Shehawi, S. Ahmad and S. Farooq. 2021. Integrated nitrogen management improves productivity and economic returns of wheat-maize cropping system. *J. King Saud Uni. Sci*., 33(5): 101475.

Singh, R., M. Lal, G. Singh and T. Kumar. 2019. Effect of nitrogen and phosphorus on growth parameter and yield of canola (*Brassica napus* L.). *J. Pharmacog. Phytochem.*, 8: 380-384.

Sintim, H.Y., V.D. Zheljazkov, A.K. Obour, A. Garcia y Garcia and T.K. Foulke. 2016. Evaluating agronomic responses of Camelina to seeding date under rain - fed conditions. *Agron. J.*, 108: 349-357.

Solis, A., I. Vidal, L. Paulino, B.L. Johnson and M.T. Berti. 2013. Camelina seed yield response to nitrogen, sulfur, and phosphorus fertilizer in South Central Chile. *Ind. Crops Prod.*, 44: 132-138.

Tyoakoso, M.M., M.D. Toungos and M. Babayola. 2019. Effects of nitrogen rate on growth and yield of bambara groundnut (*Vigna subterranea* (L.) verdc.) in jalingo, taraba state, nigeria. *J. Int. J. Res. Granthaalayah*, 7: 67-76.

Urbaniak, S.D., C.D. Caldwell, V.D. Zheljazkov, R. Lada and L. Luan. 2008. The effect of cultivar and applied nitrogen on the performance of *Camelina sativa* L., in the maritime provinces of Canada. *Can. J. Plant Sci.*, 88: 111-119.

Vollmann, J., T. Moritz, C. Kargl, S. Baumgartner and H. Wagentristl. 2007. Agronomic evaluation of camelina genotypes selected for seed quality characteristics. *Ind. Crops Prod.*, 26: 270-277.

Waraich, E.A., Z. Ahmed, R. Ahmad, M.Y. Ashraf, M.S. Naeem and Z. Rengel. 2013. "Camelina sativa", a climate proof crop, has high nutritive value and multiple-uses: A review. *Aust. J. Crop Sci.*, 7: 1551-1559.

Westerman, R.L. 1990. Soil Testing and Plant Analysis, Volume 3, Third Edition. Soil Science Society of America, Inc.

Wysocki, D.J., T.G. Chastain, W.F. Schillinger, S.O. Guy and R.S. Karow. 2013. Camelina: Seed yield response to applied nitrogen and sulfur. *Field Crop. Res.*, 145: 60-66.

Yan, W. and M.S. Kang. 2002. GGE biplot analysis: A graphical tool for breeders, geneticists, and agronomists. CRC press, Boca Raton, FL.

Yang, Z., Y. Chen, Y. Wang, H. Xia, S. Zheng, S. Xie, Y. Cao, J. Liu, S. Sehar, Y. Lin, Y. Guo and I.H. Shamsi. 2022. Nitrogen metabolic rate and differential ammonia volatilization regulate resistance against opportunistic fungus *Alternaria alternata* in tobacco. *Front. Plant Sci.*, 13.

Załuski, D., J. Tworkowski, M. Krzyżaniak, M.J. Stolarski and J. Kwiatkowski. 2020. The characterization of 10 spring Camelina genotypes grown in environmental conditions in North-Eastern Poland. *Agronomy*, 10: 64.

Zubr, J. and B. Matthäus. 2002. Effects of growth conditions on fatty acids and tocopherols in *Camelina sativa* oil. *Ind. Crops Prod.*, 15: 155-162.

(Received for publication 5 February 2024)