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LIGNO-CELLULOSE QUALITY AND CALORIFIC VALUE OF *ELYMUS ELONGATUS* L. AND THE NOVEL *SECALE CEREANUM* TESTED UNDER CENTRAL EUROPEAN CONDITIONS

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The objective of the paper is to determine ligno-cellulose quality and calorific value of tall wheatgrass Szarvasi-1 and Alkar, as well as perennial rye Kriszta and Gergő cultivars, tested within a huge pilot field experiment. The experiment was established in the autumn of 2016 and was carried out until 2020, while four trial sites with marginal soil and three nutrition treatments (intensive, semi-intensive and untreated control) were included as well. The impact of the nutrition, years, sites, and cultivars on quality was statistically evaluated as the main effects, with two complete data set points of acid-detergent fibre (ADF), acid-detergent lignin (ADL), crude cellulose (CE), hemicellulose (HEM), neutral-detergent fibre (NDF) and high heating value (HHV), primarily in terms of quality content and a secondarily in terms of quality yield. In terms of quality content, the impact decreased in alternating order: of sites, years, and cultivars, each of them over the least important nutrition, while in terms of quality yield nutrition has been confirmed as the most important factor followed by sites, then by years, and finally by cultivars with the least impact. Average ADF content according to cultivars sequence Szarvasi-1 – Alkar – Kriszta – Gergő was 45.95 – 45.65 – 42.25 – 42.97%, ADL 8.67 – 8.24 – 8.51 – 8.37%, CE 37.27 – 37.41 – 33.74 – 34.60%, HEM 24.14 – 24.78 – 25.46 – 25.00%, NDF 70.03 – 70.43 – 67.71 – 67.71% and HHV 16.86 – 16.89 – 17.21 – 17.17 MJ/kg, respectively. The maximum yield values of ADF yield according to the order were 6.373 – 6.180 – 6.112 – 4.983 t/ha, ADL 1.340 – 1.374 – 1.261 – 1.027 t/ha, CE 5.253 – 5.111 – 4.851 – 3.997 t/ha, HEM 3.000 – 3.097 – 3.052 – 2.655 t/ha, NDF 9.285 – 9.133 – 9.164 – 7.626 t/ha and HHV 225.3 – 221.1 – 228.9 – 185.7 GJ/ha, respectively.

Key words: tall wheatgrass, perennial rye, marginal soils, ligno-cellulose quality, calorific value, mineral nutrition

There are currently several socio-economic, environmental and agronomic approaches to energy crops, one of which is the old-new intention to use marginal land as a concept commonly associated with the promotion of agrofuels regarding environmental issues (Peterson & Galbraith 1932; Nalepa & Bauer 2012). In Europe, over 10 million hectares have been categorized as marginal land (Von Cosel *et al*. 2019), on most of these lands tall wheatgrass (*Elymus elongatus* L.) could perform well in terms of phytomass production and water use efficiency, due to its low requirements (Ciria *et al.* 2020 a, b). In addition, there are more than 5 million hectares around the world that are sown with winter rye (*Secale cereale* L.) (FAOStat 2020), which offers a doubtful positive economic margin and environmental balance concerning usual field crops (Ciria *et al.* 2020 a, b). Both marginal lands and rye fields could be used to cultivate perennial rye (*Secale cereanum*), a perennial grass newly recognized for

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bioenergy purposes and multiple uses. Both these perennial grasses have a wider ecological amplitude than winter rye, however, some soil-climate specifics need to be taken into account because there is no universal crop (Halasz & Sipos 2007; Sipos & Halasz 2007; Schneider *et al.* 2016; Szakács *et al*. 2020; Szöke-Pázsi *et al*. 2021; Tóth 2023).

In an effort to maximize feedstock availability for cellulosic ethanol or other biomass-based industries, it will be necessary the cultivation of dedicated crops with both high biomass yields and high structural carbohydrate content. Therefore, to decide which herbaceous perennial crops should be cultivated as feedstocks for future cellulosic biorefineries, it is important to research closely the variability in their carbohydrate content and quality profit, resulting to a potentially high ethanol yield (Monomo *et al.* 2013). Despite much research that has been done on examining the carbohydrate composition of a lot of herbaceous perennials as forage crops, the suitable candidates for energy crops respectively, most of these studies focus on crude protein and other contents, which are less valuable for biorefinery feedstocks purpose (Monomo *et al.* 2013). Some studies deal with the chemical composition of various high-fibre forages (Jensen *et al.* 2016; Kron *et al.* 2017; Martyniak *et al.* 2017; Miccoli *et al*. 2018), whereas some papers investigated the potential of tall wheatgrass as an energy crop or directly evaluated the phytomass for biorefinery feedstock (Jafari *et al.* 2014; Yu *et al.* 2014; Kikas *et al.* 2016; Boros-Lajszner *et al.* 2021; Jablonowski *et al.* 2022). Some papers even present various advanced concepts of a biorefinery that provides valuable bioproducts from phytomass conversion instead of fossil-based products (Moncada *et al.* 2016; Borand & Karaosmanoğlu 2018; Ortiz-Sanchez & Cardona 2022). Despite the fact that some works are focused on cultivation from the point of view of quality (Dickeduisberg *et al.* 2017; Briggs *et al.* 2020; Ciria *et al.* 2020a; Kopecký *et al.* 2021; Barro *et al.* 2022), limited knowledge about cultivations impact is a big challenge even in the case of tall wheatgrass (Csete *et al.* 2011; Li *et al.* 2022, Scordia *et al.* 2022), while knowledge about the ligno-cellulose quality of perennial rye is probably still lacking. The aim of the presented research was to determine the quality of ligno-cellulose and calorific value of tall wheatgrass and perennial rye, while nutrition, years, sites and cultivars were statistically evaluated as the main effects in a huge, large-scale pilot field experiment. Two equal aspects of quality were followed, primary content quality and secondary revenue quality.

MATERIAL AND METHODS

Pilot field trials 2016/17 – 2020

During 2016/17 – 2020 a huge, large-scale poly-factorial pilot field experiment with newly introduced energy crops (i) *Elymus elongatus* (Host) Runemark and (ii) *Secale cereanum* (tall wheatgrass and perennial rye, respectively) was established and carried out on 4 sites under continental Central European climate. The weather conditions, during the main vegetation period (from April till September) of the experiment, were typical of 18.2°C dealing with average daily temperature and 334 mm concerning the sum of precipitations. The sites were located on marginal and mutually contrasting soil-climatic conditions (Site-1: Regosol, light soil, and arid climate; Site-2: Gleyic Fluvisol, heavy soil and arid climate; Site-3: Gleyic Fluvisol, heavy soil and semi-humid climate; and Site-4: Stragnic Cambisol, heavy soil and humid climate). The cultivars Szarvasi-1 and Alkar for tall wheatgrass (TW) and Kriszta and Gergő for perennial rye (PR) were tested in the experiments. Each cultivar had three levels of nutrition intensity (i) intensive nutrition 245.0 kg/ha NPK, (ii) semi-intensive nutrition 122.5 kg/ha NPK, and (iii) untreated control without nutrition treatment 0.0 kg/ha NPK.

A more detailed description of the field experiments in terms of used agronomy, soil-climatic conditions, plant material, biometric parameters, and collection of plant samples is presented in a related paper (Tóth 2023).

Laboratory analyses

The collection of plant samples was timed to optimal harvest maturity in terms of crop development, whereas the crop stands were not desiccated before harvest. The sampling, storage and processing were done in relevance to the European standard EN ISO 13906/2008. The samples were analysed in the labo-

ratory of the National Agricultural and Food Centre -Research Institute of Plant Production, Institute of Agroecology in Michalovce, whereas the standard methodology was used regarding followed quality indicators. The indicators of ligno-cellulose quality, acid-detergent fibre (ADF), neutral-detergent fibre (NDF), acid-detergent lignin (ADL), crude cellulose (CE), and hemicellulose (HEM) respectively, were determined according to the regulation of MPRV SR no. 2136 / 2004-100 by extraction systems: Fibre extractor – Fibertest (Raypa), Model F-6 and Cold Extraction Unit, Model EF-6. The applied indicator of calorific value, the high heating value (HHV) was determined by IKA C 5000 calorimetric system, in accordance with STN standard ISO 1928.

Statistic methods

The presented study evaluates 2,304 original quality data, exactly half of it in terms of quality content and half in terms of quality yield. A primary data set consists of 1,152 quality content data, whereas each of the data is an average of two analytical repetitions (classic twins analyses) done within 192 plant samples for each of the 6 quality indicators. A secondary set of 1,152 data was generated in terms of quality yield (quality profit respectively), whereas a simple equation was used:

$$quality\ yield = quality\ content\ x\ crop\ yield$$

where: quality content [%, or kJ/g] concerning each of the 6 quality parameters (ADF-HHV) and the crop yield in DM yield [t/ha] was applied.

Multi-factorial analyses of variance (MANOVA) were performed to identify significant factors influencing quality variability using Statgraphics 15.2.14, whereas each of the quality indicators was evaluated. Separately and within both data set points (Tables 1, 2). Moreover, second-order polynomial functions in the case of trend analyses were also performed. For this purpose, it was applied 576 other biometric data as independent variables, whereas the analytical study of these complementary parameters (crop yield, plant height and dry matter content at harvest) itself is the subject of the related paper (Tóth 2023). These dependencies of quality indicators on biometric parameters have an additional character nonce, therefore the simple description of the trend by shape type is preferred over giving complex polynomial formulas (Tyler & Olsson 2001), only the reliability index is displayed in the figures. However, a complete set of linear equations is given (Table 3) for the dependence with the highest reliability index (dependence of quality yield on dry matter yield). Finally, a box plot was performed and added to increase the intelligibility of the paper.

RESULTS

Main effects

In terms of quality content, the impact of main factors increased in the order: nutrition, cultivars, followed by years and sites in general, whereas in terms of quality yield nutrition has been confirmed as the most important factor followed by sites and years, while cultivars had the least impact (Tables 1A, B). In contrast to the ambiguous impact of main factors on quality content, the valuation within quality yield is unambiguous, while the impact of each main factor was significant by all quality indicators (Table 1B).

Concerning quality content (Table 1A), in contrast to the stated general trend:

- Nutrition had a dominant impact on HEM and a significant impact on both ADL and HHV, whereas the impact on ADF, CE and NDF was not significant.
- Cultivars have a dominant impact on CE and a subdominant impact on both ADF and HHV, whereas the impact on NDF was significant also, but the impact on ADL and HEM was not significant.

Levels of main effects

Quality content

Statistical evaluation of levels of the main effects shows differentiated forming of homogenous groups (Table 2A), whereas:

- Nutrition was accompanied by the highest proportion of the same homogeneous group, which is adequate for the lowest impact of nutrition (Table 1A). Within nutrition, the highest average values of indicators majority are associated with intensive nutrition (ADF, ADL, CE, and HHV),

T a b l e 1A

Parameters of statistical analyses of variance for data of phytomass quality, the content of qualitative indicators in % (ADF, ADL, CE, HEM, NDF) or in J/g (HHV) evaluated for main effects

Main source / parameter	ADF			ADL			CE			HEM			NDF			HHV		
	IO	*F*-ratio	*P*-value	IO	*F*-ratio	*P*-value	IO	*F*-ratio	*P*-value	IO	*F*-ratio	*P*-value	IO	F-ratio	*P*-value	IO	*F*-ratio	*P*-value
Cultivars	2	21.85	0.0000	4	1.45	0.2287	1	24.94	0.0000	4	0.25	0.7777	3	9.00	0.0000	2	20.93	0.0000
Sites	3	14.87	0.0000	2	7.15	0.0001	3	9.57	0.0000	3	3.61	0.0145	2	12.13	0.0000	1	27.31	0.0000
Years	1	26.69	0.0000	1	23.23	0.0000	2	15.89	0.0000	2	7.05	0.0002	1	30.75	0.0000	3	17.25	0.0000
Nutrition	4	0.44	0.6467	3	3.89	0.0223	4	0.26	0.7689	1	7.19	0.0001	4	0.15	0.8646	4	8.58	0.0003

IO – impact order, an order based on F-ratio; ADF – acid-detergent fibre; NDF – neutral-detergent fibre; ADL – acid-detergent lignin; CE – crude cellulose; HEM – hemicellulose; HHV – high heating value.

T a b l e 1B

Parameters of statistical analyses of variance for data of quality harvested, profit of qualitative indicators in t/ha (ADF, ADL, CE, HEM, NDF) or in GJ/ha (HHV) evaluated for main effects

Main source / parameter	ADF			ADL			CE			HEM			NDF			HHV		
	IO	*F*-ratio	*P*-value	IO	*F*-ratio	*P*-value	IO	*F*-ratio	*P*-value	IO	*F*-ratio	*P*-value	IO	*F*-ratio	*P*-value	IO	*F*-ratio	*P*-value
Cultivars	4	8.70	0.0000	4	6.02	0.0006	4	9.35	0.0000	4	5.07	0.0021	4	7.41	0.0001	4	5.03	0.0023
Sites	2	16.25	0.0000	2	14.40	0.0000	2	16.31	0.0000	2	14.49	0.0000	2	15.80	0.0000	2	13.66	0.0000
Years	3	9.94	0.0000	3	9.01	0.0000	3	10.10	0.0000	3	8.81	0.0000	3	9.64	0.0000	3	8.11	0.0000
Nutrition	1	70.15	0.0000	1	67.26	0.0000	1	69.06	0.0000	1	74.85	0.0000	1	73.18	0.0000	1	73.74	0.0000

IO – impact order, an order based on F-ratio; for ADF-HHV see the explanations under Table 1A.

and the highest average values of both remaining indicators (HEM and NDF) are associated with untreated control.

- Cultivars were accompanied by forming of two homogenous groups identical to the crops in general. The groups were unequivocally crop specific within the majority of indicators (ADF, CE, NDF, and HHV), and the groups of both remaining indicators (ADL and HEM) were more cultivar specific.
- Sites and years were accompanied by the highest proportion of differentiated homogeneous groups, however:
  – The highest average values within indicators majority belong to Site-3 (ADF, ADL, CE, and NDF), and the highest values of both remaining indicators belong to Site-1 (HEM and HHV).
  – The highest average values within indicators majority were achieved unequivocally in 2020, only except HEM content for its highest average value was achieved in 2019.

Quality yield

A similar evaluation of the levels of main effects on the homogenous groups formed (Table 2B) points to:

- Nutrition with the highest proportion of unambiguously differentiated homogeneous groups, which is adequate for the highest impact of nutrition (Table 1B). Within nutrition, the highest average values of each indicator always belong to intensive nutrition and the least one always belongs to untreated control without nutrition.
- Cultivars were accompanied by creating two homogenous groups identical to the crops in general, except for three groups in the case of ADL yield and unambiguous affiliation of HEM yield within the Kriszta cultivar.
- Sites and years were accompanied by a high proportion of differentiated homogeneous groups, however:
  – The highest average values of each indicator always belong to Site-3 (the site with the highest DM yield).
  – The highest average values of each indicator were achieved always in 2020 (the year with the highest DM yield).

Impact of DM yield, quality indicators by cultivars

Figure 1 presents the range and average values of quality indicators by cultivars, whereas data in terms of quality content are presented in Figure 1A and quality yield in Figure 1B. To include HHV values in Figure 1, while in orders of magnitude higher, appropriate values in both units [kJ/g and GJ/ha] were recalculated with a conversion factor of 1/1000 or 1/100, what changed the decimal resolution and the applied units respectively. Therefore, the changed unit is signed either as kJ/kg or hGJ/ha respectively. Figures 3 – 8 show the dependencies of quality content and yield on dry matter yield by cultivars. Figures A 3 – 8 are optimized to show the whole data cluster in terms of quality content, while the second-order polynomial line acquires one of 5 shape types (i) U (ii) ∩ (iii) / (iv) – and (v) \, in general. The shape type is usually similar within the cultivars of the crops and usually is different or even opposite when comparing the two crops.

Regardless to shape type, for that quality content trend lines, it is a typical weak reliability with R^2 ranging within 0.0027 – 0.2555. In contrast to quality content, for adequate quality yield trend lines, it is typically strong reliability with R^2 ranging from 0.9343 – 0.9996, whereas the only shape type "/" indicates also a strong linear dependence valid for ligno-cellulose indicators as for calorific value (Figures B 3 – 8).

Ligno-cellulose indicators

Acid-detergent fibre

Within acid-detergent fibre (ADF) content, it was achieved two homogenous groups identical to the crops. Higher values were achieved for TW 45.95% for Szarvasi-1 45.65% for Alkar and lower ones for PR as 42.25% for Kriszta 42.97% for Gergő (Table 2A). ADF content ranged between 38.27 – 51.83% for Szarvasi-1, 39.07 – 54.83% for Alkar, 33.81 – 47.84% for Kriszta, and 34.03 – 49.72% for Gergő (Figure 1A).

Also concerning ADF yield, it was achieved two homogenous groups identical to the crops. In agreement with ADF content, higher values of ADF yield were reached for TW as 2.79 t/ha for Szarvasi-1 as 2.73 t/ha for Alkar, and lower ones for PR as 2.16 t/ha for Kriszta as 1.84 t/ha for Gergő (Table 2B). ADF yield varied between 0.477 – 6.373 t/ha for Szarva-

T a b l e 2A

Parameters of statistical analyses of variance for data of phytomass quality within levels of main effects, the content of qualitative indicators in % (ADF, ADL, CE, HEM, NDF) or J/g (HHV)

Main source / parameter	ADF			ADL			CE			HEM			NDF			HHV		
	H	LS Mean	LS Sigma	H	LS Mean	LS Sigma	H	LS Mean	LS Sigma	H	LS Mean	LS Sigma	H	LS Mean	LS Sigma	H	LS Mean	LS Sigma
cultivars																		
Szarvasi-1	a	45.9508	0.39975	a	8.66875	0.15243	a	37.2740	0.37337	b	24.1375	0.28955	a	70.0333	0.46457	b	16855.7	40.5926
Alkar	a	45.6483	0.39975	b	8.24125	0.15243	a	37.4071	0.37337	ab	24.7842	0.28955	a	70.4325	0.46457	b	16890.2	40.5926
Kriszta	b	42.2519	0.39975	ab	8.51062	0.15243	b	33.7413	0.37337	a	25.4594	0.28955	b	67.7110	0.46457	a	17211.3	40.5926
Gergő	b	42.9690	0.39975	ab	8.37083	0.15243	b	34.5981	0.37337	a	25.0046	0.28955	b	67.9737	0.46457	a	17173.9	40.5926
sites																		
Site-1	b	44.5502	0.39975	a	8.63875	0.15243	b	35.9052	0.37337	a	25.5358	0.28955	a	70.0860	0.46457	a	17245.9	40.5926
Site-2	c	42.5302	0.39975	b	8.08396	0.15243	c	34.4462	0.37337	a	25.3927	0.28955	b	67.9306	0.46457	b	17082.1	40.5926
Site-3	a	46.1585	0.39975	a	8.93083	0.15243	a	37.2277	0.37337	b	24.5715	0.28955	a	70.7298	0.46457	b	17063.9	40.5926
Site-4	bc	43.5810	0.39975	b	8.13792	0.15243	bc	35.4413	0.37337	b	23.8856	0.28955	b	67.4042	0.46457	c	16739.2	40.5926
years																		
2017	b	43.5773	0.39975	c	7.74708	0.15243	b	35.8283	0.37337	b	24.0660	0.28955	c	67.6433	0.46457	c	16877.1	40.5926
2018	c	42.2481	0.39975	b	8.24104	0.15243	c	34.0008	0.37337	b	24.3296	0.28955	c	66.5154	0.46457	b	17037.1	40.5926
2019	b	43.8798	0.39975	b	8.23125	0.15243	b	35.5585	0.37337	a	25.7069	0.28955	b	69.5940	0.46457	bc	16950.9	40.5926
2020	a	47.1148	0.39975	a	9.48208	0.15243	a	37.6327	0.37337	a	25.2831	0.28955	a	72.3979	0.46457	a	17265.9	40.5926
nutrition																		
Intensive	a	44.4159	0.34619	a	8.74797	0.13201	a	35.9464	0.32335	a	24.7028	0.25076	a	69.1187	0.40238	a	17130.3	35.1542
Semi-int.	a	43.9617	0.34619	b	8.31078	0.13201	a	35.6509	0.32335	a	24.8991	0.25076	a	68.8606	0.40238	a	17043.0	35.1542
Control	a	44.2373	0.34619	b	8.28484	0.13201	a	35.6680	0.32335	a	24.9373	0.25076	a	69.1336	0.40238	b	16925.1	35.1542

H – homogenous groups; for ADF-HHV see the explanations under Table 1A.

T a b l e 2B

Parameters of statistical analyses of variance for data of quality harvested quality within levels of main effects, profit of qualitative indicators in t/ha (ADF, ADL, CE, HEM, NDF) or MJ/ha (HHV)

Main source / parameter	ADF			ADL			CE			HEM			NDF			HHV		
	H	LS Mean	LS Sigma	H	LS Mean	LS Sigma	H	LS Mean	LS Sigma	H	LS Mean	LS Sigma	H	LS Mean	LS Sigma	H	LS Mean	LS Sigma
cultivars																		
Szarvasi-1	a	2.7896	0.15573	a	0.54052	0.03229	a	2.24888	0.12513	a	1.44098	0.08104	a	4.22960	0.23447	a	101444	5791.78
Alkar	a	2.7301	0.15573	ab	0.49569	0.03229	a	2.23441	0.12513	a	1.44376	0.08104	a	4.17386	0.23447	a	99199.0	5791.78
Kriszta	b	2.1563	0.15573	bc	0.43680	0.03229	b	1.71951	0.12513	ab	1.27236	0.08104	b	3.42865	0.23447	b	87326.5	5791.78
Gergő	b	1.83916	0.15573	c	0.35721	0.03229	b	1.48196	0.12513	b	1.05782	0.08104	b	2.89698	0.23447	b	73162.1	5791.78
sites																		
Site-1	b	2.07039	0.15573	b	0.40167	0.03229	b	1.66856	0.12513	ab	1.19737	0.08104	b	3.26775	0.23447	cb	81246.0	5791.78
Site-2	b	2.22053	0.15573	b	0.42986	0.03229	b	1.79067	0.12513	b	1.28459	0.08104	b	3.50553	0.23447	b	87625.6	5791.78
Site-3	a	3.30246	0.15573	a	0.63654	0.03229	a	2.66591	0.12513	a	1.73105	0.08104	a	5.03349	0.23447	a	120798	5791.78
Site-4	b	1.9218	0.15573	b	0.36214	0.03229	b	1.55961	0.12513	c	1.00191	0.08104	b	2.92232	0.23447	c	71461.4	5791.78
years																		
2017	a	2.63361	0.15573	ab	0.47588	0.03229	a	2.15769	0.12513	a	1.43011	0.08104	a	4.06373	0.23447	a	100705	5791.78
2018	b	1.67676	0.15573	c	0.32693	0.03229	b	1.34968	0.12513	b	0.94423	0.08104	b	2.61961	0.23447	b	66134.6	5791.78
2019	a	2.42162	0.15573	b	0.46639	0.03229	a	1.95523	0.12513	a	1.39679	0.08104	a	3.81880	0.23447	a	93267.6	5791.78
2020	a	2.78317	0.15573	a	0.56103	0.03229	a	2.22215	0.12513	a	1.44378	0.08104	a	4.22695	0.23447	a	101024	5791.78
nutrition																		
Intensive	a	3.53302	0.13487	a	0.69620	0.02796	a	2.83682	0.10836	a	1.91805	0.07018	a	5.45107	0.20305	a	134209	5015.82
Semi-int.	b	2.32775	0.13487	b	0.43757	0.02796	b	1.89018	0.10836	b	1.28916	0.07018	b	3.61690	0.20305	b	88517.8	5015.82
Control	c	1.2756	0.13487	c	0.23890	0.02796	c	1.03656	0.10836	c	0.70399	0.07018	c	1.97885	0.20305	c	48121.4	5015.82

H – homogenous groups; for ADF-HHV see the explanations under Table 1A.

si-1, 0.288 – 6.180 t/ha for Alkar, 0.004 – 6.112 t/ha for Kriszta and 0.024 – 4.983 t/ha for Gergő (Figure 1B).

Acid-detergent lignin

Within acid-detergent lignin (ADL) content, it was achieved two homogenous groups non-identical to the crops. Both the highest and the lowest values belong to TW at 8.67% for Szarvasi-1 and 8.24% for Alkar, while the middle ones belong to PR at 8.51% for Kriszta at 8.37% for Gergő (Table 2A). ADL content varied between 6.23 – 11.04% for Szarvasi-1, 5.87 – 11.11% for Alkar, 6.36 – 11.94% for Kriszta, and 5.87 – 11.49% for Gergő (Figure 1 A).

Concerning ADL yield, it was achieved three homogenous groups, whereas in agreement to ADL content, higher values were achieved for TW as 0.54 t/ha for Szarvasi-1 as 0.50 t/ha for Alkar and lower ones for PR as 0.44 t/ha for Kriszta as 0.36 t/ha for Gergő (Table 2B). ADL yield varied between 0.089 – 1.340 t/ha for Szarvasi-1, 0.054 – 1.374 t/ha for Alkar, 0.001 – 1.261 t/ha for Kriszta and 0.004 – 1.027 t/ha for Gergő (Figure 1B).

Cellulose

Similar to ADF content, within cellulose (CE) content it was achieved two homogenous groups identical to the crops. Higher values were reached for TW at 37.27% for Szarvasi-1, 37.41% for Alkar, and lower ones for PR as 33.74% for Kriszta as 34.60% for Gergő (Table 2A). CE content varied between 30.36 – 43.87% for Szarvasi-1, 31.63 – 45.24% for Alkar, 26.03 – 38.71% for Kriszta, and 27.60 – 42.01% for Gergő (Figure 1A).

Also concerning CE yield, it was achieved two homogenous groups identical to the crops. In agreement with CE content, higher values of CE yield were achieved for TW as 2.25 t/ha for Szarvasi-1 as 2.23 t/ha for Alkar, and lower ones for PR as 1.72 t/ha for Kriszta as 1.48 t/ha for Gergő (Table 2B). CE yield varied between 0.389 – 5.253 t/ha for Szarvasi-1, 0.234 – 5.111 t/ha for Alkar, 0.003 – 4.851 t/ha for Kriszta and 0.019 – 3.997 t/ha for Gergő (Figure 1B).

Hemicellulose

Within hemicellulose (HEM) content, it was achieved two homogenous groups nearly identical to crops, whereas lower values were reached for TW at 24.14% for Szarvasi-1, 24.78% for Alkar, and higher ones for PR as 25.46% for Kriszta as 25.00% for Gergő (Table 2A). HEM content varied between 19.09 – 29.27% for Szarvasi-1, 18.64 – 29.98% for Alkar, 21.38 – 29.05% for Kriszta, and 20.43 – 29.46% for Gergő (Figure 1A).

Concerning HEM yield, it was achieved two homogenous groups, whereas in contrast to HEM content higher values were reached for TW as 1.44 t/ha for Szarvasi-1 as 1.44 t/ha for Alkar and lower ones for PR as 1.27 t/ha for Kriszta as 1.06 t/ha for Gergő (Table 2B). HEM yield varied between 0.296 – 3.000 t/ha for Szarvasi-1, 0.160 – 3.097 t/ha for Alkar, 0.002 – 3.052 t/ha for Kriszta and 0.013 – 2.655 t/ha for Gergő (Figure 1B).

Neutral-detergent fibre

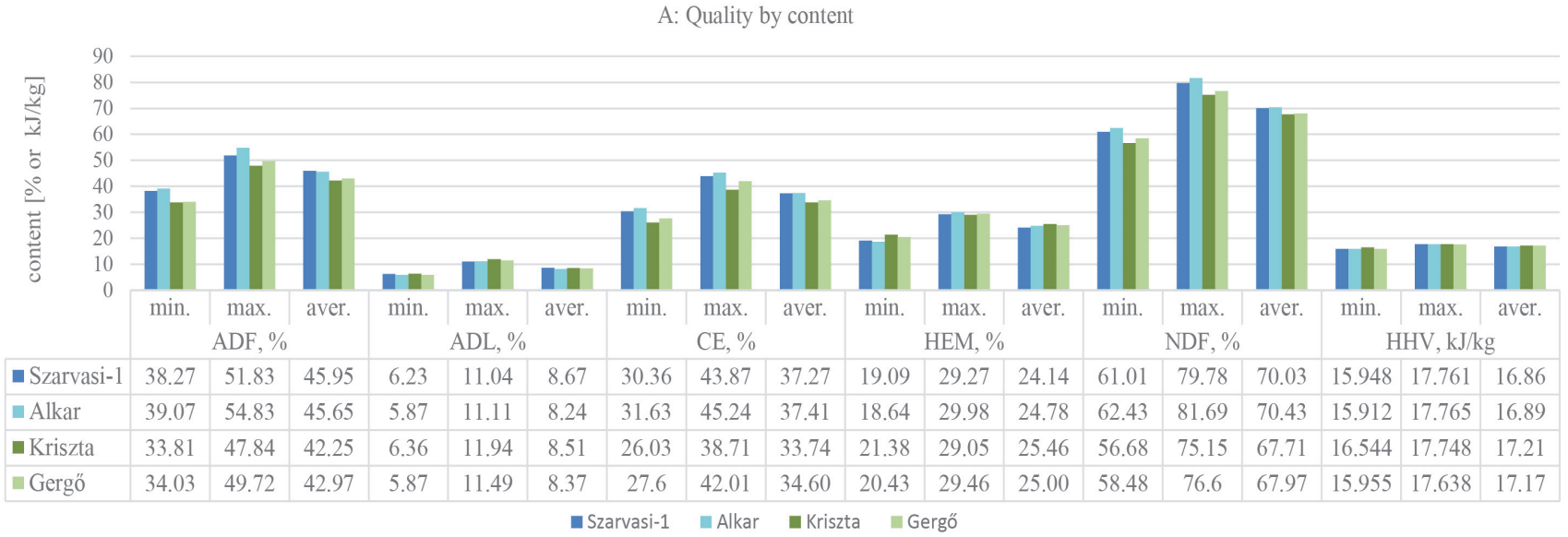
Like ADF and CE content, within neutral-detergent fibre (NDF) content, it was achieved two homogenous groups identical to the crops, whereas the highest values were achieved for TW at 70.03% for Szarvasi-1 as 70.43% for Alkar and the lower ones for PR as 67.71% for Kriszta as 67.97% for Gergő (Table 2A). NDF content varied between 61.01 – 79.78% for Szarvasi-1, 62.43 – 81.69% for Alkar, 56.68 – 75.15% for Kriszta, and 58.48 – 76.60% for Gergő (Figure 1A).

Also, like ADF and CE yield, NDF yields it was achieved in two homogenous groups identical to the crops. In agreement with NDF content, higher values of NDF yield were achieved for TW as 4.23 t/ha for Szarvasi-1 as 4.17 t/ha for Alkar, and lower ones for PR as 3.43 t/ha for Kriszta as 2.90 t/ha for Gergő (Table 2B). NDF yield varied between 0.773 – 9.285 t/ha for Szarvasi-1, 0.448 – 9.133 t/ha for Alkar, 0.006 – 9.164 t/ha for Kriszta and 0.037 – 7.626 t/ha for Gergő (Figure 1B).

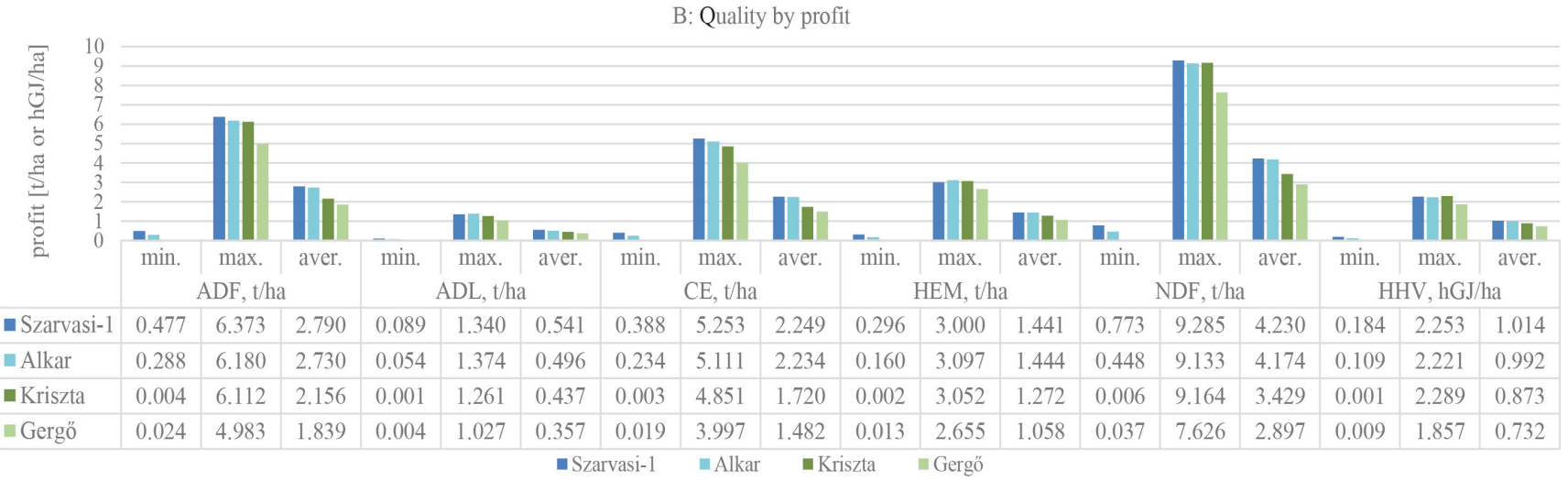
Calorific value

High heating value

Like HEM content, within high heating value (HHV) content, it was achieved two homogenous groups identical to the crops, whereas lower values belong to TW as 16.856 MJ/kg for Szarvasi-1 as 16.890 MJ/kg for Alkar and higher ones for PR as 17.211 MJ/kg for Kriszta as 17.174 MJ/kg for Gergő (Table 2A). HHV content ranged between 15.948 – 17.761 MJ/kg for Szarvasi-1, 15.912 – 17.765 MJ/kg



	ADF, %			ADL, %			CE, %			HEM, %			NDF, %			HHV, kJ/kg		
	min.	max.	aver.	min.	max.	aver.	min.	max.	aver.	min.	max.	aver.	min.	max.	aver.	min.	max.	aver.
Szarvasi-1	38.27	51.83	45.95	6.23	11.04	8.67	30.36	43.87	37.27	19.09	29.27	24.14	61.01	79.78	70.03	15.948	17.761	16.86
Alkar	39.07	54.83	45.65	5.87	11.11	8.24	31.63	45.24	37.41	18.64	29.98	24.78	62.43	81.69	70.43	15.912	17.765	16.89
Kriszta	33.81	47.84	42.25	6.36	11.94	8.51	26.03	38.71	33.74	21.38	29.05	25.46	56.68	75.15	67.71	16.544	17.748	17.21
Gergő	34.03	49.72	42.97	5.87	11.49	8.37	27.6	42.01	34.60	20.43	29.46	25.00	58.48	76.6	67.97	15.955	17.638	17.17



	ADF, t/ha			ADL, t/ha			CE, t/ha			HEM, t/ha			NDF, t/ha			HHV, hGJ/ha		
	min.	max.	aver.	min.	max.	aver.	min.	max.	aver.	min.	max.	aver.	min.	max.	aver.	min.	max.	aver.
Szarvasi-1	0.477	6.373	2.790	0.089	1.340	0.541	0.388	5.253	2.249	0.296	3.000	1.441	0.773	9.285	4.230	0.184	2.253	1.014
Alkar	0.288	6.180	2.730	0.054	1.374	0.496	0.234	5.111	2.234	0.160	3.097	1.444	0.448	9.133	4.174	0.109	2.221	0.992
Kriszta	0.004	6.112	2.156	0.001	1.261	0.437	0.003	4.851	1.720	0.002	3.052	1.272	0.006	9.164	3.429	0.001	2.289	0.873
Gergő	0.024	4.983	1.839	0.004	1.027	0.357	0.019	3.997	1.482	0.013	2.655	1.058	0.037	7.626	2.897	0.009	1.857	0.732

Figure 1. Minimal, maximal and average values of quality indicators (ADF, ADL, CE, HEM, NDF, and HHV) in terms of quality content A [% or kJ/kg] and quality yield, B [t/ha or hGJ/ha]; for ADF-HHV see the explanations under Table 1A.

T a b l e 3

Parameters of linear dependence of quality yield on dry matter yield, by cultivars and indicators ADF, ADL, CE, HEM and NDF (in t/ha), and HHV (in GJ/ha)

Indicator	Szarvasi-1		Alkar		Kriszta		Gergő	
	LF	ID	LF	ID	LF	ID	LF	ID
ADF	y = 0.774x – 0.0809	0.990	y = 0.4923x – 0.1554	0.979	y = 0.4402x – 0.069	0.987	y = 0.4445x – 0.0494	0.985
ADL	y = 0.1002x – 0.062	0.954	y = 0.0925x – 0.0464	0.930	y = 0.0915x – 0.0259	0.961	y = 0.085x – 0.004	0.948
CE	y = 0.3773x – 0.0195	0.983	y = 0.3998x – 0.109	0.978	y = 0.3487x – 0.0432	0.982	y = 0.3595x – 0.0454	0.983
HEM	y = 0.2313x + 0.0503	0.969	y = 0.2355x + 0.0635	0.970	y = 0.2429x + 0.0447	0.985	y = 0.2471x + 0.0077	0.981
NDF	y = 0.7092x – 0.0345	0.994	y = 0.7278x – 0.0919	0.986	y = 0.6831x – 0.0244	0.994	y = 0.6916x – 0.0417	0.995
HHV	y = 16.935x – 0.3835	0.998	y = 17.025x – 0.5928	0.998	y = 17.329x – 0.2745	1.000	y = 17.311x – 0.3957	0.999

LF – linear formula y = ax + b, where x = dry matter yield in t/ha; ID – index of determination, equal to r^2, where r is correlation coefficient, for ADF-HHV see the explanations under Table 1A.

Figure 2. Box plot for quality indicators (ADL, ADF, CE, HEM, NDF, and HHV) according to the nutrition treatments (I – intensive, E – semi-intensive and C – control) – AB, and cultivars (SZ – Szarvasi-1, A – Alkar, K – Kriszta, and G – Gergő) – CD, displaying the minimum, first quartile, median, mean, third quartile, and maximum; for ADF-HHV see the explanations under Table 1A.

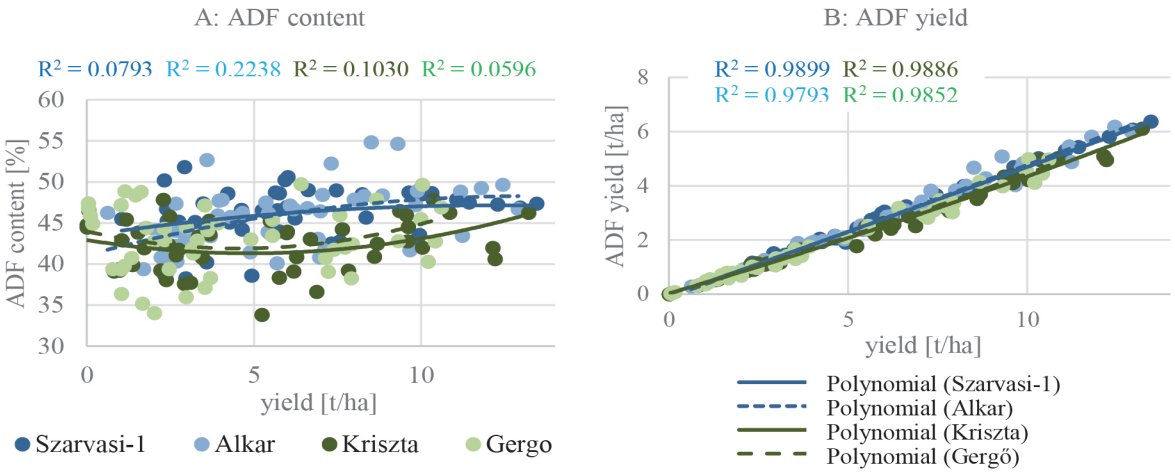
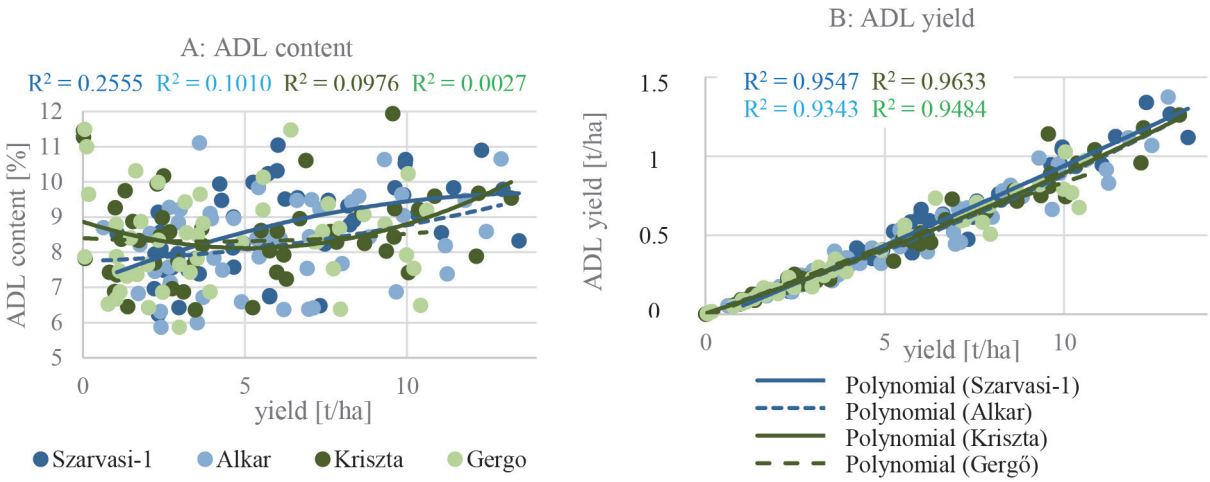


Figure 3. Dependence of ADF content and ADF yield on phytomass DM yield, for ADF see the explanation under Table 1A.



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Figure 4. Dependence of ADL content and ADL yield on phytomass DM yield, for ADL see the explanation under Table 1A.

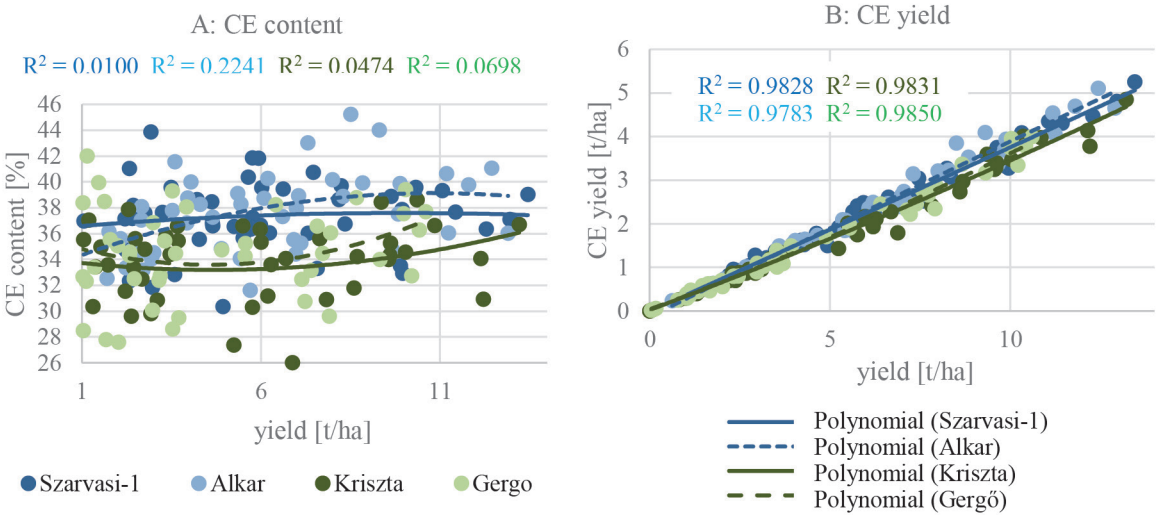


Figure 5. Dependence of CE content and CE yield on phytomass DM yield, for CE see the explanation under Table 1A.

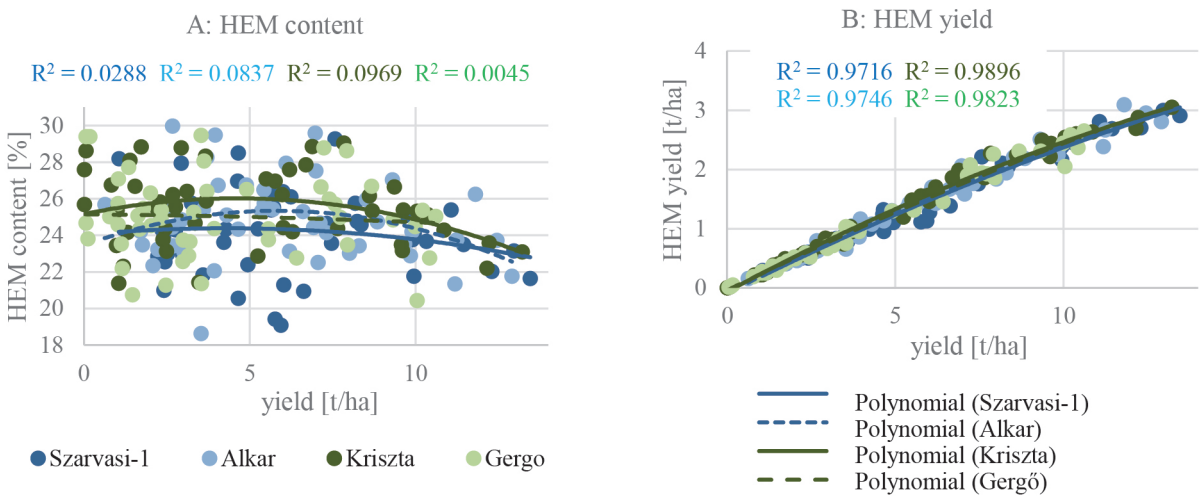


Figure 6. Dependence of HEM content and HEM yield on phytomass DM yield, for HEM see the explanation under Table 1A.

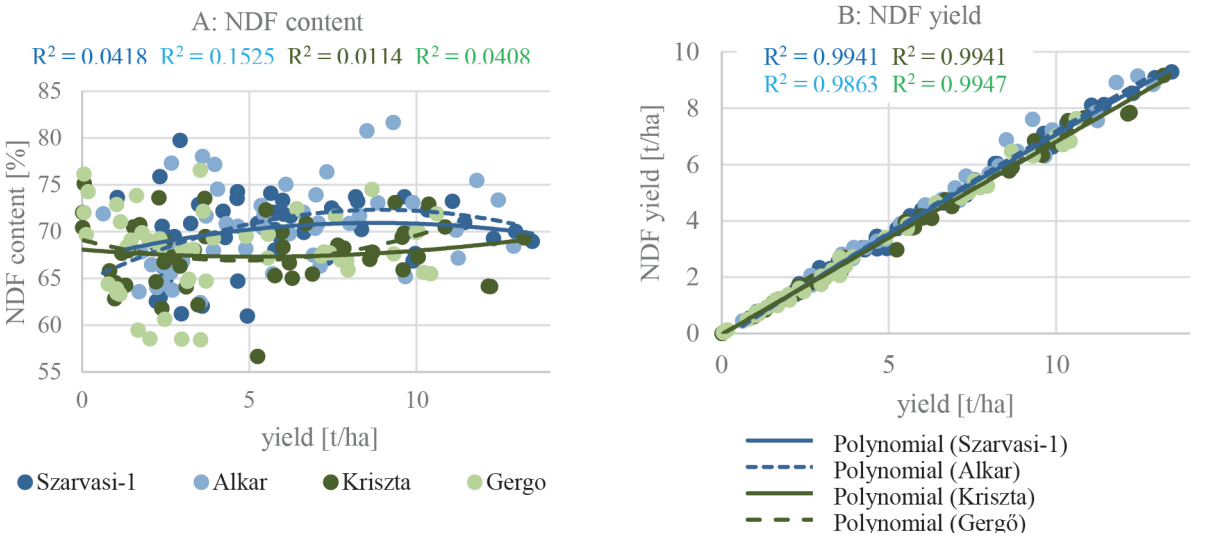


Figure 7. Dependence of NDF content and NDF yield on phytomass DM yield, for NDF see the explanation under Table 1A.

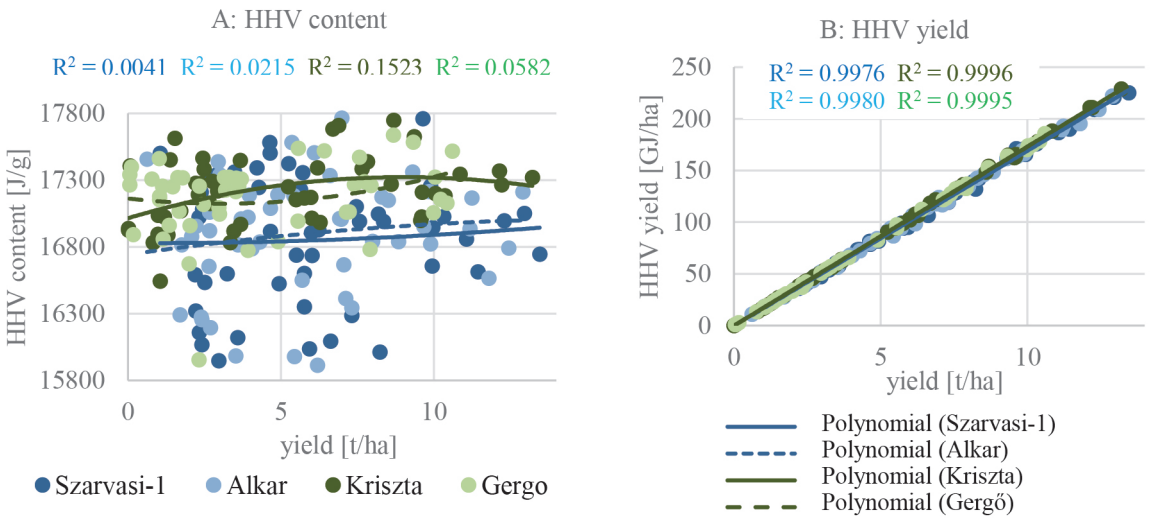


Figure 8. Dependence of HHV content and HHV yield on phytomass DM yield, for HHV see the explanation under Table 1A.

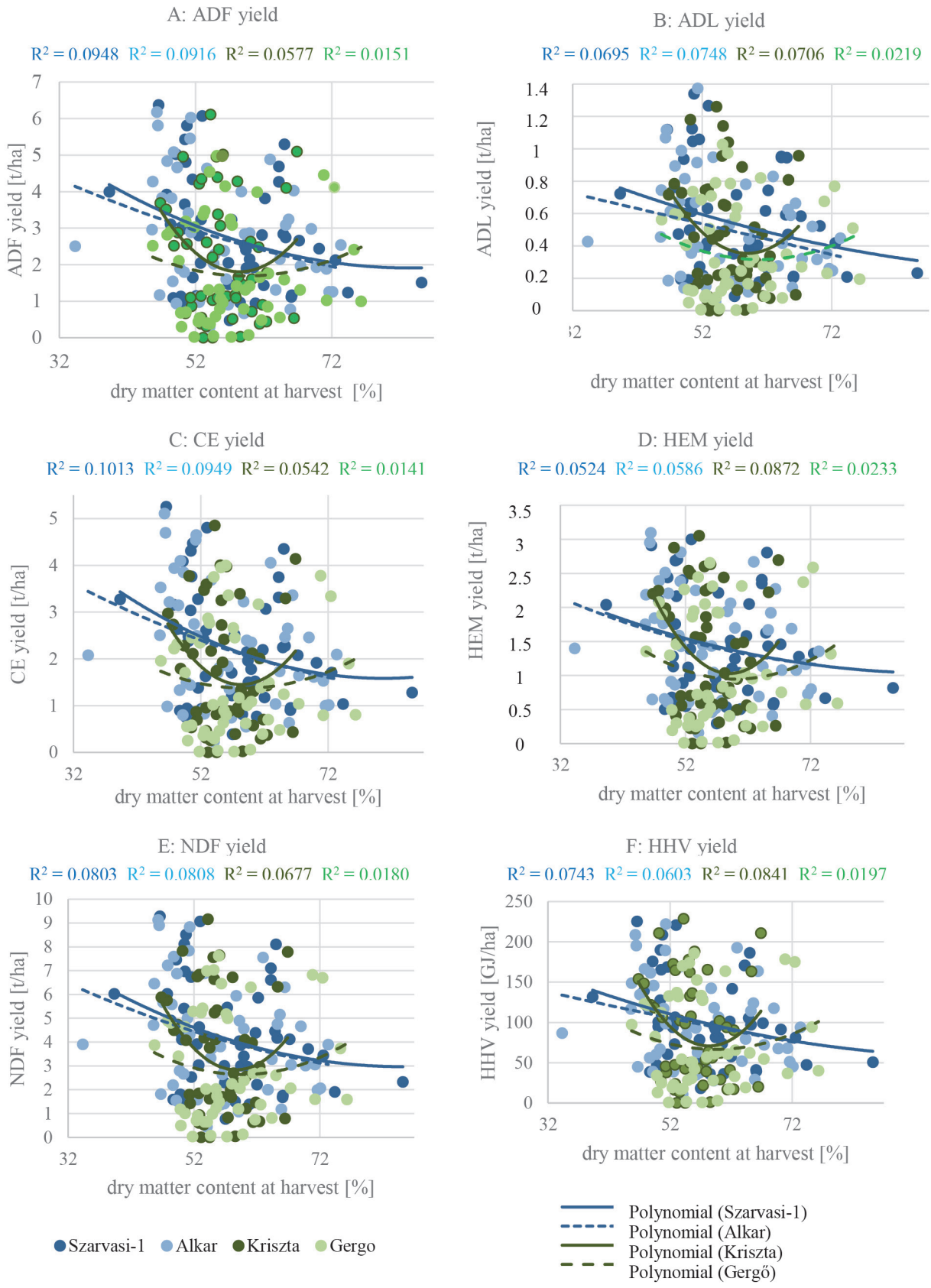


Figure 9. Dependence of ADF, ADL, CE, HEM, NDF, and HHV content on DM content at harvest, for ADF-HHV see the explanations under Table 1A.

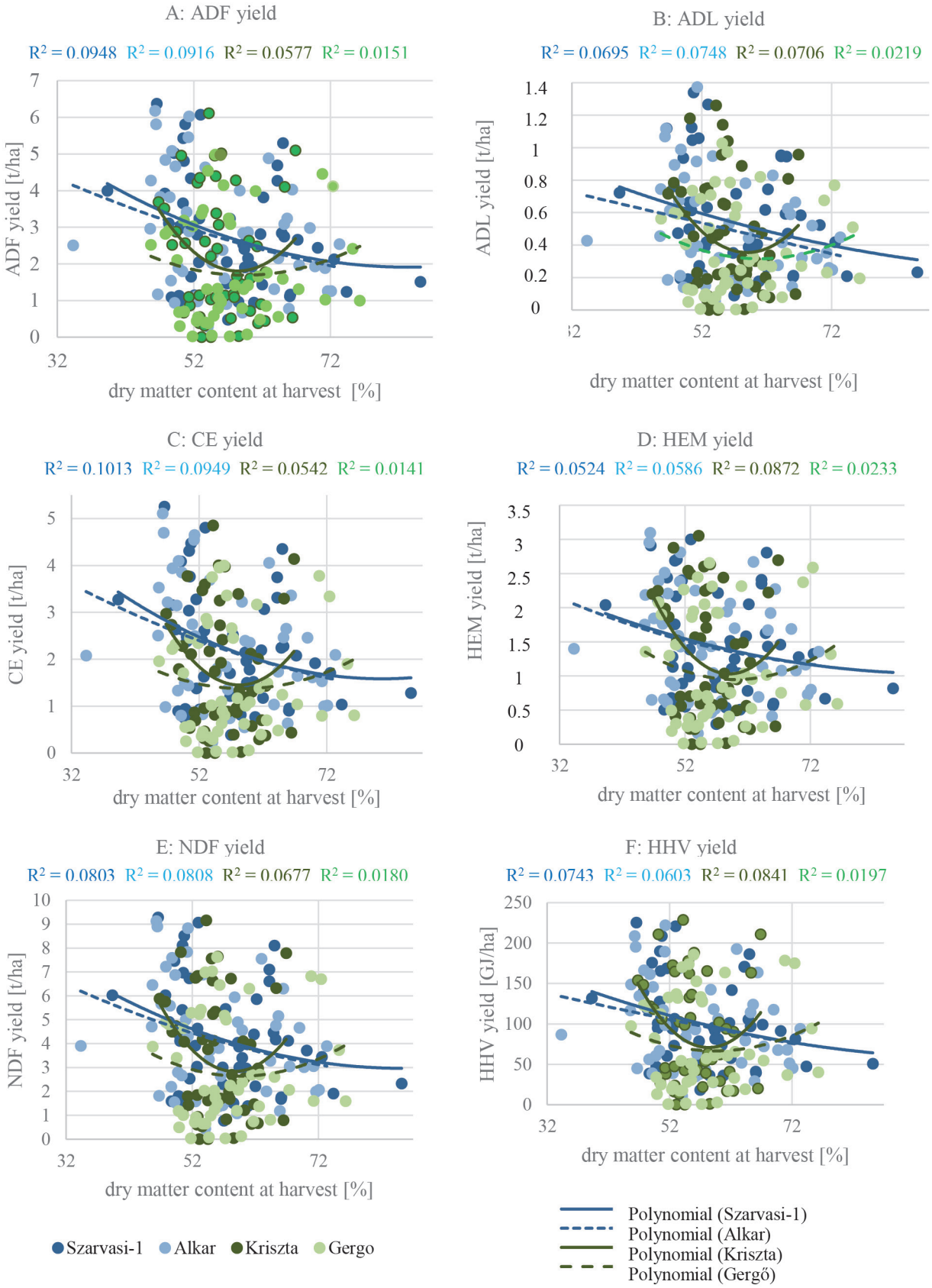


Figure 10. Dependence of ADF, ADL, CE, HEM, NDF, and HHV yield on DM content at harvest, for ADF-HHV see the explanations under Table 1A.

for Alkar, 16.544–17.748 MJ/kg for Kriszta and 15.955–17.638 MJ/kg for Gergő (Figure 1A).

And like ADF and CE yield, concerning HHV yield it was achieved two homogenous groups identical to the crops, whereas in contrast to HHV content higher yield of energy was achieved for TW as 101.4 GJ/ha for Szarvasi-1 as 99.2 GJ/ha for Alkar and lower ones for PR as 87.3 GJ/ha for Kriszta as 73.2 GJ/ha for Gergő (Table 2B). HHV yield ranged between 18.4–225.3 GJ/ha for Szarvasi-1, 10.8–222.1 GJ/ha for Alkar, 0.1–228.9 GJ/ha for Kriszta and 0.9–185.7 GJ/ha for Gergő (Figure 1 B).

Impact of DM content

Figure 9 shows the dependence of quality content on dry matter content at harvest. Despite the fact, that harvest was timed to an optimal harvest maturity in terms of crop development, the values of dry matter content at harvest ranged from 34 to 85%. The majority of the values ranged from 45–75%, the remaining values are distant points measured mainly at TW. Regardless to shape type, the impact of dry matter content at harvest on quality content is typically weak reliability, with R^2 ranging within 0.0020–0.2959.

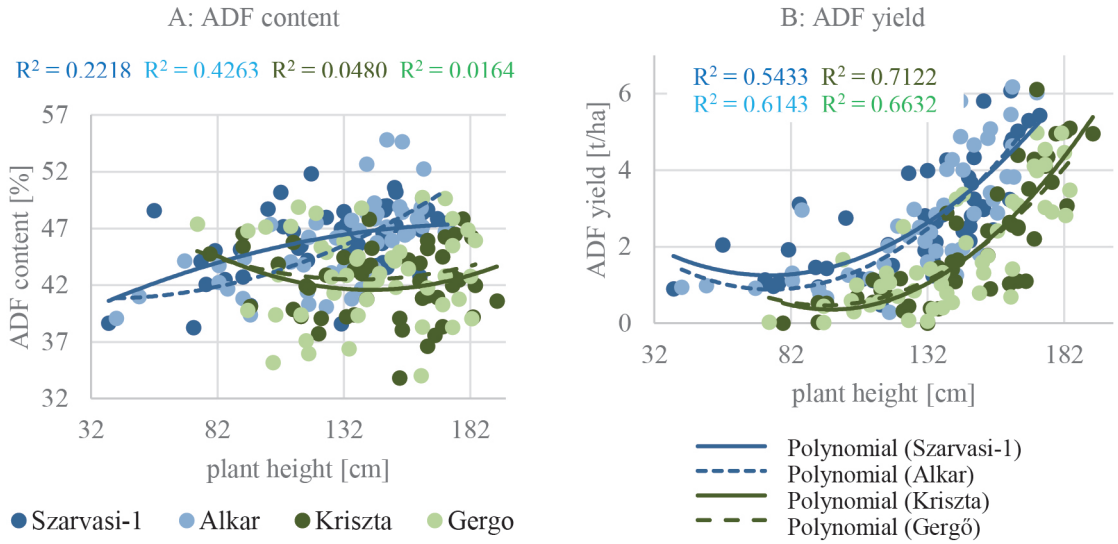


Figure 11. Dependence of ADF content and ADF yield on plant height see the explanations under Table 1A.

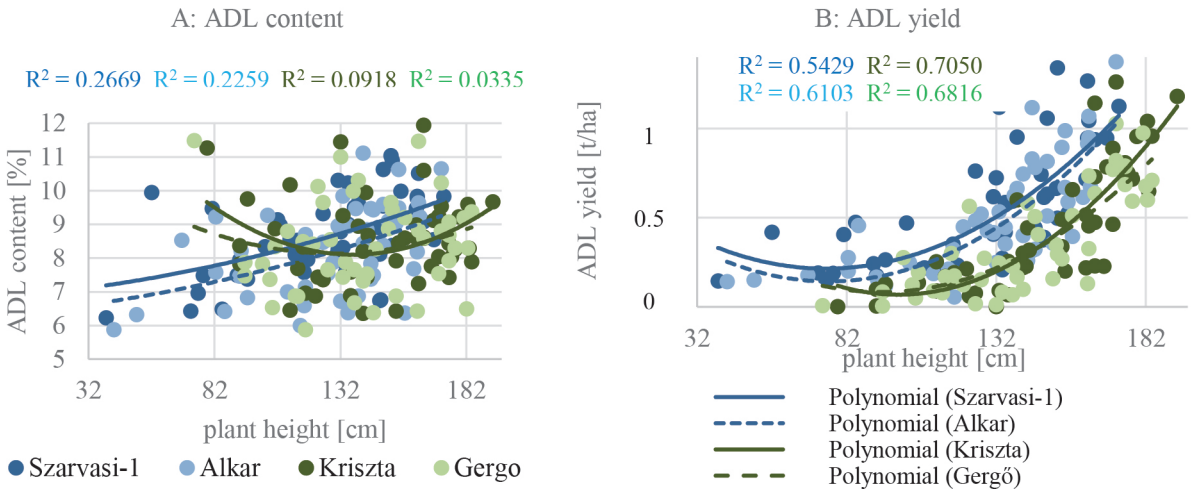


Figure 12. Dependence of ADL content and ADL yield on plant height, for ADL see the explanation under Table 1A.

By the quality indicator, Figures 9A–F are optimized to show the whole data cluster. Similarly, to the impact of dry matter yield, the shape type of dry matter content impact corresponds to one of 5 shape types (i) U, (ii) ∩, (iii) /, (iv) —, and (v) \. Probably, these crop-specific dependences of quality content and yield on dry matter content at harvest may correspond with different ripening and senescence of the crops. The practical impact of dry matter content at harvest on quality yield remaining on weak reliability, R^2 ranging within 0.0141–0.1013 (Figure 10A–F), however, it should be emphasized that the collection of plant samples was timed to optimal harvest maturity in terms of crop development. The issue is desirable to be parametrized in more detail, mainly to verify the impact of early harvesting and late harvesting.

Impact of plant height

Figures 11–16 show the dependence of quality content and yield on plant height. Plant height at harvest ranged within 127–173 cm for TW and within 141–193 cm for PR. Figures 11A–16B are optimized to show the whole data cluster according to quality indicator, whereas the A figures are aimed at quality content and B ones to quality yield.

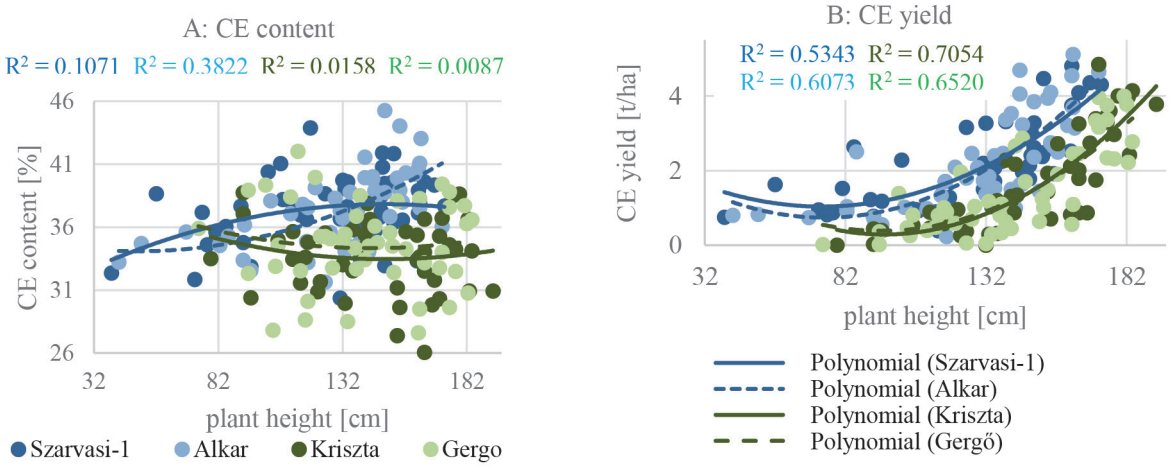


Figure 13. Dependence of CE content and CE yield on plant height, for CE see the explanation under Table 1A.

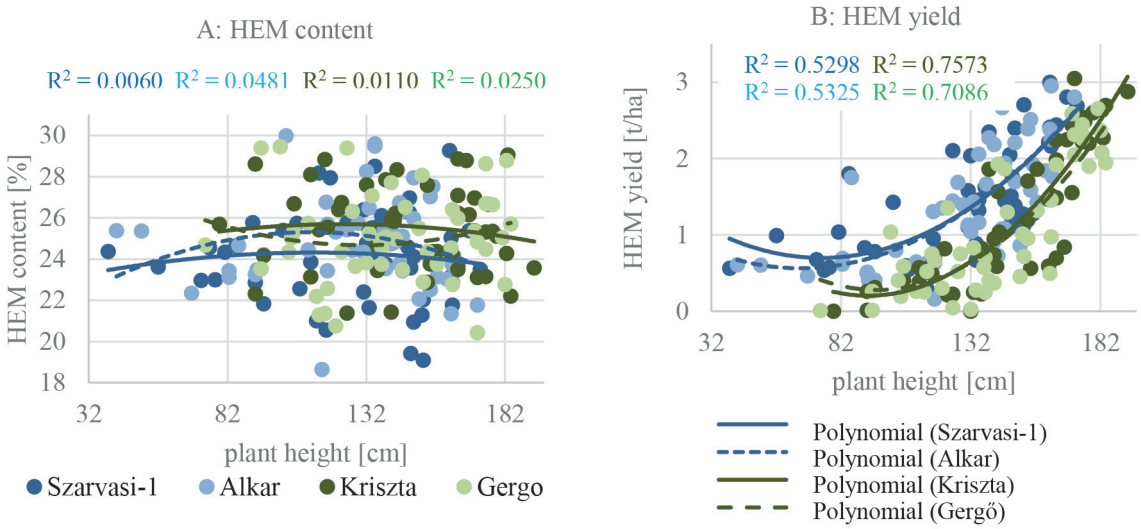


Figure 14. Dependence of HEM content and HEM yield on plant height, for HEM see the explanation under Table 1A.

In contrast to the impact of dry matter content at harvest on quality content, the impact of plant height corresponds with one of 4 shape types in general. Regardless of quality content, the shape type acquires to be "J"-shape when quality yield dependence on plant height is analysed, Figures 11 – 16B. From the figures, it is obvious, that:

- Data clusters and trend lines are differentiated into 2 data subcluster identical to the crops.
- Within the crops, the data subclusters are no longer differentiated according to cultivars.

For the impact of plant high on quality content, it is typically a weak to middle reliability with R^2 ranging within 0.0060 – 0.4263. In contrast to quality content, within quality yield, it is typically middle to strong reliability with R^2 ranging within 0.5264 – 0.7573. Probably, the only shape type "J" may indicate the lowest quality at the highest proportion of lower quality parts of plants at suboptimal height, probably the leaves. Nevertheless, plant height proves to be a reliable indicator of good ligno-cellulose and calorific quality yield for both TW and PR, similar to the impact of dry matter yield on quality yield.

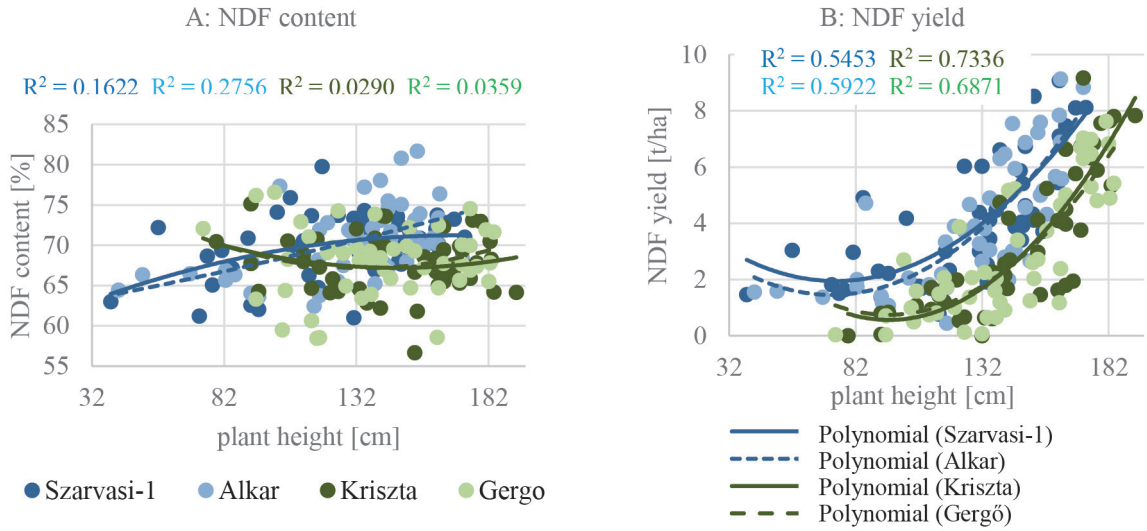


Figure 15. Dependence of NDF content and NDF yield on plant height, for NDF see the explanation under Table 1A.

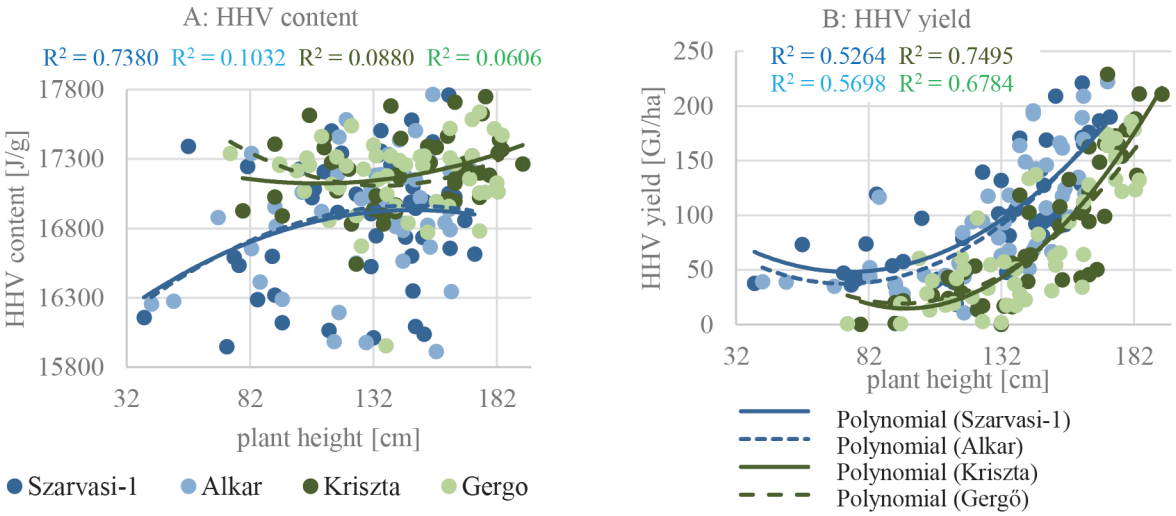


Figure 16. Dependence of HHV content and HHV yield on plant height, for HHV see the explanation under Table 1A.

Linear intercept

In Table 3, it is displayed the main parameters of quality yield dependence on dry matter yield for a simple linear relationship, by cultivars and indicators. The determination index of the linear dependence is very strong, r^2 ranged within 0.930 – 1.000 and is similar to adequate reliability index within second-order polynomic dependencies, R^2 ranged 0.9484 – 0.9996 (Figures 3 – 8B).

Intercept (a), the constant to transfer DM yield (x) on ADF yield (y) according to cultivars sequence Szarvasi-1 – Alkar – Kriszta – Gergő is 0.477 – 0.49 2 – 0.440 – 0.444, ADL 0.100 – 0.092 – 0.092 – 0.085, CE 0.377 – 0.400 – 0.349 – 0.359, HEM 0.231 – 0.235 – 0.243 – 0.247, NDF 0.709 – 0.728 – 0.683 – 0.692, and HHV 16.935 – 17.025 – 17.329 – 17.311, respectively by the simple linear formula using: $y = ax + b$. Intercepts ($a_1 – a_3$) of second-order polynomic equations are not displayed in the figures due to space limitations.

DISCUSSION

Both the tested crops are perennial grasses (Sipos & Halas 2007; Csete *et al.* 2011), like other forms of biomass with a botanical origin, including herbaceous phytomass as well, are composed of cellulose, hemicellulose, lignin, extractives, and inorganic substances (ash) (Monomo *et al.* 2013). According to assuming conclusions (Monomo *et al.* 2013; Kron *et al.* 2017; Symanowicz *et al.* 2019; Giertl *et al.* 2022; Kintl *et al.* 2022) on herbaceous phytomass, the primary components (cellulose, hemicellulose, and lignin) are vital resources in sugar platform (fermentation of biomass sugars) as well as in thermochemical platform (e.g., gasification followed by biological or chemical processing) technologies.

Tall wheatgrass

According to a huge study by Csete *et al.* (2011), the average HHV of Szarvasi-1 was 17.983 – 17.597 – 17.645 MJ/kg, whereas green phytomass was finalised in bale – chips/chaff – pellet. Yu *et al.* (2014) state HHV of 17.92 MJ/ha for TW. By Boros-Lajszner *et al.* (2021) the combustion value (low heating value respectively) of 1 kg of air-dry biomass of the tested *Elymus elongatus* was relatively high and ranged from 14.6 to 15.1 MJ.

By Ciria *et al*. (2020b) HHV of TW ranged between 18.0 – 19.4 MJ/kg within cultivars tested during a 5-year trial 2014 – 18 conducted on marginal soils under Mediterranean climate, whereas HHV was 18.6 ± 0.2 MJ/kg for Szarvasi-1 and 18.9 ± 0.3 MJ/kg for Alkar. According to them, differences within the composition among different perennial grass species and cultivars including Szarvasi-1 and Alkar do not affect combustion value from a practical point of view. However, they also conclude a need for further research to assess whether later harvest dates will improve the quality of the biomass produced, under marginal conditions.

Barro *et al.* (2022) researched the influence of nutrition intensity, and annual N applications (0, 30 and 80 kg/ha) on the production, composition, and calorific value of TW phytomass, based on 9-year trials established on marginal lands in Mediterranean conditions. The differences found in the chemical composition of TW across years and N applications are not expected to be of any practical relevance if the phytomass is utilized for combustion purposes. However, a harvest delay until late winter greatly improved combustion quality but led to matter losses of 36 – 48%.

By Kopecký *et al.* (2021) composition of phytomass varies depending on the intensity of fertilisation, while the most important for calorific value, the HHV respectively is the content of C. However, no large differences in the composition of phytomass depending on nutrition treatments were observed in their experiment. They achieved calorific values of TW in the range 17.684 – 18.030 MJ/kg in control, 17.839 – 18.189 MJ/kg in mineral treatment, and 17.943 – 18.050 MJ/ kg in digestate treatment. The adequate values of energy yield were 116 ± 47 GJ/ha in control, 133 ± 46 GJ/ha in mineral treatment, and 133 ± 56 GJ/ha in digestate treatment, on average per year while the monitored period of 5 years 2014 – 2018.

According to the results of 2-year trials by Dickeduisberg *et al*. (2017) aimed at TW four ecotypes and three cutting heights (5, 10 and 15 cm above soil surface) and three levels of cutting frequency (one, two, and four cuts per year), only small differences in the followed quality indicators among the

ecotypes were found in general, while determined DM yield, crude nutrient, and fibre content. In their conclusion based on the trial established in German conditions with semi-humid to humid climate, TW is suitable for biogas production and responds to cutting frequency and height with both the highest DM yield and methane profit in the two–cut system and 5 – 10 cm cutting height. Central European conditions with a semi-arid to semi-humid climate are quite different from those in Germany, so it is questionable how long TW stands will maintain their performance if they are cutted more often than once a year.

According to the results of Kikas *et al.* (2014), Szarvasi-1 contains 37.85% cellulose, 27.33% hemicellulose, 9.65% lignin, and ash 7.01%, whereas phytomass collected from third-year vegetation grown in northern European conditions in Estonia was analysed.

By the conclusions of a huge USDA study by Briggs *et al.* (2020), Szarvasi-1 may be better suited as a biofuel feedstock than the other tested cultivars due to its higher lignin content and a lower percentage of ash and potassium. They recommend, inter alia, additional trials of TW should be conducted to evaluate establishment speed and biomass production under low, intermediate, and high management intensities. Mean chemical composition values of Szarvasi-1 vs. Alkar was 75 vs. 75% NDF, 48 vs. 46% ADF, 6.9 vs. 6.1% ADL, and 5.2 vs. 5.6% ash content, whereas the range of NDF – ADF – ADL and ash were 71 – 82, 44 – 52, 5.8 – 7.3 and 4.1 – 5.6% within Szarvasi-1 and 73 – 82, 41 – 50, 5.4 – 6.3 and 4.8 – 6.5% within Alkar.

Perennial rye

In contrast to TW, research papers on PR (Halasz & Sipos 2007; Sipos & Halasz 2007; Szakács *et al.* 2020; Szőke-Pázsi *et al.* 2021) do not consist of data on ligno-cellulose quality and calorific value. The present study is probably the first of that issue, more precisely, it is related to the paper focused on the green phytomass yield main effects (Tóth 2023). Therefore, it can be important to state with emphasis that perennial rye *Secale cereanum* is a novel crop, which is completely different from perennial ryegrass *Lolium perenne* L., a weedy species commonly spread on fields (Tóth 2008).

The results presented on PR ligno-cellulose quality, compared to TW, confirm the general conclusions of Monomo *et al.* (2013) that the carbohydrate content of different herbaceous perennial crops is much less variable than the variability in phytomass yields under different environments over several years. The results presented on PR quality confirm the main conclusions of Martyniak *et al.* (2017) related to phytomass quality and quantity of TW, including Szarvasi-1 and a few wild populations as well, that high phytomass yield can be stated as a suitable indicator of relatively high quality. This can be valid in general, but the way of phytomass is used can be the change factor and decisive for the quality required (Porvaz *et al.* 2012; Kron *et al.* 2017 and others).

CONCLUSIONS

Ligno-cellulose quality and calorific value of tall wheatgrass and perennial rye vary with plant species/cultivars, environment, and management practices. The impact of nutrition, years, sites, and cultivars are precisely calculated as the main effects on acid-detergent fibre, acid-detergent lignin, crude cellulose, hemicellulose, neutral-detergent fibre, and high heating value, whereas the calculations are based on a huge pilot field experiment.

Two equal aspects of quality are evaluated in the paper, a primary one deals with content-basis quality [% or kJ/g], which is considered to be a general indicator concerning phytomass quality of the herbaceous crops, and a secondary one deals with yield-basis quality [kg/ha or GJ/ha], which will be important for processors to design sustainable supply-chain as it will impact the area required for dedicating crops.

In content-basis quality indicators, nutrition was confirmed as the factor with the lowest impact, whereas years and sites also had a greater impact than cultivars, in general. In contrast to the quality content, when evaluating the yield-basis quality nutrition has been confirmed as the most important factor followed by sites as the second and years as the third factor, whereas cultivars have the least impact as the fourth factor, however, the impact of each factor was significant.

Because the quality yield depended strongly on DM yield, the DM yield is a strong indicator of ligno-cellulose profit and energy yield as well. In addition, the influence of plant height and DM content at harvest on quality was also evaluated, by second-order polynomial trend. The quality content trend line corresponds to one of 5 types of shape (i) U (ii) ∩ (iii) / (iv) – and (v) \, the shape being usually similar within the crops but different or even opposite when comparing these of two crops in general. In terms of quality yield, the trend acquires only a "J"-shape, under the middle to the strong dependence on plant height. Therefore, plant height is a good indicator of ligno-cellulose quality and energy yield as well. Even the lowest quality yield is indicated by the shape type, probably because the highest proportion of lower quality plant parts is present at the suboptimal plant height, which is confirmed as crop specific and no cultivar. Also, for these reasons, related agronomic studies aimed at phytomass production are desirable. Finally, the most crop-specific dependence of quality on the dry matter content at harvest may indicate different ripening and senescence of the crops, which should be evaluated in more detail.

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