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How growing conditions are influential on the agronomic attributes and fiber-related quality parameters of flax (*Linum usitatissimum* L.) fibers: A seismomorphogenesis approach

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Abstract
Among industrial crops, flax (*Linum usitatissimum* L.) is a multi-purpose crop grown for production of stem fiber and seed oil. Through longterm domestication for these purposes, cultivated flax has diversified into two main types, namely fiber and oil or linseed types, as well as an intermediate type. This study was designed to investigate the effect of flax fibers of flax varieties (Antares, Dakota and Mures) in field and greenhouse cultivation on fiber mechanical performances, morphological properties and fatty acid composition in flaxseed was investigated. Additionally, plants can change their morphology and mechanical properties when exposed to stress, as is particularly the case when plants respond to wind, a phenomenon known as seismomorphogenesis. Greenhouse plants were found to be significantly lower than field grown plants, with an increase of 16.79cm in technical stem length and 56.02cm in technical stem height. In addition, the total plant height of flax grown in the field was 59.33 cm compared to 17.32 cm in the greenhouse. The Mures variety was found to be the highest both in the field (79.50-76.10cm) and in the greenhouse (18.36-17.47cm). Considering the fatty acid percentages, the highest α-linolenic acid was found in Dakota (29.23%) and the lowest in Antares (20.53%) in the field, while the highest was found in Dakota (19.25%) and the lowest in Mures (16.13%) in the greenhouse. In addition, the highest tensile strength was found in Dakota (704.6 Mpa) and the closest Antares (692.2 Mpa) under field conditions, while the lowest was found in Dakota (198.5 Mpa) and Mures varieties (288.8 Mpa) under greenhouse conditions. In order to reduce the dimension, correlate and visualize the measured parameters, the relevant data of the study were subjected to principal component analysis and heat-map clustering.
Keywords: Flaxseed, Linum usitatissimum, Plant muscles, Seismomorphogenesis, SEM

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INTRODUCTION

Flax/Linseed (*Linum usitatissimum* L.), one of the oldest plants grown for its seeds or fiber s among industrial crops, is grown as; i) oil flax for flaxseed oil production and ii) fiber flax for fiber production (Saleem et al., 2020; Koçak, 2022; Stavropoulos et al., 2023). In addition, the genus Linum, belonging to the Linaceae family is an herbaceous, annual, self-pollinated, oldest domesticated diploid species (Sarmast et al., 2014; Tork et al., 2019). Flax can be called by many different names. In Türkiye, local names such as "bezir, bızıktan, cimit, kön, siyelek and zeyrek" are used for the flax plant (Davis, 1982; Dumanoğlu, 2020). There is evidence for it being used in ancient Egypt and Mesopotamia (Carmona and Ezzamel, 2007), with Ethiopia, Central Asia, and India being considered to be secondary centers. The species is distributed in other regions of the world as well, including the Middle East, North and Southwest America, and the Mediterranean Basin (Vavilov 1951; Chen 2022). Its also an important cultivated plant grown for its fiber and oil-rich seeds (Choudhary et al., 2017; Saroha et al., 2022). Mechanical conditioning is the deliberate application of physical stimulation and stress to control the growth and quality of plants (Koçak et al., 2023). Flax fiber has always been used for textile production. In addition to clothing and upholstery, a newer tech-nical application involving the use of flax fibers as reinforcements for composite materials has been extensively developed over the last few decades (Goutianos et al., 2006; Yan et al., 2014). Besides, flax fibers play an important role as reinforcement by supporting plant tissues in the stem and can even act as "plant muscles" (Gorshkova et al., 2012; Baley et al., 2018). Due to its industrial importance, flax has been subjected to a century of extensive variety selection aimed at increasing fiber yield and the plants' lodging stability and resistance to diseases (Bourmaud et al., 2016; Goudenhooft, 2017). One of the main concerns is the improvement of fiber mechanical properties of the fibers optimise the mechanical performance of composites. In addition, results from the literature show that although variety selection can increase fiber yield, fiber mechanical properties are less affected by flax variety (Van de Weyenberg, 2003; Omrani et al., 2017). The effect of mechanically induced stress (MIS) on plant traits such as yield or quality has also been studied. As well as being a natural source caused by wind, rain or animal movement, MIS can also be induced in greenhouses by rubbing or brushing plants. The plant response is called 'tigmomorphogenesis' in the case of physical contact and 'seismomorphogenesis' in the case of wind action (Börnke and Rocksch, 2018; Goudenhooft et al., 2018; Šic Žlabur et al., 2021). Additionally, the first example of such responses is the reduction in plant height that usually occurs in plants exposed to wind or other MIS (Biddington, 1986). In this context, it has been shown that trees exposed to wind are shorter and more pointed, but have lower overall stiffness, although their mechanical properties are less affected by their morphology (Paul-Victor and Rowe, 2011; Shiba et al., 2023). In contrast, wheat plants are stronger and less flexible, but do not show a significant change in stem height under the influence of wind sway (Crook and Ennos, 1996). Seismomorphogenesis causes changes in plant characteristics such as stem diameter, fiber quality or chlorophyll content, with different responses to observations made between species. In addition to causing morphological and mechanical changes in plants, seismomorphogenesis has generally been reported to result in a significant increase in crop yield when plants are grown in the greenhouse under optimum conditions (Koçak et al., 2023). Flax is an industrial crop usually grown in the field and changes in morphology and fiber yield are expected when grown under much milder windy conditions. From this point of view, it is of great interest to grow flax in a greenhouse environment and to study fiber yields (Heller et al., 2015; Jacobsson, 2018). Flax, like any plant, responds to external stresses and its development and stem structure can be affected by seismomorphogenesis, gravitropizm and growing conditions (Moulia et al., 2016).

Concerning industrial uses of the crop, the beneficial effects are mainly due to the lipids in flaxseed. Flaxseed oil is one of the richest plant sources of α-linolenic acid (omega-3) and linoleic acid (omega-6) polyunsaturated fatty acids (PUFAs), which are essential for human nutrition as they cannot be synthesized by the body. In addition to other important uses, flaxseed is characterized by its oil content of approximately 30-60%. The oils in flaxseed contain valuable amounts of the fatty acid compounds α-linolenic acid, linoleic acid, oleic acid, palmitic acid and stearic acid', as well as high levels of lignans, fiber, protein, vitamins and micronutrients (Dubey et al., 2020; Deme et al., 2021; Yang et al., 2021). Corresponding to the litarature review/potential mechanism of the plants, it was hypothesized that plants grown under openfield conditions would be thicker and dense structure. This study investigates the effect of seismomorphogenesis on the stems and fibres of registered flax cultivars under greenhouse and field conditions in terms of structure/mechanical properties and quality. It also includes a comparison between field-grown and greenhouse grown flax at plant maturity. This comparison is firstly based on morphological analysis of flax stalks and fibre structure properties. Subsequently, changes in the quality (fatty acid composition) of flax seeds were evaluated.

MATERIALS AND METHODS

Plant material and experimental design

The relevant study was conducted at the greenhouses (grown in greenhouses for a 14/10 h photoperiod, 26–30 °C/ day and 16–20 °C/ night; relative humidity: 60%) and experimental area in 2022 at the Agricultural Application and Research Center of Iğdır University using in a randomized block design with three replications. The flaxseeds were provided by different agricultural institutions in Türkiye. The flaxseeds of the foreign registered varieties (Antares, Dakota and Mures) was obtained from different provinces of Türkiye. Agromorphological traits were determined 84 days after sowing by randomly selecting 5 plants from each plot. In this context, promising flaxseed varieties for oil and natural fiber have been identified.

Experimental area and characteristics of the experimental soil

The Iğdır region is the lowest plain of the East Anatolian region with microclimatic characteristics, and it is one of the largest plains in terms of surface area compared to the surrounding provinces. Due to the microclimatic characteristics of the Iğdır region; with salty and calcareous soils, not all of its lands are suitable for agriculture. The soil properties used in the field experiment and in the greenhouse environment were determined (Table 1) (Karaoğlu and Çelim, 2018). In addition, the soil used in the greenhouse was taken from the soil used in the field (Kocak et al., 2023).

Table 1. Soil characteristics of the experimental area

Examined trials/analysis types	Value/result	Soil structure
pH	9.70	Strong alkaline
EC (dS/m)	3.05	Moderately tolerant
Total salt (%)	82.44	Too salty
$CaCO_3$ (%)	9.29	Medium lime
Organic matter (%)	0.42	Very little
P_2O_5 (ppm)	0.44	Very little
K_2O (ppm)	42.56	Sufficient
Saturation (%)	52.29	Clay-loamy

Phenotypic evaluation of flax

On five randomly selected plants, 12 morphological plant traits were determined at 84 days after sowing (DAS) from field and greenhouse conditions were determined for fiber and seed traits, respectively; plant height (cm/plant) (PH), number of flowering days (days) (NFD), ripening days (days) (RD), number of siblings (number/plant) (NS), capsule branches per plant (number/plant) (CBPP), capsule branches in plant (number) (CBP), capsule weight per plant (g/plant) (CWPP), number of seeds per plant (number/plant) (NSPP), number of seeds in capsule (number/capsule) (NSC), seed yield per plant (g/plant) (SYPP), stem weight (g/plant) (SW), technical stem length (cm) (TSL) Table 2. Fiber quality parameters were evaluated according to (Pisupati et al., 2021). The variable numbers, codes of each individual morphological trait are presented in Table 3.

Table 2. Morphological characteristics assessed in flax

Trait name	Code	Detail
Plant height(cm)	PH	Height of main stem from cotyledon scar to top boll
Number of flowering days	NFD	The date on which 75% of the plants on the parcel flowered
Ripening days	RD	The period until the maturity of 90% of the plants in the parcel
Number of tillering (number/plant)	NS	Count of the branches
Capsule of branches per plant (number/plant)	CBPP	Primary branches on the plant body
Capsule branches in plant (number)	CBP	Capsules being on each plant
Capsule weight per plant (g/plant)	CWPP	Wight of capsules on each plant
Number of seeds per plant (number/plant)	NSPP	Seeds in capsule per plant
Number of seeds in capsule (number/capsule)	NSC	Seeds in capsule
Seed yield per plant (g/plant)	SYPP	Seeds of plants taken from each parcel
Stem weight (g/plant)	SW	Weight at stem of plants taken from each parcel
Technical stem length (cm)	TSL	From the first cotyledon leaves to the first branching

Extraction of flaxseed oil

Flaxseeds from the field and greenhouse were pulverised and 5g of the sample was treated by Soxhlet extraction with N-hexane for 5 hours. The used seed pulp was then filtered and the solvent was removed in a rotary evaporator (HEIDOLPH Hei-VAP Core (HL/ML)) under vacuum at 40°C. The oil samples were then stored in a refrigerator at 4°C for analysis. The oil obtained after the treatments was considered as the total oil content of the flaxseed (Lamani et al., 2021)

Flaxseed oil yields (kg/ha) were calculated using the following formula;

Flaxseed oil yield (kg/ha) = Oil content (%) x Flaxseed yield (kg/ha) (Xie et al., 2020).

Fatty acid profile using High Performance Liquid Chromatography (GC-FID)

Flaxseed oil (0.2g) was taken into 15 ml centrifuge tubes and shaken with 10 ml of hexane. The samples were dissolved in 0.2mL of 1 N-methanol and KOH was added. The tube was shaken and phase separation was observed and it was kept in the dark for 2 hours until the upper phase became clear. Clarification after process, some of the upper phase was taken into vials, and fatty acids were analyzed with the help of Agilent 7820 A GC-FID (Agilent Technologies, USA) device with a SP 2560 100m*0.25mm*0.2µm capillary column with a flame ionization detector (FID). Injection port and FID temperature is 240ºC, 1/10 split ratio at 400 ml/min pressure in split injection mode. After waiting for 5 minutes at 140ºC, the column temperature increased by 4ºC per minute to reach 250ºC and reached 260ºC after waiting for 15 minutes. Helium carrier gas 41 cm/sec (Hydrogen) was used. Samples injected with 1 µL into the device were compared with the GC-FID chromatogram obtained in the analysis of the "Supelco ® 37 Component FAME Mix-Sigma-Aldrich" standard mixture for a total of 37.75 minutes. As a result of the analysis; α-linolenic acid (C18:3n6), linoleic acid (C18:2n6), oleic acid (C18:1n9c), Palmitic acid (C16:0), stearic acid (C18:0) fatty acids were determined as % (Table 4).

Mechanical structure of flax fiber and Scanning Electron Microscopy (SEM)

A testing machine with a 5 kN load cell (Zwick/Roell) was used to determine fiber parameters and yield analysis of high fiber flax varieties harvested in the field and in the greenhouse. Diameter measurements (left, right and centre) were made using a digital caliper (MİTUTOYO). Furthermore, images of fibers structures were obtained using scanning electron microscope (SEM) (ZEISS Sigma 300). For the SEM, a field emission scanning electron microscope was used with an accelerating voltage of 10 kV was used to observe the morphology of the leaf samples. Prior to FE-SEM analysis, as herbal products are not electrically conductive, the surface of the samples was coated with a gold plating device, Qurom, to ensure electron scattering from the surface. A secondary electron (SE) detector was used to display the morphological information of the samples.

Data analysis

For the study, three replicates (each with 5 plants) were used and each replicate corresponded to the five seedlings. In order to evaluate the results, the flax plants were compared for their agronomic and morphological attributes using one-way variance analysis ($p<0.05$) (SPSS 22). Pearson correlation (r) was used to determine the association between the investigated characteristics. A principal component analysis (PCA) at (PAST Software) and a heat-map clustering (ClustVis) were employed to define the dependent variable parameters corresponding to the registered varieties (independent variables).

RESULTS

Morphological evaluation

Growth and development parameters were analysed to evaluate the effects of seismomorphogenesis on flax (L. usitatissimum L.) under field and greenhouse conditions. Some basic parameters such as plant height, number of days to flowering, number of days to maturity, number of tillers, capsule branches per plant, capsule weight per plant, number of seeds per plant, number of seeds per capsule, seed yield per plant, stem weight, technical stem length were estimated for the morphological characteristics of the 3 varieties considered for the analysis (Table 3). Greenhouse plants were found to be significantly lower than field-grown plants, with an increase of 16.79cm in technical stem length and 56.02cm in technical stem length. In addition, the total plant height of flax grown in the field was 59.33cm, while the plant height in the greenhouse environment was 17.32cm. Significant differences were found in plant height, number of siblings, capsule branches per plant, number of seeds per plant stem weight and technical stem length between the morphological characteristics of the cultivars (Antares, Dakota, Mures) under field and greenhouse conditions. In terms of plant height and technical stem length among the morphological characteristics between the varieties; the Mures variety was found to be the highest both in the field (79.50-76.10*cm*) and in the greenhouse (18.36-17.47*cm*) (Table 3).

Heat-map clustering and Principal Component Analysis (PCA) of plant growth and development traits

We performed heat-map clustering (Fig. 1) and PCA (Fig. 2) to visualise and clarify the morphological traits associated with cultivars used under field and greenhouse conditions. The present results showed that heat map clustering revealed two main clusters under both growing conditions. While the first cluster was number of flowering days, ripening days in field conditions, number of flowering days, number of seeds in capsule, stem weight in greenhouse conditions, the second main cluster was plant height, number of siblings, capsule branches per plant, capsule branches in plant, capsule weight per plant, number of seeds per plant, number of seeds per plant, number of seeds in capsule, seed yield per plant, stem weight, technical stem length in the field; plant height, ripening days, number of siblings, capsule branches per plant, capsule branches in plant, capsule weight per plant, number of seeds per plant, seed yield per plant, technical stem length were associated with the growth and development characteristics of flax. In order to explain the percentage of variation, PCA was carried out to reveal the kind of relationship and the level of variations between varieties and related parameters (Fig. 2). Accordingly, two components with eigen values above

1 were observed under field conditions. These two components (F_1: 87.7% and F_2: 12.2%) explain a total variation of 99.9%. In addition, two components with eigen values above 1 were observed under greenhouse conditions. These two components (F_1: 57.7% and F_2: 42.1%) explain a total variation of 99.8%.

Table 3. Growth and development parameters of flax varieties used for traits in the field (A) and in the greenhouse (B)

Field morphology(A)

Variety	Plant height(cm/plant)	Number of flowering days (days)	Ripening days (days)	Number of siblings (number/plant)	Capsule branches per plant (number/plant)	Capsule branches in plant (number)	Capsule weight per plant (g/plant)	Number of seeds per plant (number/plant)	Number of seeds in capsule (number/capsule)	Seed yield per plant (g/plant)	Stem weight (g/plant)	Technical stem length (cm)
Antares	43.50±0.50c	83.00±3.60a	92.00±2.64a	9.00±1.00b	7.66±0.57a	8.33±0.57b	0.50±0.02b	68.33±3.51c	8.33±0.57b	0.53±0.01b	0.85±0.01c	39.60±1.40c
Dakota	55.00±1.00b	73.33±2.08b	78.66±2.51b	11.33±0.57a	8.66±1.52a	11.00±1.00a	0.55±0.05b	87.33±1.52b	8.33±0.57b	0.56±0.05b	0.92±0.02b	52.36±0.80b
Mures	79.50±0.50	65.50±0.50c	71.00±1.00c	11.00±1.00a	9.33±1.52a	10.66±0.57a	0.71±0.01a	113.33±7.09a	9.66±0.57a	0.69±0.01a	2.11±0.01a	76.10±1.01a
Mean	59.33±15.93a	73.94±7.87	80.55±9.39	10.44±1.33	8.55±1.33	10.00±1.41	0.58±0.10	89.66±19.97	8.77±0.83	0.59±0.08	1.29±0.61	56.02±16.06
F	2028.50	39.332	70.90	6.143	1.267	11.400	26.355	70.662	5.333	19.493	5364.428	847.511
p	.000	.000	.000	.035	.348	.009	.001	.000	.047	.002	.000	.000

Field morphology(A) T test

Variety	Plant height(cm/plant)		Number of flowering days (days)		Ripening days (days)		Number of siblings (number/plant)		Capsule branches per plant (number/plant)		Capsule branches in plant (number)		Capsule weight per plant (g/plant)		Number of seeds per plant (number/plant)		Number of seeds in capsule (number/capsule)		Seed yield per plant (g/plant)		Stem weight (g/plant)		Technical stem length (cm)	
	t	p	t	p	t	p	t	p	t	p	t	p	t	p	t	p	t	p	t	p	t	p	t	p
Antares* Dakota	-17.816	.000	4.022	.016	6.325	.003	-3.500	.025	-1.061	.349	-4.000	.016	-1.264	.275	-8.593	.001	.000	1.000	-.925	.407	-4.890	.008	-13.679	.000
Antares* Mures	-88.182	.000	8.327	.001	12.860	.000	-2.449	.070	-1.768	.152	-4.950	.008	-14.469	.000	-9.846	.001	-2.828	.047	-13.065	.000	-133.830	.000	-36.561	.000
Dakota* Mures	-37.955	.000	6.337	.003	4.904	.008	.500	.643	-.535	.621	.500	.643	-4.670	.010	-6.205	.003	-2.828	.047	-4.014	.016	-76.122	.000	-31.684	.000

Greenhouse (B)

Variety	Plant height(cm/plant)	Number of flowering days (days)	Ripening days (days)	Number of siblings (number/plant)	Capsule branches per plant (number/plant)	Capsule branches in plant (number)	Capsule weight per plant (g/plant)	Number of seeds per plant (number/plant)	Number of seeds in capsule (number/capsule)	Seed yield per plant (g/plant)	Stem weight (g/plant)	Technical stem length (cm)
Antares	16.13±.80b	59.67±2.52a	63.33±0.58a	2.67±0.58a	2.33±0.58a	2.67±0.58a	0.24±0.02b	22.33±5.03a	8.67±0.58a	0.18±0.01b	0.24±0.01a	15.40±0.60b
Dakota	17.46±.50ab	58.00±3.00a	61.00±3.00ab	3.33±0.58a	2.67±0.58a	3.00±1.00a	0.34±0.05a	24.67±7.02a	8.33±0.58a	0.31±0.01a	0.16±0.00b	17.50±0.50a
Mures	18.36±1.00a	55.00±1.00a	58.67±1.53b	2.33±0.58a	2.33±0.58a	3.00±0.00a	0.25±0.01b	24.67±2.08a	8.33±0.58a	0.17±0.01b	0.27±0.02a	17.47±0.47a
Mean	17.32± 1.19	57.56±2.88	61.00±2.65	2.78±0.67	2.44±0.53	2.89±0.60	0.28±0.05	23.89±4.59	8.44±0.53	0.22±0.07	0.22±0.05	16.79±1.14
F	5.949	3.082	4.200	2.333	.333	.250	8.518	.207	.333	181.980	64.927	15.628
p	.038	.120	.072	.178	.729	.787	.018	.819	.729	.000	.000	.004

Greenhouse(B) T test

Variety	Plant height(cm/plant)		Number of flowering days (days)		Ripening days (days)		Number of siblings (number/plant)		Capsule branches per plant (number/plant)		Capsule branches in plant (number)		Capsule weight per plant (g/plant)		Number of seeds per plant (number/plant)		Number of seeds in capsule (number/capsule)		Seed yield per plant (g/plant)		Stem weight (g/plant)		Technical stem length (cm)	
	t	p	t	p	t	p	t	p	t	p	t	p	t	p	t	p	t	p	t	p	t	p	t	p
Antares* Dakota	-2.425	.072	.737	.502	1.323	.256	-1.414	.230	-.707	.519	-.500	.643	-3.147	.035	-.468	.664	.707	.519	-16.142	.000	14.059	.000	-4.657	.010
Antares* Mures	-3.005	.040	2.985	.041	4.950	.008	.707	.519	.000	1.000	-1.000	.374	-.875	.431	-.742	.499	.707	.519	1.209	.293	-1.965	.121	-4.687	.009
Dakota* Mures	-1.391	.237	1.643	.176	1.200	.296	2.121	.101	.707	.519	.000	1.000	3.027	.039	.000	1.000	.000	1.000	17.029	.000	-9.915	.001	.084	.937

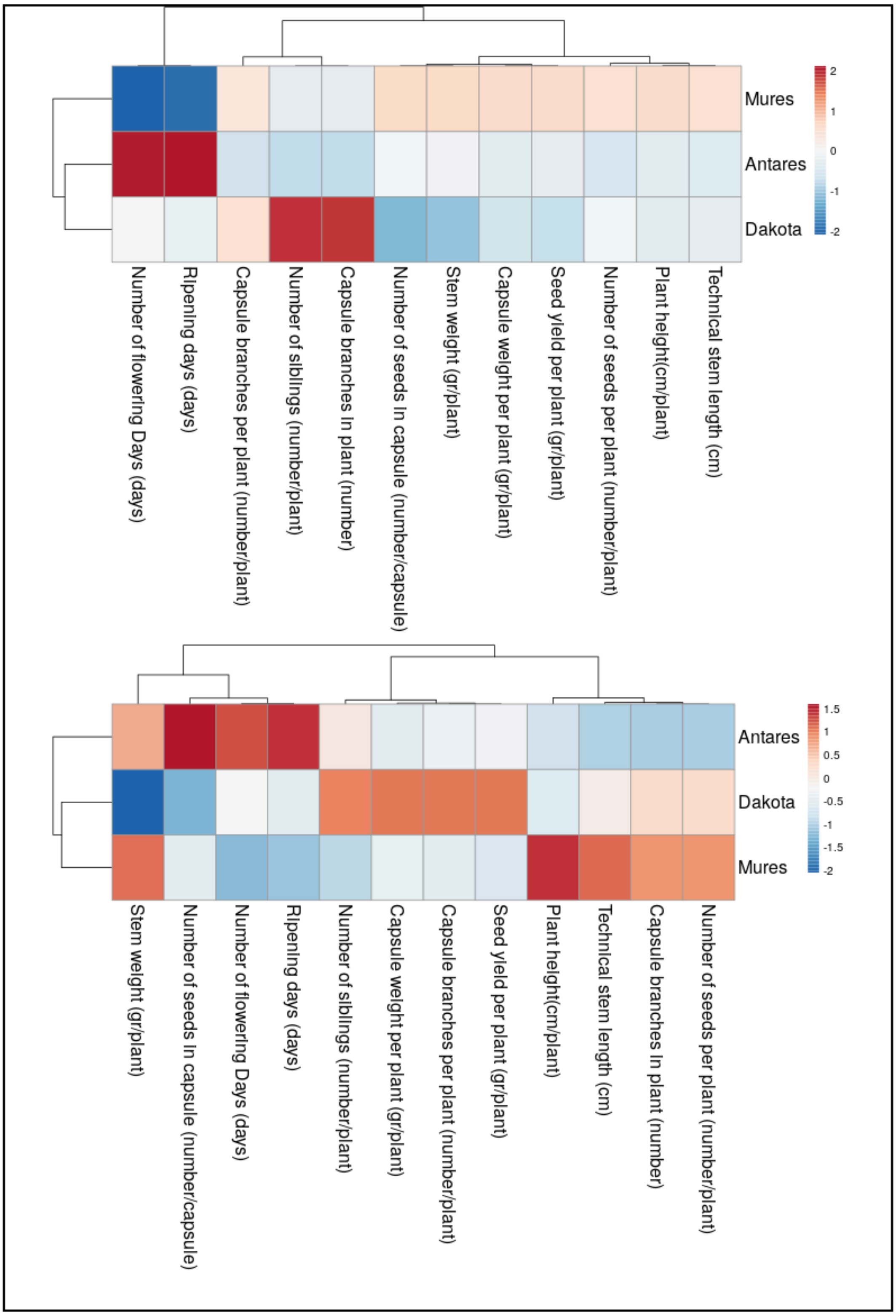

Figure 1. Heatmap clustering of growth and development parameters of flax cultivars used for treatments under the field (A) and the greenhouse conditions (B).

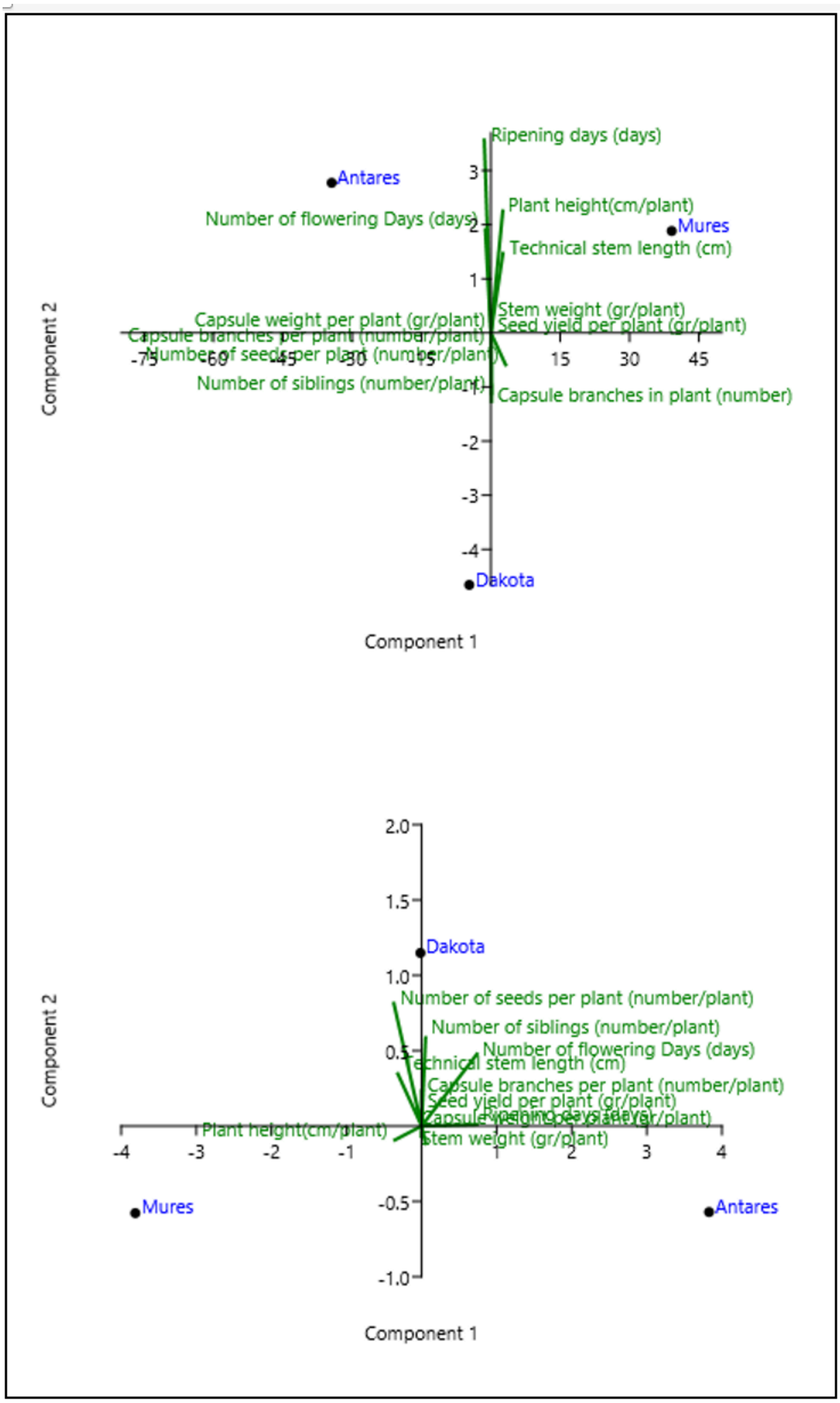

Figure 2. Principal Component Analysis (PCA) of growth and development parameters of flax cultivars used for treatments under the field (A) and the greenhouse conditions (B).

Heat-map clustering and Principal Component Analysis (PCA) of flaxseed oil and fatty acid compositions

For visualization, correlate and clarify the flaxseed oil and fatty acid compositions considered to the cultivars, we performed heat-map (Fig. 3) clustering and PCA (Fig. 4). In addition to the quantitative analysis of plant characteristics, the oil yield and fatty acid composition of seeds obtained from field and greenhouse conditions were also investigated. For the respective analysis, flax varieties characterised by high oil content (Antares, Dakota and Mures) were tested. Accordingly, oil yields ranged from 1.03, 0.94 to 0.56g for "Antares, Mures and Dakota" in the field and from 0.77, 0.68 to 0.41g in the greenhouse, respectively (Table 4). We analysed the ratio of quality and quantity indicators and the fatty acid composition of the oils after extraction. GC-FID analysis revealed that α-linolenic acid, linoleic acid, linoleic acid, palmitic acid, oleic acid and stearic acid were the major fatty acid components of the respective flax plant seed oils obtained both in the field and under greenhouse conditions. Considering the fatty acid percentages, the highest α-linolenic acid was found in Dakota (29.23%) and the lowest in Antares (20.53%) in the field, while the highest was found in Dakota (19.25%) and the lowest in Mures (16.13%) in the greenhouse. In linoleic acid, the highest was found in Dakota (19.57%) and Antares (11.37%) and the lowest in Antares (12.66%) and Dakota (9.44%) in the field and greenhouse, respectively. In addition, two components with Eigen values above 1 were observed under field conditions. These two components (F_1: 77.6% and F_2: 22.3%) explain a total variation of 99.9%. Accordingly, two components with Eigen values above 1 were observed under greenhouse conditions. These two components (F_1: 75.7% and F_2: 24.2%) explain a total variation of 99.9%.

Table 4. Oil and fatty acid compositions (%) of flaxseed varieties used in field and greenhouse treatments

Greenhouse fatty acids							
Variety	Oil content (g)	Crude oil yield (%)	Palmitic acid (C16.0)	Stearic acid (C18.0)	Oleic acid (C18.1)	Linoleic acid (C18.2)	α-Linolenic acid (C18.3)
Mures	0.68	13.6	6.11	7.42	13.11	10.28	16.13
Antares	0.77	14.4	7.14	8.2	12.54	11.37	18.73
Dakota	0.41	8.2	5.33	7.26	11.22	9.44	19.25
Field fatty acids							
Variety	Oil content (g)	Crude oil yield (%)	Palmitic acid (C16.0)	Stearic acid (C18.0)	Oleic acid (C18.1)	Linoleic acid (C18.2)	α-Linolenic acid (C18.3)
Mures	0.94	19.1	6.95	6.85	20.11	13.05	26.14
Antares	1.03	20.6	8.15	9.28	14.36	12.66	20.53
Dakota	0.56	11.7	6.13	10.32	10.04	19.57	29.23

Mechanical properties of flax fiber and scanning electron microscopy (SEM)

Due to the low fiber content of flax in relation to its fineness and strength, flax cannot compete with other fiber crops such as hemp and cotton. That caused gradual decreases in uses of flax for fiber. Regarding the fiber content, (Yılmaz and Uzun, 2019) reported the fiber content in flax stalk as 16-24% and 34-37%. In the present study, according to the results obtained from the analyses (tensile strength, puller strength, rupture stretched and fiber diameter measurement) on the varieties evaluated in the field and greenhouse; it was determined that Dakota varieties (1%) was the highest strain in greenhouse conditions and the lowest (0.58%) in field conditions and also the lowest (0%) in strain at break in the field. In addition, the highest tensile strength was found in Dakota (704.6 Mpa) and the closest Antares (692.2 Mpa) under field conditions, while the lowest was found in Dakota (198.5 Mpa) and Mures varieties (288.8 Mpa) under greenhouse conditions (Tablo 5). In addition, structural analyses were carried out with the help of Scanning Electron Microscopy (SEM) to determine the differences in the microstructures of the related varieties both in the field and greenhouse conditions. Additionaly, it was observed that the layers between the fiber and matrix were separated in the SEM images (Fig. 5).

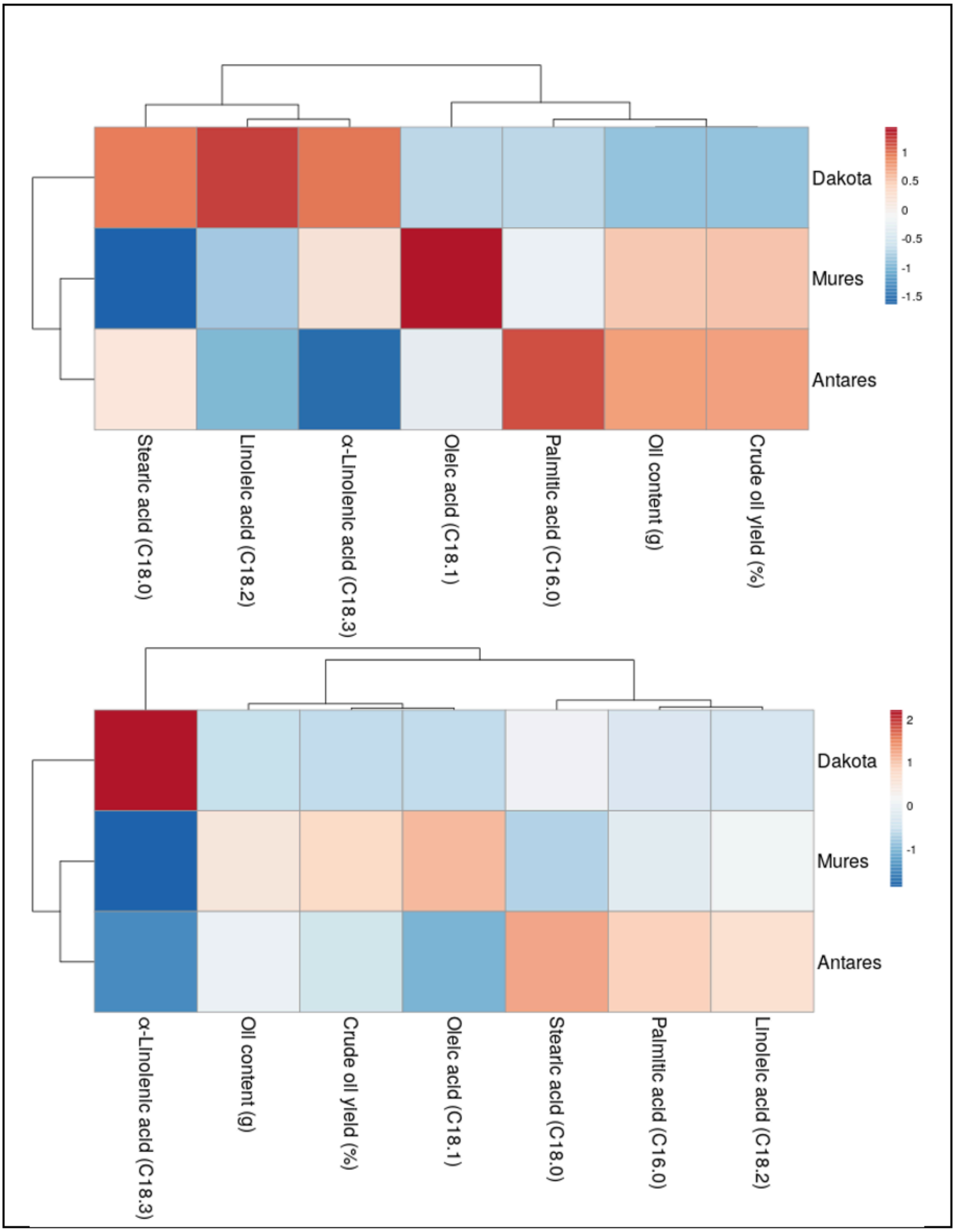

Figure 3. Heatmap clustering of oil and fatty acid compositions (%) of flaxseed cultivars used for treatments under the field (A) and the greenhouse conditions (B).

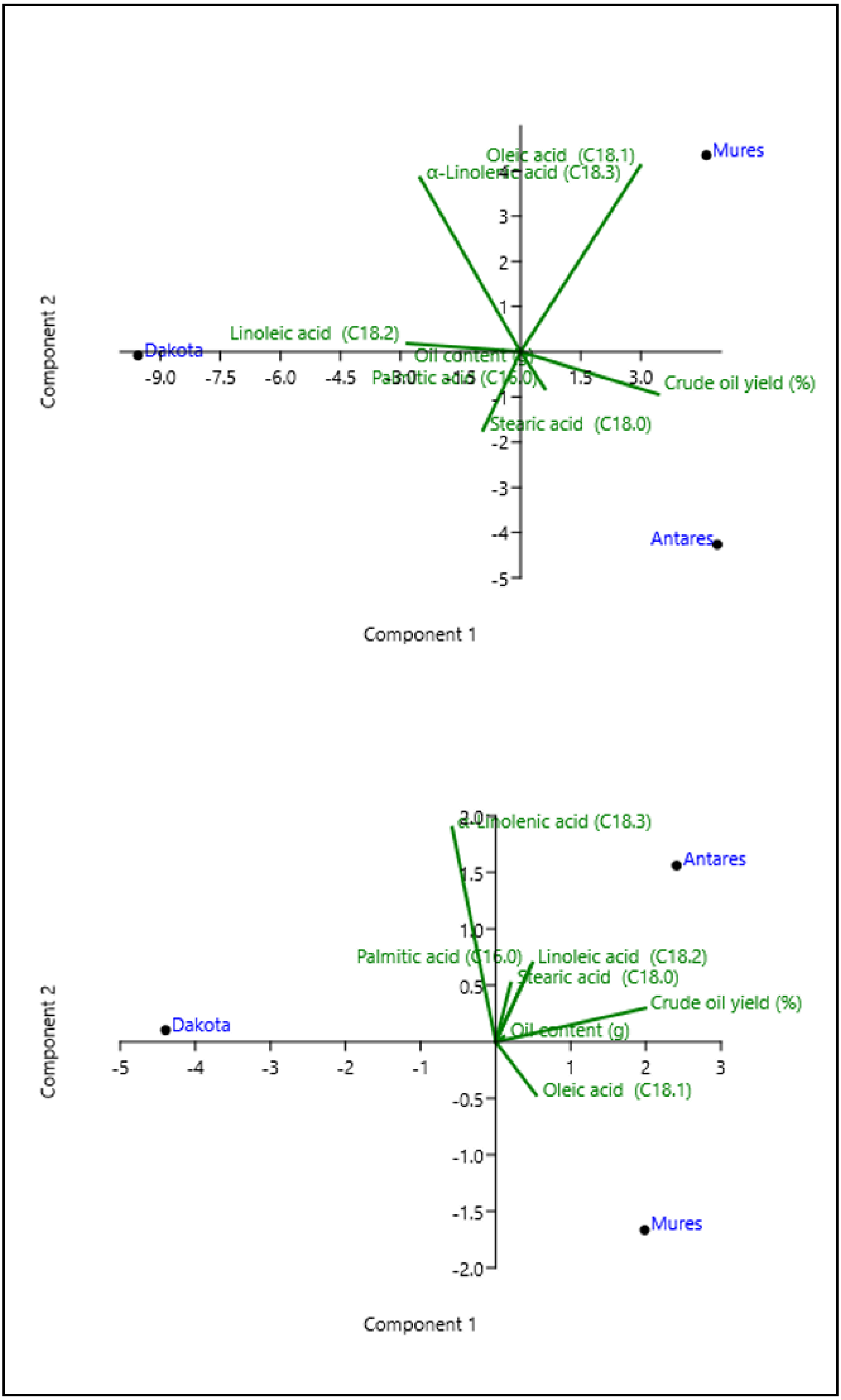

Figure 4. Principal Component Analysis (PCA) of oil and fatty acid compositions (%) of flaxseed cultivars used for treatments under the field (A) and the greenhouse conditions (B).

Table 5. Fiber mechanical properties of flax varieties used in field (A) and greenhouse (B).

Varieties	Growth conditions	Series (n=3)	Strain at fmax (%)	Tensile strength (Mpa)	Strain at break (%)
Dakota	field	mean value	0.58	704.6	1.2
	greenhouse	mean value	1	198.5	0
Mures	field	mean value	0.71	692.2	0.9
	greenhouse	mean value	0.73	288.8	1.2
Antares	field	mean value	0.83	587.4	1.2
	greenhouse	mean value	0.75	587.4	0.7

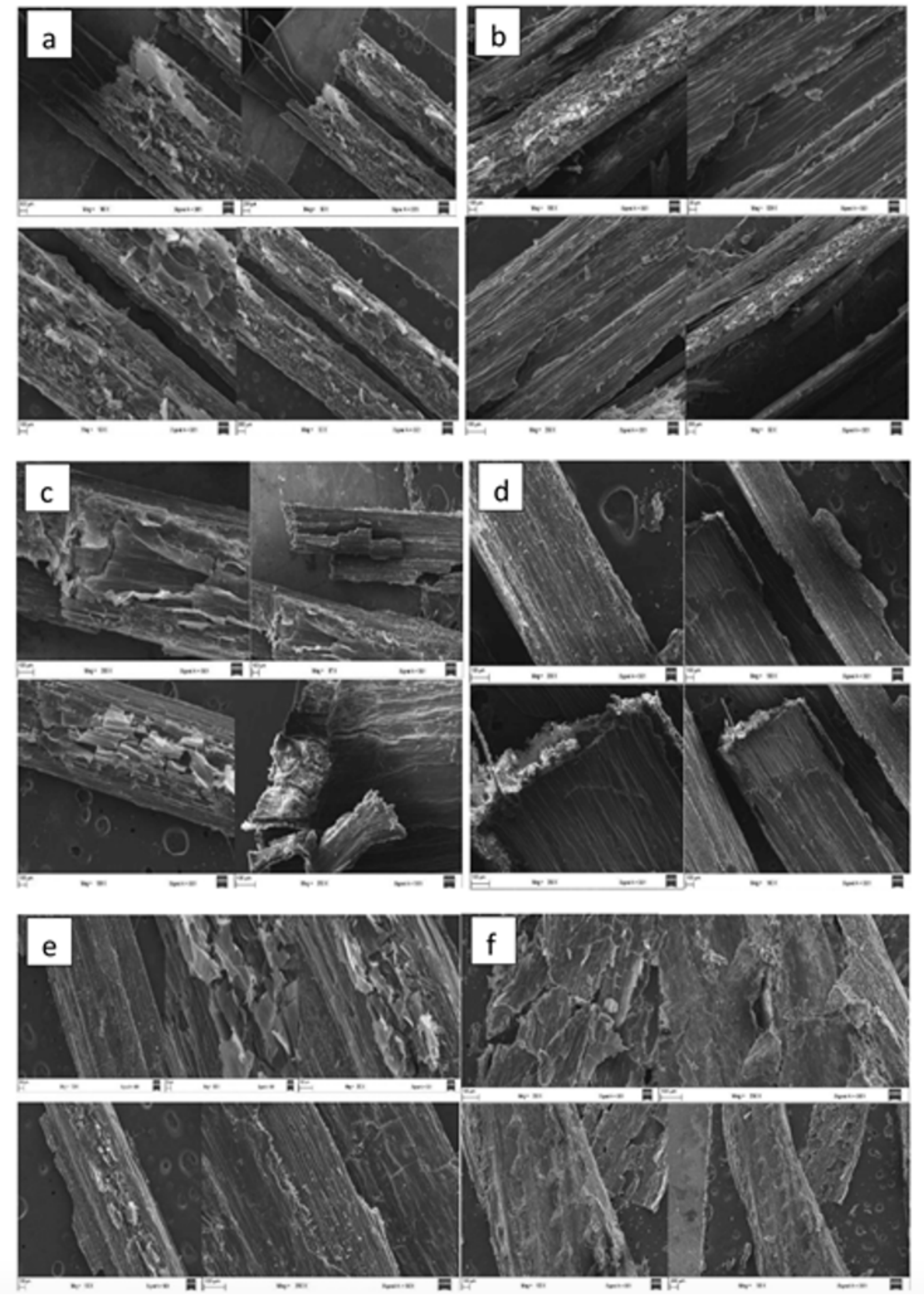

Figure 5. Scanning Electron Microscope (SEM) images the effect of growth conditions (field and greenhouse) on the flax varieties, **a).** Dakota (field); **b).** Dakota (greenhouse); **c).** Mures (field); **d).** Mures (greenhouse); **e).** Antares (field); **f).** Antares (greenhouse).

DISCUSSION

Choosing the right type of plant is critical in the face of everchanging environmental conditions. Due to the expanding world population and the increasing demand for food and materials, raw materials from the agricultural industry are increasingly in demand. In order to meet these increasing needs, we need to utilise productive and high quality varieties. In this context, flax, an important industrial plant with useful oil and fiber properties, has spread over a large part of the world. It is also one of the oldest cultivated plants (Melelli et al., 2022). In addition, it highlights the changes in plant height and technical stem height that affect the fiber structure and quality of the flax plant, as well as the fatty acid profile from the seeds obtained after harvest variety (Goudenhooft et al., 2018). These changes result in significant increases in plant height and thinness, the risk of lodging due to wind and rain, and significant changes in the fiber structure of the plants, which are the main characteristics that distinguish field crops from those grown in greenhouses (Li et al., 2022; Brulé et al., 2016). In addition, plants change in height and fineness, and even in fibrous plants such as flax, the structural performance and morphological characteristics of the fibers experience the same situation. At the same time, it is assumed that seismomorphogenesis is the only phenomenon that causes differences between the two states (Goudenhooft et al., 2019). In this context; flax, which is an important industrial plant with both oil, and fiber, properties, has its own distribution area in almost every geography of the world (Tian et al., 2021; Li et al., 2022; Melelli et al., 2022). In addition, the agro-morphological characteristics of the flax cultivars under field and greenhouse conditions, the fatty acid composition of the seeds and the fiber structure of the cultivars were studied by SEM. The flax varieties (Antares, Dakota and Mures) were tested for the first time for seismomorphogenesis in relation to their cultivation under field and greenhouse conditions.

High plant height, technical stem length and less branched structure are desirable for fibrous flax varieties. Plant height and technical stem length, which is a critical indicator/parameter, can be an important criterion in the selection of flax grown for fiber (Heller et al., 2015; Poudyal, 2017). According to the present results, the lowest value for plant height in flax was found in Antares (43.50 cm) and the highest value was found in Mures (79.50 cm), which is fibrous in field conditions. In addition, in greenhouse conditions this result is the lowest value for plant height was found in Antares (16.13 cm) and the highest value was found in Mures (18.36 cm). Our current findings in field and greenhouse conditions were found to be lower than previous reports (Goudenhooft et al., 2018). In addition, were found in parallel (Sheng et al., 2022). Furthermore, as regards the technical stem length of the flax varieties, the lowest value was found in Antares (39.60 cm) and the highest in Mures (76.10 cm) un-der field conditions; the lowest value was found in Antares (15.40 cm) and the highest in Dakota (17.50 cm) under greenhouse conditions (Goudenhooft et al., 2018). Our results were found to have lower values compared to previous studies. In this context, the plant height and technical stem lengths of the varieties used in the field and greenhouse were lower than in previous reports, in line with our present findings, it was found that there were significant differences in the fiber structures of the varieties in the field and in the greenhouse. The results of flax fiber tensile strength (Mpa) and strain at break (%) were found to be lower compared to previous studies (Chuah et al., 2014). In particular, quality parameters such as fiber strain at fmax (%) tensile strength (Mpa) and strain at break (%) were reported to be important. It was also emphasised that quality parameters may be related to the matrix between the fibers (da Silva et al., 2023). According to the measurements made on the technical system and the SEM images, it was found that the fiber breaking stress values (0-1,2%) of the related plant under field and greenhouse conditions were lower than previous studies. Furthermore, it is stated that the mechanical properties of the matrix structure in the fiber structure of flax deteriorate due to hydrolysis and the layers between the fiber and the matrix are separated, especially as a result of this separation, rupture and fracture increase, as well as the strain at break is significantly negatively affected (Moudood et al., 2019).

As expressed in this study; the oil yields of the cultivars varied between 11.7-20.6% under field conditions and 8.2-14.4% in the greenhouse, respectively; the field conditions were similar to previous studies, while those in the greenhouse were found to be low (Keskin et al., 2020; Njembe et al., 2021). In addition, α-linolenic acid (20.53-29.23%; 16.13-19.25%) and linoleic acid (12.66-19.57%; 9.44-11.37%) were observed in the field and greenhouse conditions, respectively. In this context, α-linolenic acid was determined as 48.41% (Hatanaka et al., 2021) and linoleic acid as 14.90% (Xie et al., 2020; Njembe et al., 2021). The present findings were found to be lower than previous studies. As expressed, it has been reported that agro-morphological traits are interdependent and show differences especially when evaluated as oil and fiber (Mirshekari et al., 2012). In this context, it was found that the differences determined in agro-morphological traits observed in the related plant in our results taken under field and greenhouse conditions may be related to soil organic matter content, pH and lime (Pisupati et al., 2021), and it was found that our results are different from previous studies and compatible with the literature; in addition, it is predicted that these differences may be the quality of the seed used and the climatic conditions of the growing environment. In contrast, field-grown plants are actually more exposed to a wide range of other factors, such as rainfall or greater temperature fluctuations, which can influence many climatic factors. For this reason, growing flax in greenhouses may be of interest to avoid yield losses due to lodging, severe weather events or other undesirable factors, while maintaining fiber properties.

In addition, growing conditions can be controlled in the greenhouse, which is not the case in the field. This control is important because it can allow several har-vests per year, thus increasing the availability of flax fiber to the industry while providing fiber with similar positive properties.

CONCLUSIONS

In response to stresses of mechanical origin, such as wind, the shape and mechanical parameters of plants can be greatly affected. Moreover, in the case of the flax, plants those grown in greenhouses have specific shape parameters that differ significantly from those of plants grown in the field. In fact, when flax is subjected to a much milder mechanical stress, both the structure of the whole plant (such as the fiber) and the height of the technical stems increase considerably. Due to these shapes, the flax fibers are distributed differently along the stems. In the findings of this study, the highest plant height and technical stem length of the registered cultivars (Antares, Dakota, Mures) in terms of fiber-related traits were observed in the Mures cultivar under field and greenhouse conditions, respectively. In addition, it is predicted that varieties with fiber structure characteristics will be grown in ecologically suitable regions, that field conditions will have high morphological values compared to green-houses and that fiber structures will be stronger.

COMPLIANCE WITH ETHICAL STANDARDS

Peer-review

Externally peer-reviewed.

Conflict of interest

The author declare that they have no competing, actual, potential or perceived conflict of interest.

Author contribution

The author read and approved the final manuscript. The author verifies that the Text, Figures, and Tables are original and that they have not been published before.

Ethics committee approval

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Data availability

All data created and analyzed during the experiments are presented in this study.

Consent to participate

Not applicable.

Consent for publication

Not applicable.

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REFERENCES

Baley, C., Goudenhooft, C., Gibaud, M., & Bourmaud, A. (2018). Flax stems: from a specific architecture to an instructive model for bioinspired composite structures. Bioinspiration & Biomimetics, 13(2), 026007. https://doi.org/10.1088/1748-3190/aaa6b7

Biddington, N. L. (1986). The effects of mechanically-induced stress in plants—a review. Plant growth regulation, 4, 103-123. https://doi.org/10.1007/BF00025193

Bourmaud, A., Gibaud, M., & Baley, C. (2016). Impact of the seeding rate on flax stem stability and the mechanical properties of elementary fibres. Industrial Crops and Products, 80, 17-25. https://doi.org/10.1016/j.indcrop.2015.10.053

Börnke, F., & Rocksch, T. (2018). Thigmomorphogenesis–control of plant growth by mechanical stimulation. Scientia Horticulturae, 234, 344-353. https://doi.org/10.1016/j.scienta.2018.02.059

Brulé, V., Rafsanjani, A., Pasini, D., & Western, T. L. (2016). Hierarchies of plant stiffness. Plant Science, 250, 79-96. https://doi.org/10.1016/j.plantsci.2016.06.002

Choudhary, S. B., Sharma, H. K., Kumar, A. A., Maruthi, R. T., Mitra, J., Chowdhury, I., & Karmakar, P. G. (2017). SSR and morphological trait based population structure analysis of 130 diverse flax (*Linum usitatissimum* L.) accessions. Comptes rendus biologies, 340(2), 65-75. https://doi.org/10.1016/j.crvi.2016.12.002

Chuah, S., Pan, Z., Sanjayan, J. G., Wang, C. M., & Duan, W. H. (2014). Nano reinforced cement and concrete composites and new perspective from graphene oxide. Construction and Building materials, 73, 113-124. https://doi.org/10.1016/j.conbuildmat.2014.09.040

Carmona, S., & Ezzamel, M. (2007). Accounting and accountability in ancient civilizations: Mesopotamia and ancient Egypt. Accounting, Auditing & Accountability Journal, 20(2), 177-209. https://doi.org/10.1108/09513570710740993

Crook, M. J., & Ennos, A. R. (1996). Mechanical differences between free-standing and supported wheat plants, *Triticum aestivum* L. Annals of Botany, 77(3), 197-202. https://doi.org/10.1006/anbo.1996.0023

da Silva, T. R., de Matos, P. R., Júnior, L. U. D. T., Marvila, M. T., & de Azevedo, A. R. G. (2023). A review on the performance of açaí fiber in cementitious composites: Characteristics and application challenges. Journal of Building Engineering, 106481. https://doi.org/10.1016/j.jobe.2023.106481

Davis, P. H. (1982). Flora of Turkey and the East Aegean Islands. Vol. 3. Flora of Turkey and the East Aegean Islands. Vol. 3. https://www.jstor.org/stable/10.3366/j.ctvxcrhxk

Deme, T., Haki, G. D., Retta, N., Woldegiorgis, A., & Geleta, M. (2021). Fatty acid profile, total phenolic content, and antioxidant activity of niger seed (*Guizotia abyssinica*) and linseed (*Linum usitatissimum*). Frontiers in Nutrition, 8, 674882. https://doi.org/10.3389/fnut.2021.674882

Dubey, S., Bhargava, A., Fuentes, F., Shukla, S., & Srivastava, S. (2020). Effect of salinity stress on yield and quality parameters in flax (*Linum usitatissimum* L.). Notulae Botanicae Horti Agrobotanici Cluj-Napoca, 48(2), 954-966. https://doi.org/10.15835/NBHA48211861

Dumanoğlu, Z. (2020). Keten (*Linum usitatissimum* L.) Bitkisi tohumlarının genel özellikleri. Bütünleyici ve Anadolu Tıbbı Dergisi, 2(1), 3-9. (in Turkish). Retrieved from https://dergipark.org.tr/en/pub/batd/issue/59277/800008

Gorshkova, T., Brutch, N., Chabbert, B., Deyholos, M., Hayashi, T., Lev-Yadun, S., Pilate, G. (2012). Plant fiber formation: state of the art, recent and expected progress, and open questions. Critical Reviews in Plant Sciences, 31(3), 201-228. https://doi.org/10.1080/07352689.2011.616096

Goudenhooft, C., Bourmaud, A., & Baley, C. (2017). Varietal selection of flax over time: Evolution of plant architecture related to influence on the mechanical properties of fibers. Industrial Crops and Products, 97, 56-64. https://doi.org/10.1016/j.indcrop.2016.11.062

Goudenhooft, C., Bourmaud, A., & Baley, C. (2018). Conventional or greenhouse cultivation of flax: What influence on the number and quality of flax fibers?. Industrial crops and products, 123, 111-117. https://doi.org/10.1016/j.indcrop.2018.06.066

Goudenhooft, C., Bourmaud, A., & Baley, C. (2019). Flax (*Linum usitatissimum* L.) fibers for composite reinforcement: exploring the link between plant growth, cell walls development, and fiber properties. Frontiers in Plant Science, 10, 411. https://doi.org/10.3389/fpls.2019.00411

Goutianos, S., Peijs, T., Nystrom, B., & Skrifvars, M. (2006). Development of flax fibre based textile reinforcements for composite applications. Applied composite materials, 13, 199-215. https://doi.org/10.1007/s10443-006-9010-2

Hatanaka, T., Yamamoto, N., Araki, R., Kishigami, M., Nakamoto, T., Masumura, T., & Sugimoto, T. (2021). Fatty acid compositions of triacylglycerols in flax (*Linum usitatissimum* L.) seeds with varied seeding dates and nitrogen fertilization in a temperate region of Japan: Seeding date and fatty acids in flax seed. Soil Science and Plant Nutrition, 67(3), 269-276. https://doi.org/10.1080/00380768.2021.1908093

Heller, K., Sheng, Q. C., Guan, F., Alexopoulou, E., Hua, L. S., Wu, G. W., & Fu, W. Y. (2015). A comparative study between Europe and China in crop management of two types of flax: linseed and fibre flax. Industrial Crops and Products, 68, 24-31. https://doi.org/10.1016/j.indcrop.2014.07.010

Jacobsson, E. (2018). Environmental Impact Analysis of Flax Fibre Cultivation for Composite Reinforcement. urn: nbn: se: miun: diva-34881

Karaoğlu, M., & Çelim, Ş. (2018). Doğu Anadolu Bölgesi Ve Iğdır'ın Jeolojisi Ve Toprak Özellikleri. Journal of Agriculture, 1(1), 14-26. (in Turkish)

Keskin, N. Ç., Öztürk, Ö., Eğribaş, Z. E., & Yılmaz, E. (2020). Bazı yağlık keten çeşitlerinde farklı sıra aralıklarının verim ve verim unsurları üzerine etkilerinin belirlenmesi. Ziraat Fakültesi Dergisi, 109-120. ISSN 1304-9984. (in Turkish)

Koçak, M. Z. (2022). Fatty acid and organic acid compositions of some Türkiye registered flax (*Linum usitatissimum* L.) varieties grown under alkaline soils. International Journal of Agriculture Environment and Food Sciences, 6(3), 358-369. https://doi.org/10.31015/jaefs.2022.3.4

Koçak, M. Z., Kumlay, A. M., & Alma, M. H. (2023). Morphological and molecular characterization of flax (*Linum usitatissimum* L.) accessions obtained from different locations in Turkey. Genetic Resources and Crop Evolution, 1-27. https://doi.org/10.1007/s10722-023-01589-6

Lamani, S., Anu-Appaiah, K. A., Murthy, H. N., Dewir, Y. H., & Rihan, H. Z. (2021). Fatty acid profile, tocopherol content of seed oil, and nutritional analysis of seed cake of wood apple (*Limonia acidissima* L.), an underutilized fruit-yielding tree species. Horticulturae, 7(9), 275. https://doi.org/10.3390/horticulturae7090275

Li, Q., Fu, C., Liang, C., Ni, X., Zhao, X., Chen, M., & Ou, L. (2022). Crop lodging and the roles of lignin, cellulose, and hemicellulose in lodging resistance. Agronomy, 12(8), 1795. https://doi.org/10.3390/agronomy12081795

Li, Y., Hoogenboom, G., Asseng, S., Niu, J. Y., Wu, L., & Kang, L. H. (2022). Adaptation of the SIMPLE model to oilseed flax (*Linum usitatissimum* L.) for arid and semi-arid environments. Agronomy, 12(6), 1267. https://doi.org/10.3390/agronomy12061267

Melelli, A., Jamme, F., Beaugrand, J., & Bourmaud, A. (2022). Evolution of the ultrastructure and polysaccharide composition of flax fibres over time: When history meets science. Carbohydrate polymers, 291, 119584. https://doi.org/10.1016/j.carbpol.2022.119584

Mirshekari, M., Amiri, R., Nezhad, H. I., Noori, S. S., & Zandvakili, O. R. (2012). Effects of planting date and water deficit on quantitative and qualitative traits of flax seed. American Eurasian Journal of Agricultural and Environment Science, 12(7), 901-913. https://doi.org/10.5829/idosi.aejaes.2012.12.07.1781

Moulia, B., Coutand, C., & Lenne, C. (2006). Posture control and skeletal mechanical acclimation in terrestrial plants: implications for mechanical modeling of plant architecture. American Journal of Botany, 93(10), 1477-1489. https://doi.org/10.3732/ajb.93.10.1477

Moudood, A., Rahman, A., Öchsner, A., Islam, M., & Francucci, G. (2019). Flax fiber and its composites: An overview of water and moisture absorption impact on their performance. Journal of Reinforced Plastics and Composites, 38(7), 323-339. https://doi.org/10.1177/073168441881889

Njembe, M. N., Dormal, E., Gardin, C., Mignolet, E., Debier, C., & Larondelle, Y. (2021). Effect of the dietary combination of flaxseed and *Ricinodendron heudelotii* or *Punica granatum* seed oil on the fatty acid profile of eggs. Food Chemistry, 344, 128668. https://doi.org/10.1016/j.foodchem.2020.128668

Omrani, F., Wang, P., Soulat, D., & Ferreira, M. (2017). Mechanical properties of flax-fibre-reinforced preforms and composites: Influence of the type of yarns on multi-scale characterisations. Composites Part A: Applied Science and Manufacturing, 93, 72-81. https://doi.org/10.1016/j.compositesa.2016.11.013

Paul-Victor, C., & Rowe, N. (2011). Effect of mechanical perturbation on the biomechanics, primary growth and secondary tissue development of inflorescence stems of *Arabidopsis thaliana*. Annals of botany, 107(2), 209-218. https://doi.org/10.1093/aob/mcq227

Pisupati, A., Willaert, L., Goethals, F., Uyttendaele, W., & Park, C. H. (2021). Variety and growing condition effect on the yield and tensile strength of flax fibers. Industrial crops and products, 170, 113736. https://doi.org/10.1016/j.indcrop.2021.113736

Poudyal, S. (2017). Application of cleaner production technique followed by experimentation on high yield semi-chemical pulping of rice straw and sabai grass for corrugating medium and linerboard (Doctoral dissertation). http://archive.nnl.gov.np:8080/handle/123456789/407

Saleem, M. H., Ali, S., Hussain, S., Kamran, M., Chattha, M. S., Ahmad, S., Abdel-Daim, M. M. (2020). Flax (*Linum usitatissimum* L.): A potential candidate for phytoremediation? Biological and economical points of view. Plants, 9(4), 496. https://doi.org/10.3390/plants9040496

Sarmast, M. K., Salehi, H., & Khosh-Khui, M. (2014). Seismomorphogenesis: a novel approach to acclimatization of tissue culture regenerated plants. 3 Biotech, 4, 599-604. https://doi.org/10.1007/s13205-013-0191-8

Saroha, A., Pal, D., Kaur, V., Kumar, S., Bartwal, A., Aravind, J., Wankhede, D. P. (2022). Agro-morphological variability and genetic diversity in linseed (*Linum usitatissimum* L.) germplasm accessions with emphasis on flowering and maturity time. Genetic Resources and Crop Evolution, 69(1), 315-333. https://doi.org/10.1007/s10722-021-01231-3

Šic Žlabur, J., Radman, S., Fabek Uher, S., Opačić, N., Benko, B., Galić, A., Voća, S. (2021). Plant response to mechanically-induced stress: a case study on specialized metabolites of leafy vegetables. Plants, 10(12), 2650. https://doi.org/10.3390/plants10122650

Sheng, Q. C., Stybayev, G., Fu, W. Y., Begalina, A., Hua, L. S., Baitelenova, A., Tussipkan, D. (2022). Flax varieties experimental report in Kazakhstan in 2019. Journal of natural fibers, 19(6), 2356-2365. https://doi.org/10.1080/15440478.2020.1813674

Shiba, M., Mizuno, T., & Fukuda, T. (2023). Effect of strong wind on laminas and petioles of *Farfugium japonicum* (L.) Kitamura var. japonicum (Asteraceae). Frontiers in Plant Science, 14, 1182266. https://doi.org/10.3389/fpls.2023.1182266

Stavropoulos, P., Mavroeidis, A., Papadopoulos, G., Roussis, I., Bilalis, D., & Kakabouki, I. (2023). On the path towards a "Greener" EU: A Mini review on Flax (*Linum usitatissimum* L.) as a Case Study. Plants, 12(5), 1102. https://doi.org/10.3390/plants12051102

Tian, X., Engel, B. A., Qian, H., Hua, E., Sun, S., Wang, Y. (2021). Will reaching the maximum achievable yield potential meet future global food demand?. Journal of Cleaner Production, 294, 126285. https://doi.org/10.1016/j.jclepro.2021.126285

Tork, D. G., Anderson, N. O., Wyse, D. L., & Betts, K. J. (2019). Domestication of perennial flax using an ideotype approach for oilseed, cut flower, and garden performance. Agronomy, 9(11), 707. https://doi.org/10.3390/agronomy9110707

Van de Weyenberg, I., Ivens, J., De Coster, A., Kino, B., Baetens, E.,Verpoest, I. (2003). Influence of processing and chemical treatment of flax fibres on their composites. Composites science and technology, 63(9), 1241-1246. https://doi.org/10.1016/S0266-3538(03)00093-9

Vavilov, N. I., & Chester, K. S. (1951). The origin, variation, immunity and breeding of cultivated plants: selected writings. (No Title).

Xie, Y., Yan, Z., Niu, Z., Coulter, J. A., Niu, J., Zhang, J., Wang, L. (2020). Yield, oil content, and fatty acid profile of flax (*Linum usitatissimum* L.) as affected by phosphorus rate and seeding rate. Industrial Crops and Products, 145, 112087. https://doi.org/10.1016/j.indcrop.2020.112087

Yan, L., Chouw, N., & Jayaraman, K. (2014). Lateral crushing of empty and polyurethane-foam filled natural flax fabric reinforced epoxy composite tubes. Composites Part B: Engineering, 63, 15-26. https://doi.org/10.1016/j.compositesb.2014.03.013

Yang, J., Wen, C., Duan, Y., Deng, Q., Peng, D., Zhang, H., & Ma, H. (2021). The composition, extraction, analysis, bioactivities, bioavailability and applications in food system of flaxseed (*Linum usitatissimum* L.) oil: A review. Trends in Food Science & Technology, 118, 252-260. https://doi.org/10.1016/j.tifs.2021.09.025

Yılmaz, S.; Uzun, A. "Keten Tarımı", Tarım ve Orman Bakanlığı. TAGEM. Karadeniz Tarımsal Araştırma En-stitüsü Müdürlüğü, 2019, 04, 34. (in Turkish)