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A two-year study of the maturity stages influence on the properties of flax (*Linum usitatissimum* L.) plants and fibres

Dvogodišnje istraživanje utjecaja vremena zriobe na svojstva predivog lana (*Linum usitatissimum* L.) i vlakana

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ABSTRACT

To revitalise the production of flax fibres in Croatia, a joint effort of different experts, such as textile and agronomist specialists, was needed. Considering that flax fibres were a significant part of Croatian cultural heritage and that natural fibres are now attracting increasing interest in fashion, the need for reviving flax production seems meaningful. To revitalise flax fibre production, an interdisciplinary collaboration between researchers of the University of Zagreb Faculty of Textile Technology and the Faculty of Agriculture was established. The goal was to revive flax production in Croatia in the traditional way to define and improve the quality of flax fibres. The paper presents the results of several achieved morphological and physical-mechanical properties of foreign flax fibre cultivars, pulled at three different maturity stages (green, yellow, and full). The trial involved five flax fibre cultivars: Viking, Viola, Venica, Agatha, and Electra, which were cultivated over two years at two different experimental fields (Zagreb, Križevci). The investigation in this way enables the identification of the possibility of introducing foreign cultivars to the continental lowland region of north-western Croatia. The results indicate that cultivars Viola and Agatha achieved higher values, particularly at the Križevci location. The highest values of investigated properties were recorded when the fibre flax was pulled at the green maturity stage compared to other maturity stages.

Keywords: *Linum usitatissimum* L., cultivars, maturity stages, morphological properties of the plant, physical-mechanical properties of fibre

SAŽETAK

Za revitalizaciju proizvodnje lanenih vlakana u Hrvatskoj bio je potreban zajednički rad različitih stručnjaka, poput tekstilaca i agronoma. S obzirom na to da su lanena vlakna bila značajan dio hrvatske kulturne baštine i da su ta prirodna vlakna ponovno u modi, potreba za oživljavanjem proizvodnje lana čini se smislenom. U svrhu revitalizacije proizvodnje lanenih vlakana, uspostavljena je interdisciplinarna suradnja između istraživača Sveučilišta u Zagrebu Tekstilno-tehnološkog i Agronomskog fakulteta. Cilj je bio oživjeti proizvodnju lana u Hrvatskoj na tradicionalni način, s naglaskom na definiranje i poboljšanje kvalitete lanenih vlakana. U radu su prikazani rezultati nekoliko postignutih morfoloških svojstava stranih kultivara predivog lana i fizikalno-mehanička svojstva lanenih vlakana, ubran u tri različita vremena zriobe (zelena, žuta i puna). Pet kultivara predivog lana – Viking, Viola, Venica, Agatha i Electra – uzgajane su tijekom dvije godine na dva različita pokusna polja, u Zagrebu i Križevcima. Istraživanje na ovaj način omogućuje utvrđivanje mogućnosti introdukcije stranih kultivara u kontinentalno nizinsko područje sjeverozapadne Hrvatske. Rezultati pokazuju da su kultivari Viola i Agatha postigle veće vrijednosti, posebice na lokaciji Križevci. Također, najveće vrijednosti ispitivanih svojstava zabilježene su kada je predivi lan ubran u zelenoj zriobi.

Ključne riječi: *Linum usitatissimum* L., kultivari, vrijeme zriobe, morfološka svojstva biljke, fizikalno-mehanička svojstva vlakana

INTRODUCTION

Flax has a rich tradition as a raw material dating back thousands of years. Its versatility in various industries, such as textile, food, pharmaceutical, chemical, graphics, and paper, positions it as a material of the future. Research by Muir and Dudarev has demonstrated that flax is one of the plants with minimal environmental impact in both production and use (Muir and Westcott, 2003; Dudarev, 2020). It is called a waste-free crop because of its use as raw materials (flax fibre, seeds) and its waste (flax shive). Harvesting flax presents challenges because its fibres start from the beginning of the stem, making cutting difficult, especially with scythes that require frequent sharpening. Therefore, the crop is pulled which also has the advantage that no fibre is wasted (Kozlowski et al., 2012). As global demand for flax continues to rise, in alignment with the trend of sustainable development and responsible resource management, the importance of this crop is continuously growing (Shekhar Sharma and Sumere, 1992; Šurina et al., 2009).

Fibre flax remains a rare crop that is still produced in Western Europe, benefiting from extremely favourable climatic conditions for cultivation (Alliance for European Flax-Linen & Hemp, 2024). Fibre flax is a spring crop, characterized by a relatively short vegetation period, which in European conditions lasts on average 90–120 days. The growth and development rate of fibre flax is influenced by the specificity of grown cultivars and local environmental conditions, (Shekhar Sharma and Sumere, 1992; Muir and Westcott, 2003; Salmon-Minotte and Franck, 2005; Kozlowski et al., 2012). From an economic point of view, to justify the cultivation of fibre flax, it is very important to preserve the yield of flax and the quality of its fibres. The differences between flax and other crops become especially apparent during harvesting. At harvest time, the flax is pulled from the ground with the roots, which is the most important stage in flax production and greatly depends on whether condition. To increase the fibre yield and at the same time preserve the fibre quality, it is desirable to perform harvesting at the most optimal time (Brittain, 1931; Dudarev, 2020). The farmer usually follows the rule of harvesting when one-third to one-half of the seed bolls are yellow to brown with fully developed brownish seeds (Brittain, 1931; Dudarev, 2020). This stage is considered to produce good-quality fibre under average conditions and represents the most profitable period for harvesting flax in terms of economic gain. Therefore, experts hold a great responsibility in estimating the optimal time for harvesting. There is no standard calendar date for harvesting fibre flax; it is too dependent on environmental conditions, which can vary widely (Mushtaq et al., 1984; Shekhar Sharma and Sumere, 1992; Kozlowski et al., 2012).

Flax can be harvested at three maturity stages: green, yellow, and full (Shekhar Sharma and Sumere, 1992; Butorac et al., 2012). When flax is harvested too early, during the green maturity stage (about a week after flowers fade), it produces very fine but weak fibres. At this stage, the stems remain green throughout their length, while the leaves start turning yellow at the lower part of the stem. Capsules are still green, and seeds are white-green and soft. The fibres are not fully developed, appearing soft, weak, very thin, and greenish (Šurina et al., 2009; Kozlowski et al., 2012). The yellow maturity stage is the most appropriate for fibre products. Approximately one week after the early yellow maturity stage, the plants reach this point. At the yellow maturity stage, stems are completely yellow, most of the leaves have fallen from the stem, and seed bolls are yellow, with the oldest ones turning brown. Seeds are fully formed and brown at the ends. During this stage, the fibres are most suitable for further processing, exhibiting sufficient tenacity and length (Shekhar Sharma and Sumere, 1992; Kozlowski et al., 2012; Butorac et al., 2018). On the other hand, the full maturity stage follows the yellow maturity stage approximately 10–12 days later. During this stage, the stems are dark yellow and brown at the bottom, while the capsules and peduncles turn brown. Seeds become dry and rattle when hit. The stems are strong but brittle, with a too-high proportion of short fibres (Shekhar Sharma and Sumere, 1992; Pospišil et al., 2004; Butorac et al., 2006; Butorac, 2009; Paridah et al., 2011).

The available scientific literature highlights a notable lack of sufficient interdisciplinary cooperation between textile and agronomist scientists. Numerous scientific papers have been published on the introduction and acclimatization of foreign cultivars in various agroclimatic systems. However, a one-sided approach to solving problems and reaching conclusions was noted, neglecting the perspectives of other professions. For instance, Herzog and Koch's research (Herzog, 1989; Koch, 1994) presents the results of testing the properties of plants and fibres without relating these properties to each other. Furthermore, Shekhar Sharma (Shekhar Sharma, 1999) conducted very similar research, wherein they investigated the correlation between agrotechnical measures and certain fibre properties.

Since there is a great influence of the flax plant properties on the flax fibre properties (Couture et al., 2002; Booth et al., 2004; Dimmock et al., 2005), an interdisciplinary collaboration was established 20 years ago between the Faculty of Agriculture and the Faculty of Textile Technology at the University of Zagreb. This cooperation aimed to revive traditional flax production in Croatia by defining and enhancing fibre quality (Brunšek et al., 2014; Šurina et al., 2009, 2011, 2012a). The primary objective was to evaluate the introduction of foreign flax cultivars to the continental lowland region of north-western Croatia, ensuring raw materials for ecologically valuable homemade products and creating additional employment for family farms.

The earlier research, which investigated the effects of different nitrogen levels, concluded that it was unnecessary to apply more than 30 kg/ha N (Šurina et al., 2012b; Butorac et al., 2014; Brunšek et al., 2022). Furthermore, previous research on the effects of different maturity stages on the agronomic characteristics of introduced flax cultivars found that at the Križevci location, cultivars Agatha, Viola, and Electra achieved superior agronomic characteristics when harvested at the green maturity stage (Butorac et al., 2018). Considering the obtained results, the investigation continued. Accordingly, this paper presents a study on the influence of different maturity stages on the morphological properties of flax plants and the mechanical properties of fibres.

METHODOLOGY

Cultivation and processing of fibre flax

Cultivar trials were conducted in 2010 and 2011, involving five fibre flax cultivars: Viking (Cooperative Liniere de Fontaine Cany, France), Viola (Van de Bilt Zaden, the Netherlands), Venica (Agritec, Czech Republic), Agatha, and Electra (Cebecco Seed, Netherlands) (OECD Variety list Query, 2024). Since the type of soil directly affects plant and fibre properties, the experiments were set up on soils of different physical and chemical properties, at the experimental field of the Faculty of Agriculture of Zagreb on eutric cambisol and the experimental field of the College of Agriculture in Križevci on pseudogley on level terrain (Butorac et al., 2018). The content of the nutrients in the soil and pH values are given in Table 1, and weather conditions are in Tables 2 and 3.

Table 1. The content of nutrients in the soils and pH (Butorac et al., 2018)

Year	P_2O_5 (mg/100 g)	K_2O (mg/100 g)	Total nitrogen (%)	pH (KCl)
2010	19.9	19.9	0.12	6.91
2011	22.3	17.2	0.09	6.6
2010	20.9	19.4	0.09	5.04
2011	12.8	15.8	0.08	4.8

P_2O_5, K_2O – Al-method; Total nitrogen - HRN ISO 13878:2004; pH - HRN ISO 10390:2004

Before sowing flax, winter wheat had been sown in the field. All cultivars were sown at a density of 2500 seeds/m^2. As part of the basic and pre-sowing seedbed preparation fertilization with 100 kg/ha P (superphosphate) and 150 kg/ha K (potassium salt) was applied. Before sowing, 30 kg/ha N was added in a single fertilizer application at the average plant height of 0.1 m. The trials were laid out according to the randomized complete block design (RCBD) with four replications.

Table 2. Mean monthly, absolute minimum and maximum air temperatures (°C) and monthly precipitation amounts (mm) for 2010 and 2011 for Zagreb (Meteorological and Hydrological Services of the Republic of Croatia)

Month	Mean monthly air temperature (°C)	Absolute minimum air temperature (°C)	Absolute maximum air temperature (°C)	Monthly precipitation amounts (mm)
		2010		
March	6.8	-6.5	21.6	45.7
April	12.0	0.3	27.8	63.3
May	16.6	5.3	29.2	97.5
June	20.4	9.0	34.0	103.8
July	23.2	10.9	35.6	52.5
		2011		
March	7.3	-6.5	23.4	36.0
April	13.4	-3.6	26.6	42.1
May	16.9	2.3	30.8	70.0
June	21.1	8.2	32.0	67.5
July	22.2	8.7	36.7	63.4

Table 3. Mean monthly, absolute minimum and maximum air temperatures (°C) and monthly precipitation amounts (mm) for 2010 and 2011 for Križevci (Meteorological and Hydrological Services of the Republic of Croatia)

Month	Mean monthly air temperature (°C)	Absolute minimum air temperature (°C)	Absolute maximum air temperature (°C)	Monthly precipitation amounts (mm)
		2010		
March	6.2	-6.4	20.6	46.8
April	11.7	1.7	26.2	76.2
May	15.8	6.9	28.5	107.4
June	19.6	9.3	32.5	140.5
July	13.0	10.4	32.5	84.5
		2011		
March	6.4	-7.4	23.0	16.9
April	13.0	3.3	25.6	47.0
May	16.1	-0.1	29.5	45.2
June	20.5	7.6	31.5	44.2
July	21.2	8.0	36.0	47.6

The main trial plot size was 10 m^2 (10 rows × 0.1 m row spacing × 10 m length). Sowing was carried out using a plot seeder (Wintersteiger, Austria). Fibre flax seeding was performed on 29th March 2010 and 1st April 2011 (Butorac et al., 2018). Against broadleaf weeds, when the flax plants had grown 10 cm, they were treated twice (with an interval of 5–7 days) with the herbicide Basagran 600 SL (bentazon) at a total dose of 3.0 l/ha. The harvest time of flax plants is given in Table 4.

Table 4. The harvest time of flax plants (Butorac et al., 2018)

Stages of maturity	Date of harvesting	
	2010	2011
	Zagreb	
Green	15 – 19 June	16 – 20 June
Yellow	23 – 27 June	25 – 29 June
Full	9 – 13 July	11 – 15 July
	Križevci	
Green	17 – 21 June	18 – 22 June
Yellow	26 – 30 June	26 – 30 June
Full	11 – 15 July	12 – 16 July

Properties of plants and fibres

The morphological properties of the plant investigated include technical stem length and stem thickness (Table 5).

Plants were harvested from an area of 1 m^2 by hand at three different maturity stages (green, yellow and full). Flax stems were subjected to biological maceration in a water tank at 30 °C for 4 days under controlled conditions. They were dried with a stream of warm air at 60 °C for 30 hours and weighed. A cylindrical breaking machine was used to separate the woody core from the fibre. The obtained fibres are characterized by their mechanical properties – length, fineness and tenacity (Table 5).

Statistical analysis

Data of all the properties studied were statistically processed by the analysis of variance (two-factor trial – cultivar and maturity) separately for each year and each location. Differences between mean values were analysed using Duncan's multiple-range test (Duncan, 1955).

RESULTS AND DISCUSSION

Statistically significant differences were observed among the cultivars for the investigated properties of fibre flax, except stem thickness and fibre tenacity in 2010 at Zagreb, as well as technical stem length in 2010, fibre tenacity in 2011, and fibre fineness in both years at the location Križevci (Tables 6 and 7). Furthermore, statistically significant differences were found among different maturity stages for all investigated properties, except for fibre tenacity in 2010 at Zagreb, and fibre length, fibre fineness, and fibre tenacity in 2011 at both locations (Tables 8 and 9).

Table 5. Performed measurements and methods

Plant properties	Methods	
Technical stem length	Was measured from the cotyledon node to the first branch	
Stem thickness	Was determined in the middle of the technical stem length using an electronic micrometre	
Fibres properties	Methods	Adjustment of methods
Length	HRN ISO 6989 2003	/
Fineness	HRN EN ISO 1973:2021 Vibroscop 400	Cogged steel clamp Gauge length: 5 mm Testing speed: 3 mm/min Pre-tension: 1500 mg Number of measurements: 100
Tenacity	HRN EN ISO 5079:2020 Vibrodyn 400	

Table 6. Means of morphological properties of fibre flax and physical-mechanical properties of fibres in dependence on the cultivar at Zagreb (2010 and 2011)

Cultivars	Technical stem length (cm)	Stem thickness (mm)	Fibre length (cm)	Fibres fineness (dtex)	Fibres tenacity (cN/tex)
			2010		
Viking	57.92^{c}	1.43^{a}	38.16^{c}	36.02^{b}	70.55^{a}
Viola	66.92^{a}	1.69^{a}	39.03^{bc}	38.28^{ab}	73.17^{a}
Venica	60.92^{bc}	1.58^{a}	41.03^{a}	35.53^{b}	75.75^{a}
Agatha	66.75^{a}	1.58^{a}	40.46^{ab}	39.17^{a}	72.18^{a}
Electra	63.92^{ab}	1.51^{a}	41.65^{a}	37.19^{ab}	74.27^{a}
			2011		
Viking	43.75^{d}	0.62^{b}	29.94^{b}	34.54^{b}	66.00^{a}
Viola	55.58^{ab}	0.90^{a}	32.05^{a}	39.98^{a}	59.53^{b}
Venica	48.50^{c}	0.60^{b}	30.15^{b}	38.43^{ab}	62.24^{ab}
Agatha	59.08^{a}	0.8^{a}	28.84^{b}	38.65^{ab}	58.23^{b}
Electra	54.08^{b}	0.78^{a}	28.83^{b}	38.22^{ab}	63.49^{ab}

Values having the same letter are not significant at a level of 5%; as the significance value decreases, the letters become lower due to the alphabetical order

Table 7. Means of morphological properties of fibre flax and physical-mechanical properties of fibres in dependence on the cultivar at Križevci (2010 and 2011)

Cultivars	Technical stem length (cm)	Stem thickness (mm)	Fibre length (cm)	Fibres fineness (dtex)	Fibres tenacity (cN/tex)
			2010		
Viking	69.42^{a}	1.25^{a}	36.7^{0bc}	37.49^{a}	71.73^{b}
Viola	76.58^{a}	1.38^{a}	39.78^{a}	36.76^{a}	72.76^{b}
Venica	70.00^{a}	1.21^{b}	39.91^{a}	38.80^{a}	73.11^{b}
Agatha	73.75^{a}	1.28^{a}	38.87^{ab}	39.02^{a}	79.73^{a}
Electra	75.58^{a}	1.27^{a}	36.24^{c}	38.54^{a}	77.61^{ab}
			2011		
Viking	50.58^{c}	1.53^{b}	30.97^{b}	40.13^{a}	64.27^{a}
Viola	68.08^{a}	1,66^{a}	32.63^{ab}	39.15^{a}	63.99^{a}
Venica	61.00^{b}	1.73^{a}	31.13^{b}	38.27^{a}	62.52^{a}
Agatha	63.75^{ab}	1.73^{a}	34.13^{a}	37.85^{a}	65.83^{a}
Electra	63.08^{ab}	1.66^{a}	31.83^{ab}	38.35^{a}	65.71^{a}

Values having the same letter are not significant at a level of 5%; as the significance value decreases, the letters become lower due to the alphabetical order

There were no significant interactions recorded for any properties or location; therefore, interactions were not included in the factors shown here and were not discussed further. Accordingly, the factors affected the studied properties independently.

For textile purposes, the technical stem length of flax should be around 65 cm, as it is shortened to 60 cm in spinning mills. Flax with a technical stem length below 60 cm loses its value as a textile raw material for yarn production but remains suitable for technical purposes (Pasković, 1963; Norton et al., 2006). The obtained values (Tables 6 and 7) of technical stem length for all cultivars at Zagreb in 2011 were under 60 cm. The reason for such obtained results in 2011 is unfavourable weather conditions during the growth and development of flax and sandy soil at location Zagreb. Weather conditions during the research period included low temperatures with frost in April, followed by excessively low temperatures in May. In the third decade, temperatures rose sharply, with absolute maximum temperatures up to 30.8 °C, causing premature flowering. Additionally, the large amount of precipitation in May caused the lodging of flax (Table 2). At Križevci, the technical stem lengths of all cultivars in all years were higher than 60 cm, except for cultivar Viking in 2011. In May 2010, a period crucial for flax growth, there was sufficient precipitation and no low temperatures, resulting in higher plant height. However, 2011 was a dry year, leading to lower plant height. Cultivars Viola and Agatha consistently achieved significantly higher technical stem lengths in both years, along with Electra in 2010 at location Zagreb. Similarly, at the Križevci, cultivars Viola, Agatha, and Electra obtained higher technical stem lengths in 2011. The obtained technical stem length values are slightly lower than reported by other authors, likely due to differences in climatic conditions during flax cultivation (Pavelek, 2001; Daenekindt, 2003).

The quantity and quality of flax fibres are influenced by stem thickness, as the fineness of the fibres depends on the stem's thickness. A stem that is either very thin or very thick is considered less valuable for textile use. The stem thickness at Zagreb in 2010 and Križevci in both years are between 1.21 to 1.73 mm, which is in line with the research of other authors (Norton et al., 2006; Šurina et al., 2012; Butorac et al., 2014). Obtained results (Tables 6 and 7) of stem thickness are suitable for obtaining quality fibres of satisfactory quantity. In 2011, at Zagreb, the obtained stem thickness value was between 0.60 to 0.90 mm, which correlates with the obtained measurement results of technical stem length.

Table 8. Means of morphological properties of fibre flax and physical-mechanical properties of fibres in dependence of maturity stages at Zagreb (2010 and 2011)

Maturity stages	Technical stem length (cm)	Stem thickness (mm)	Fibre length (cm)	Fibres fineness (dtex)	Fibres tenacity (cN/tex)
			2010		
Green	57.35^{b}	1.74^{b}	40.36^{a}	38.49^{a}	71.67^{a}
Yellow	66.50^{a}	1.51^{a}	39.00^{b}	36.90^{ab}	73.49^{a}
Full	66.00^{a}	1.44^{a}	40.54^{a}	36.31^{b}	74.39^{a}
			2011		
Green	49.80^{b}	0.90^{a}	30.42^{a}	38.74^{a}	62.62^{a}
Yellow	52.15^{a}	0.69^{a}	30.20^{a}	36.79^{a}	62.83^{a}
Full	54.40^{a}	0.62^{b}	29.28^{a}	38.36^{a}	60.25^{a}

Values having the same letter are not significant at a level of 5%; as the significance value decreases, the letters become lower due to the alphabetical order

The thinner stem thickness observed in 2011 is likely a consequence of unfavourable weather conditions, particularly the dry year. At the Zagreb location in 2011, cultivars Viola, Agatha, and Electra achieved significantly thicker stem thickness. At the Križevci location, Venica in 2010 and Viking in 2011 achieved significantly thicker stem thickness.

The significantly longest fibre length was achieved by the cultivars Electra, Venica, and Agatha in 2010 and Viola in 2011 at Zagreb, which is in correlation with previous research (Mushtaq et al., 1984; Šurina et al., 2011; Daenekindt, 2003). Similar results were obtained at Križevci, where the cultivars Viola, Venica, and Agatha achieved the significantly longest fibre length in 2010 and the cultivars Viola, Agatha, and Electra in 2011, which followed the technical stem length. The significantly finest fibres were obtained from cultivars Venica and Viking in 2010 compared to Agatha and Viking in 2011 at Zagreb in comparison to Viola. No significant values were observed at the location Križevci, but the finest fibres were obtained by cultivars Viola (2010) and Agatha (2011). The significantly strongest fibres were obtained from cultivar Viking in 2011 at Zagreb compared to Viola and Agatha. At location Križevci in both years, the strongest fibres were obtained by cultivar Agatha.

Means of morphological properties of fibre flax and physical-mechanical properties of fibres in dependence at three different maturity stages (green, yellow and full) at Zagreb are given in Table 8 and at Križevci in Table 9 for both years.

According to the obtained values of the technical stem, the significantly shortest technical stem was obtained in green maturity stages at both locations in both years. Stem thickness at Zagreb in 2011, for all maturity stages, was under 1.00 mm (Table 8) which is following obtained results of cultivars stem thickness (Table 6). Unfavourable weather conditions in 2011 respectively low temperatures with the appearance of frost in April, followed by excessively lower temperatures can explain obtained results in May with sudden large amounts of precipitation that caused lodging of flax. Significantly, the thickest stem was achieved during the green maturity stage in 2010 and the full maturity stage in 2011 at Zagreb. Significantly, the thinnest stem was achieved in full maturity stages in both years at Križevci (Table 9).

The significantly longest fibres were achieved in the green and full maturity stages in 2010 at both locations, Zagreb and Križevci. The analysis of fibre fineness results showed that there is no significance, except in 2010 at both locations, where significantly the finest fibres

Table 9. Means of morphological properties of fibre flax and physical-mechanical properties of fibres in dependence of maturity stages at Križevci (2010 and 2011)

Maturity stages	Technical stem length (cm)	Stem thickness (mm)	Fibre length (cm)	Fibres fineness (dtex)	Fibres tenacity (cN/tex)
			2010		
Green	68.15^{b}	1.36^{a}	40.21^{a}	40.54^{a}	69.80^{b}
Yellow	73.70^{a}	1.27^{a}	35.77^{b}	35.57^{b}	78.16^{a}
Full	76.85^{a}	1.19^{b}	38.92^{a}	38.25^{ab}	76.99^{a}
			2011		
Green	55.90^{b}	1.89^{a}	31.52^{a}	37.66^{a}	65.66^{a}
Yellow	62.15^{a}	1.66^{b}	32.36^{a}	39.09^{a}	65.17^{a}
Full	65.85^{a}	1.43^{c}	32.54^{a}	39.51^{a}	62.57^{a}

Values having the same letter are not significant at a level of 5%; as the significance value decreases, the letters become lower due to the alphabetical order

were obtained in the yellow and full maturity stages at Zagreb and Križevci. Similarly, in 2010, the yellow and full maturity stages resulted in significantly the strongest fibres at Križevci. According to research by Mushtaq et al. (1984), the longest fibres were achieved in the yellow and full maturity stages, and the finest fibres were obtained in green. Additionally, the strongest fibres were obtained in the yellow maturity stage.

For textile processing, ensuring uniformity in raw material properties such as fibre length, fineness, and tenacity is crucial for yarn production. These properties, namely fibre length, fineness, and tenacity, are the most important in determining fibre quality and suitability for subsequent processing as raw material. The analysis of the obtained results concerning fibre fineness and tenacity suggests that the factors independently influenced the examined properties, satisfying the essential preconditions for further fibre processing.

CONCLUSION

To evaluate the influence of cultivars and different maturity stages on plant and fibre properties, multiple parameters have been considered that affect plant growth and development as well as fibre properties. Therefore, unambiguous general conclusions cannot be given. Nevertheless, for making conclusions, the cultivar and maturity stages were taken into consideration, which together in most investigated samples, have a similar effect on single properties. Notably, the cultivars Viola and Agatha achieved higher values, especially at location Križevci. The highest values of investigated properties were recorded when the fibre flax was harvested in the green maturity stage.

The conducted research provides valuable results, knowledge and insights directly applicable to the domestic production of flax and flax products. Moreover, reviving traditional flax fibre production presents an opportunity for rural employment, involving the cultivation of flax plants to obtain raw materials and create authentic high-value souvenirs imbued with national characteristics. Choosing appropriate cultivars and production technology as well as processing methods could supply domestic natural fibres to the textile industry and other sectors, with minimal environmental impact. Flax production in the lowland continental part of north-western Croatia is expected to be revived with the introduction of newly developed highly productive cultivars from Western Europe. This is due to the valorisation of their agronomic and textile-technological attributes, as well as their acclimatization capabilities.

REFERENCES

Alliance for European Flax-Linen & Hemp (2024) Flax-Linen and Hemp Economic Observatory. Available at: https://allianceflaxlinenhemp.eu/en/flax-linen-hemp-economic-observatory [Accessed 3 September 2024].

Booth, I., Harwood, R.J., Wyatt, J., Grishanov, S. (2004) A comparison study of the characteristics of fibre flax (*Linum usitatissimum* L.). Industrial Crops and Products, 20, 89-95. DOI: https://doi.org/10.1016/j.indcrop.2003.12.014

Brittain, B.R. (1931) The time to harvest fiber flax. Technical Bulletin, 236, 1-23.

Brunšek, R., Andrassy, M., Butorac, J. (2014) The revitalization of flax in Croatia. Tekstil, 63 (1-2), 49-58.

Brunšek, R., Butorac, J., Augustinović, Z., Pospišil, M. (2022) Effect of Nitrogen on the Properties of Flax (*Linum usitatissimum* L.) Plants and Fibres. Polymers, 14, 1-10. DOI: https://doi.org/10.3390/polym14030558

Butorac, J. (2009) Fibre flax. In: Kugler, B., ed. Fibre plants. Zagreb: Kugler, pp. 34-67.

Butorac, J., Augustinović, Z., Šurina, R., Pospišil, M. (2012). The influence of stages of maturity on fiber flax yield and share of fiber. In: Proceedings of 47th Croatian and 7th International Symposium on Agriculture, Opatija, Croatia, 13-17 February 2012., University of Zagreb Faculty of Agriculture, pp. 464-468.

Butorac, J., Brunšek, R., Augustinović, Z., Pospišil, M. (2018) The influence of stages of maturity on the agronomic traits of fibre flax introduced varieties. Journal of Central European Agriculture, 19, 142-152. DOI: https://doi.org/10.5513/JCEA01/19.1.2032

Butorac, J., Brunšek, R., Augustinović, Z., Pospišil, M., Andrassy, M. (2014) The influence of nitrogen on the agronomic traits of fibre flax cultivars. Romanian Agricultural Research, 31, 253-259. doi:10.5513/JCEA01/19.1.2032

Butorac, J., Pospišil, M., Mustapić, Z. (2006) Some characteristics of European fibre flax varieties. In: Proceedings of 41st Croatian and 1st International Symposium on Agriculture. Opatija, Croatia, 13-17 February 2006. Osijek: Faculty of Agriculture Osijek.

Couture, S.J., Asbil, W. L., DiTommaso, A., Watson A. K. (2002) Comparison of European Fibre Flax (*Linum usitatissimum* L.). Cultivars under Eastern Canadian Growing Conditions. Journal of Agronomy and Crop Science, 188, 350-356. DOI: https://doi.org/10.1046/j.1439-037X.2002.00582.x

Daenekindt, A. (2003) Belgian flax varieties in 2002. Vlas Berichten, 4, 1-4.

Dimmock, J. P. R. E., Bennett, S. J., Wright, D., Edwards-Jones, G., Harris, I. M. (2005) Agronomic evaluation and performance of flax varieties for industrial fiber production, Journal of Agricultural Research, 143, 299-309. DOI: https://doi.org/10.1017/S0021859605005277

Dudarev, I. (2020) A Review of Fibre Flax Harvesting: Conditions, Technologies, Processes and Machines. Journal of Natural Fibers, 19, 4496-4508. DOI: https://doi.org/10.1080/15440478.2020.1863296

Duncan, D. B. (1955) Multiple range and multiple F tests. Biometrics, 11, 1-42. DOI: https://doi.org/10.2307/3001478

Herzog, W. (1989) Objektive Qualitats prufung von Flachs. Melliand Textilberichte, 1 (63), 7-11.

Koch, P.-A. (1994) Flach sowie andere Bast-und Hartfasern. Chemiefasern/Textilindustrie, 44 (96), 765-785.

Kozłowski, R. M., Mackiewicz-Talarczyk, M., Allam, A. M. (2012) Bast fibres: flax. In: ed., Ryszard M. Kozłowski, ed. Handbook of natural fibres: Types, properties and factors affecting breeding and cultivation. Volume 1, 1st Woodhead Publishing Limited, pp. 56-110.

Muir, D., Westcott, N. D. (2003) Flax. In: A. D. Muir, N. D. Westcott, eds. The Genus Linum (Medicinal and aromatic plants - industrial profiles). Canada: CRC Press, pp. 235-268.

Mushtaq, A., Jamil, N. A., Hanif, A. H., Saeed, M. A. (1984) Quality characteristics of various flax (*Linum usitatissimum* L.) fibres as affected by maturity. Pakistan Journal of Agricultural Research, 5 (1), 18-22.

Norton, A.J. et al. (2006) Determining the physical properties of flax fibre for industrial applications: the influence of agronomic practice. Annals of Applied Biology, 149(1), 15-25. DOI: https://doi.org/10.1111/j.1744-7348.2006.00066.x

OECD Variety list Query (2024) Available at: https://www.niab.com/oecdv2/variety/search [Accessed 3 September 2024].

Paridah, M. T., Ahmed, A. B., SaifulAzry, S. O. A., Ahmed, Z. (2011) Retting process of some bast plant fibres and its effect on fibre quality: A review. BioResources. 6 (4), 5260-5281. DOI: https://doi.org/10.15376/BIORES.6.4.5260-5281

Pasković, F. (1963) Technological properties of some new varieties of flax. Tekstil, 12, 793-810.

Pavelek, M. (2001) New varieties – Venica. Czech Journal of Genetics and Plant Breeding, 37, 103-104.

Pospišil, M., Butorac, J., Gojšić, T. (2004) Flax-forgotten but useful culture. Gazophylacium, 9 (3-4), 81-86.

Salmon-Minotte, J., Franck, R. R. (2005) Flax. In: R. R. Franck, ed. (2005) Bast and other plant fibre. Cambridge, England: Woodhead Publishing Limited, 94-175.

Shekhar Sharma, H. S. (1999) Comparison of subjective and objective methods to assess flax straw cultivars and fibre quality after dew-retting. Annals of Applied Biology, 2 (135), 495-501. DOI: https://doi.org/10.1111/j.1744-7348.1999.tb00879.x

Shekhar Sharma, H. S., Sumere, Van C. F. (1992) The biology and processing of flax. Belfast: M. Publications.

Šurina, R., Andrassy, M., Butorac, J. (2012a) An interdisciplinary approach to flax research. In: 12th AUTEX World Textile Conference - Innovative textile for high future demands, Zadar, Croatia, 13th-15th June 2012, University of Zagreb Faculty of Textile Technology.

Šurina, R., Andrassy, M., Butorac, J., Vuksan, T. (2012b) Three-years of flax and flax fibres research. In: Book of Proceedings of the 6th International Textile, Clothing & Design Conference Magic World of Textiles, Dubrovnik, Croatia, 7th-11th October 2012, University of Zagreb Faculty of Textile Technology.

Šurina, R., Andrassy, M., Vujasinović, E. (2009) Flax - plant and fiber through century. Tekstil, 58, 625-639.

Šurina, R., Butorac, J., Andrassy, M. (2011) Dependence of fiber properties on the properties of the flax fibres. Tekstil, 60 (2-3), 87-101.