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Ligno-cellulose quality and calorific value of green phytomass of *Galega orientalis* L., a novel energy crop

Ligno-celulózová kvalita a energetická hodnota fytomasy *Galega orientalis* L., novej energetickej plodiny

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ABSTRACT

The scope of research was to determine the ligno-cellulose quality and calorific value of eastern galega, *Galega orientalis* L. Two complete datasets of acid detergent fiber (ADF), acid detergent lignin (ADL), crude cellulose (CE), hemicellulose (HEM), neutral detergent fiber (NDF), and high heating value (HHV) were evaluated, wherein the first one deals with the quality content and the second one with the quality yield. The average, minimal, and maximal content were: ADF 38.29 – 24.68 – 49.89%, ADL 8.89 – 4.98 – 14.16%, CE 29.40 – 18.74 – 40.09%, HEM 12.83 – 9.17 – 18.01%, NDF 51.11 – 34.56 – 61.69%, and HHV 17.325 – 14.871 – 19.707 MJ/kg, respectively. The adequate values of yield were: ADF 3.135 – 0.271 – 9.295 t/ha, ADL 0.698 – 0.060 – 2.115 t/ha, CE 2.438 – 0.210 – 7.180 t/ha, HEM 0.925 – 0.109 – 3.035 t/ha, NDF 4.052 – 0.379 – 12.331 t/ha, and HHV 126.140 – 20.653 – 367.872 GJ/ha, respectively. Taking into account the two harvests per year together, the adequate values of yield were: ADF 6.271 – 1.375 – 11.512 t/ha, ADL 1.340 – 0.314 –2.583 t/ha, CE 4.875 – 1.061 – 9.099 t/ha, HEM 1.851 – 0.536 – 3.425 t/ha, NDF 8.103 – 1.911 – 14.317 t/ha, and HHV 252.275 – 79.074 – 429.258 GJ/ha, respectively. To achieve ideal ligno-cellulose quality and calorific value, in terms of quality content, the optimal plant height was 120–170 cm, dry matter (DM) yield was 15–18 t/ha, and DM content at harvest was 25%, while in terms of quality yield, the optimal height and DM content at harvest were the same, but DM yield of 15–20 t/ha per harvest and even more is desirable.

Keywords: eastern galega, *Galega orientalis*, ligno-cellulose quality, calorific value, marginal soils

ABSTRAKT

Cieľom výskumu bolo preveriť ligno-celulózovú kvalitu a spaľovaciu hodnotu jastabiny východnej *Galega orientali*s L. Dva kompletné súbory údajov acidodetergentnej vlákniny (ADF), acidodetergentného lignínu (ADL), hrubej celulózy (CE), hemicelulózy (HEM), neutralnodetergentnej vlákniny (NDF) a spaľovacieho tepla (HHV) boli vyhodnotené, resp. prvotne z hľadiska obsahu kvality a druhotne z hľadiska úrody kvality. Priemerná, minimálna a maximálna hodnota obsahu ADF bola 38,29 – 24,68 – 49,89%, ADL 8,89 – 4,98 – 14,16%, CE 29,40 – 18,74 – 40,09%, HEM 12,83 – 9,17 – 18,01%, NDF 51,11 – 34,56 – 61,69% a HHV 17,325 – 14,871 – 19,707 MJ/kg. Adekvátne hodnoty úrody ADF boli 3,135 – 0,271 – 9,295 t/ha, ADL 0,698 – 0,060 – 2,115 t/ha, CE 2,438 – 0,210 – 7,180 t/ha, HEM 0,925 – 0,109 – 3,035 t/ha, NDF 4,052 – 0,379 – 12,331 t/ha a HHV 126,140 – 20,653 – 367,872 GJ/ha. Avšak pri hodnotení dvoch kosieb za rok spolu, adekvátne hodnoty úrody ADF boli 6,271 – 1,375 – 11,512 t/ha, ADL 1,340 – 0,314 – 2,583 t/ha, CE 4,875 – 1,061 – 9,099 t/ha, HEM1.81 HEM1. – 0,536 – 3,425 t/ha, NDF 8,103 – 1,911 – 14,317 t/ha a HHV 252,275 – 79,074 – 429,258 GJ/ha. Pre dosiahnutie ideálnej ligno-celulózovej kvality a kalorickej hodnoty, z hľadiska obsahu kvality boli optimálne výška rastliny 120-170 cm, úroda sušiny 15-18 t/ha a obsah sušiny pri zbere 25 %, z hľadiska úrody kvality boli optimálne výška a obsah sušiny pri zbere rovnaké, ale žiaduca je úroda sušiny 15-20 t/ha na kosbu a aj viac.

Kľúčové slová: jastrabina východná, *Galega orientalis*, ligno-celulózová kvalita, spaľovacie teplo, marginálne pôdy

INTRODUCTION

One of the lesser-known but very promising perennial fodder crops, which belongs to the plants with the recognized prospect of being used for energy purposes as well, is eastern galega, *Galega orientalis* L. (Cerempei et al, 2023; Symanowicz et al., 2019). Since it is a novel crop that is newly introduced and still not widely cultivated in Slovakia, there is little knowledge and experience regarding the cropping and uses of this leguminous plant (Tóth, 2024). Most of the studies devoted to the crop come from the temperate zone of the Northern Hemisphere, especially from various regions of northern Europe (Dubis et al., 2020; Eryashev et al., 2019; Knotova et al., 2018; Symanowicz and Kalembasa, 2003; Fairey et al., 2000). The main advantage of the crop is suitability for certain types of less-favorable heavy soil conditions, both under intensive as extensive cultivation under moderate semi-humid to humid sub-climate (Shevchenko et al., 2022; Dubis et al., 2020; Sienkiewicz et al., 2017). Due to this, the considerations of cropping for energy use are combined with second-generation technologies also, which are based on the concept of exploitation of marginal soils and appropriate ligno-cellulose and calorific value of the phytomass.

Research works related to the quality of eastern galega are focused mainly on fodder value, and the newer ones are focused partially on energy value, whereby the suitability of various technologies for biomethane production by first-generation biogas facilities are being studied particularly (Samoilova et al., 2022; Ignaczak et al., 2022; Kintl et al., 2019; Bull et al., 2011; Møller and Hostrup, 1997, 1996). As opposed to the calorific value, the ligno-cellulose quality of eastern galega is still not sufficiently parameterized, especially with regard to the quality of the phytomass at later harvest (Żarczyński et al., 2021; Symanowicz et al., 2019). The later harvest of the crop is assumed to be appropriate for the production of bioethanol by second-generation technologies, exactly where the high content and yield of oligo- and polysaccharides are of key importance.

The paper aims to determine the ligno-cellulose quality and calorific value of eastern galega. Based on the results of a large-scale field experiment conducted under continental climate conditions of Slovakia, it is possible to evaluate the impact of nutrition, years, sites, and cuts as the main effects on the quality. In the paper, two equal aspects of quality are followed: the primary one being the content-based quality and the secondary one being the yield-based quality (Monomo et al., 2013; Kikas et al., 2016; Tóth et al., 2023).

MATERIAL AND METHODS

Pilot field trials

In 2017, a pilot field experiment with eastern galega *G. orientalis* L. was conducted on two sites under a moderate continental Central European climate. The trial was carried out from 2017 to 2020. The sites are typical with marginal heavy soils and mutually contrasting climatic conditions, whereby a semi-humid sub-climate was present on Site 1 at the locality of Pozdišovce (latitude N 48.744099, longitude E 21.861136) and humid sub-climate was present on Site 2 at the locality of Košický Klečenov (latitude N 48.748984, longitude E 21.508565), characterized by an altitude of 120 and 340 m, respectively.

The Gale cultivar was used in the experiment, whereas three levels of nutrition intensity, that is (i) intensive (245.0 kg/ha NPK), (ii) semi-intensive (122.5 kg/ha NPK), and (iii) untreated control without nutrition treatment (0.0 kg/ha NPK, nitrogen – phosphorus – potassium), were included. A more detailed description of the field experiment in terms of applied agronomy, soil climatic conditions, crop development, and plant biometric parameters is presented in the previous papers (Tóth 2022, 2023). A closer description of the Gale cultivar is given in the paper of Makai et al. (2009).

Laboratory analyses

The harvest of eastern galega green phytomass was related to optimal harvest maturity in terms of high yield and crop development as well, whereas the crop stands were not desiccated. Crop sampling, processing, and storage were performed in accordance with Slovakian law no. 151/2016 Z.z. (Codex). The samples were analyzed under standard methodology in the laboratory of NPPC-VUA Michalovce (National Agricultural and Food Centre – Research Institute of Agroecology Michalovce).

The quality indicators acid detergent fiber (ADF), neutral detergent fiber (NDF), acid detergent lignin (ADL), crude cellulose (CE), and hemicellulose (HEM) were determined according to the regulation of MPRV SR no. 2136/2004-100 (Codex) by extraction systems: Fiber extractor – Fibertest (Raypa), Model F-6 and Cold Extraction Unit, Model EF-6. Combustion heat and high heating value (HHV) were determined respectively by IKA C 5000 calorimetric system, in accordance with the STN standard ISO 1928 (STN – Slovak technical norm).

Statistical methods

The study evaluated 540 exact quality data, 4/10th of it in terms of quality content and the rest in terms of quality yield. A primary dataset of quality content consisted of 216 data points, whereas each of them was an average of two analytical repetitions, since classical duplicate analysis was performed originally for every plant sample for each of the following quality indicators. A secondary set of quality yield consisted of 216 data points, which was obtained by calculation, while the data were generated according to the harvests and indicators by the following simple equation:

quality yield (by indicators) = **quality content** (by indicators) × **crop yield** (in dry matter)

The secondary set of quality yield data consisted of another 108 data points, and the third data set, respectively, which was obtained when the quality yield per harvest was counted together, according to the years and indicators. Multifactorial analysis of variance (MANOVA) and subsequently *post hoc* Fisher's test on least significant difference (LSD) were performed to identify significant factors among the main effects, using Statgraphics 15.2.14, and each of the quality indicators was evaluated within the three datasets.

In addition, a series of second-order polynomial functions in the case of trend analyses for the quality indicators was applied. For these functions, a dataset of 648 complementary data was used as independent variables. These complementary data consisted of biometric parameters of the crop, which were plant height, dry matter (DM) content at harvest, and DM yield. Since it was the subject of the previous paper, the biometric data were not studied closely. Finally, in the case of the trend with the highest reliability, a simple linear formula with an adequate index of determination is also given.

RESULTS

Mean values and main effects

The average, minimal, and maximal content in the green phytomass of eastern galega were the following: for ADF 38.29%, 24.68%, and 49.89%, respectively; for ADL 8.89%, 4.98%, and 14.16%, respectively; for CE 29.40%, 18.74%, and 40.09%, respectively; for HEM 12.83%, 9.17%, and 18.01%, respectively; for NDF 51.11%, 34.56%, and 61.69%, respectively; and for HHV 17.325, 14.871, and 19.707 MJ/kg, respectively. The average, minimal, and maximal values of yield were as follows: for ADF 3.135, 0.271, and 9.295 t/ha, respectively; for ADL 0.698, 0.060, and 2.115 t/ha, respectively; for CE 2.438, 0.210, and 7.180 t/ha, respectively; for HEM 0.925, 0.109, and 3.035 t/ha, respectively; for NDF 4.052, 0.379, and 12.331 t/ha, respectively; and HHV 126.140, 20.653, and 367.872 GJ/ha, respectively. Taking into account the cuts separately, the data are displayed according to the years in Figure 1 (AB). Concerning the cuts together, the average, minimal, and maximal values of yield were as follows: for ADF 6.271, 1.375, and 11.512 t/ha, respectively; for ADL 1.340, 0.314, and 2.583 t/ha, respectively; for CE 4.875, 1.061, and 9.099 t/ha, respectively; for HEM 1.851, 0.536, and 3.425 t/ha, respectively; for NDF 8.103, 1.911, and 14.317 t/ha, respectively; and HHV 252.275, 79.074, and 429.258 GJ/ha, respectively (Figure 1 C). No data on quality content for the cuts together was calculated.

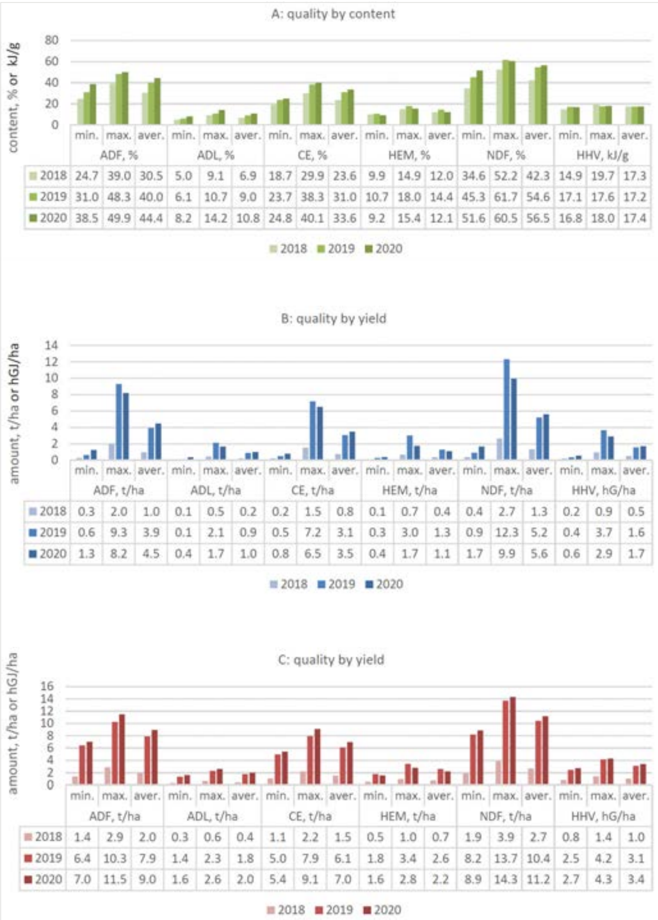

Figure 1. Minimal, maximal, and average values of quality indicators – A (content, in % or kJ/g), BC (profit, in t/ha or hGJ/ha), by the harvests separately (AB) and together (C)

In terms of quality content, the influence of sites was generally the most significant main factor for calorific value, in contrast to the influence of years, harvests, and nutrition, which were alternately the most significant one for lignocellulose quality indicators (Table 1). In terms of quality yield, harvests have been confirmed as the most important factor, followed by years, then by nutrition, and finally by sites with the least impact (Table 2). That impact order of years–nutrition–sites was valid for each of the solved parameters, even when the harvests were counted together and excluded from the main factors (Table 3).

Due to including HHV values into figures when displayed joined with lingo-cellulose indicators, which of average and range data as well while three or five orders of magnitude higher, appropriate values in general units (kJ/g and GJ/ha) were calculated with a conversion factor that changed a decimal resolution when units of kJ/kg and hGJ/ha are applied.

Levels of main effects

Quality content

From statistical evaluation of the influence of the levels of main factors, it is evident that the values were in a single homogeneity group within both the sites and within the three nutrition treatments, at all monitored indicators (Table 4). Unlike the sites and nutrition treatments, within the two harvests, two groups of homogeneity were formed at half of the monitored indicators, whereby lower values were typical for the second harvest compared to the first harvest. The years were accompanied by the highest proportion of forming differentiated homogeneous groups, while the calorific value was the most stable indicator, even across all the factors and levels. All the statistical comparisons are displayed closely in a box plot including the whole dataset, where differences within the two harvests and 3 years are markedly different from the sites and treatments (Figure 2).

Quality yield, the two harvests per year, separately and together

Similar to the impact of the levels of main effects on quality content, the formation of homogeneity groups was kindred in regard to quality yield (Tables 5, 6, and Figure 3). In general, a higher quality yield was accompanied by a higher phytomass yield, and therefore with the levels of the factors responsible for the higher DM yield as well. The forming of homogeneity groups was evident within the evaluation of the harvests separately. It remained significant even when the harvests were counted together.

Table 1. MANOVA for the main effects (the harvests included) for the dataset of quality content

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
Sites	4	0.16	0.6955	4	0.14	0.7129	4	0.43	0.5161	3	2.03	0.1650	3	2.76	0.1076	1	1.72	0.1995
Years	2	111.34	0.0000	1	19.23	0.0000	2	61.23	0.0000	1	5.99	0.0067	1	93.10	0.0000	3	0.21	0.8138
Harvests	1	128.24	0.0000	2	1.86	0.1829	1	112.97	0.0000	2	2.24	0.1449	2	66.56	0.0000	4	0.02	0.8880
Nutrition	3	1.52	0.2359	3	0.56	0.5757	3	1.67	0.2055	4	1.38	0.2665	4	0.79	0.4645	2	0.27	0.7674

IO – impact order, an order based on F-ratio

Table 2. MANOVA for the main effects (the harvests included) for the dataset of quality yield

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
Sites	4	0.12	0.7325	4	0.01	0.9233	4	0.16	0.6883	4	0.00	0.9787	4	0.05	0.8170	4	0.15	0.7020
Years	2	19.42	0.0000	2	21.52	0.0000	2	18.34	0.0000	2	13.07	0.0001	2	11.83	0.0015	2	17.53	0.0000
Harvests	1	53.04	0.0000	1	47.32	0.0000	1	53.05	0.0000	1	29.49	0.0000	1	50.24	0.0000	1	51.03	0.0000
Nutrition	3	0.54	0.5876	3	0.57	0.5705	3	0.61	0.5508	3	0.15	0.8590	3	0.41	0.6643	3	0.51	0.6073

IO – impact order, an order based on F-ratio

Table 3. MANOVA for the main effects (ME) for dataset of quality yield (the harvests together, excluded from ME)

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
Sites	3	0.25	0.6240	3	0.02	0.8976	3	0.36	0.5599	3	0.00	0.9711	3	0.11	0.7426	3	0.28	0.6065
Years	1	41.28	0.0000	1	9.34	0.0000	1	40.17	0.0000	1	24.67	0.0001	1	39.32	0.0000	1	32.85	0.0000
Nutrition	2	1.15	0.3489	2	1.05	0.3806	2	1.13	0.3000	2	0.29	0.7546	2	0.86	0.4476	2	0.95	0.4137

IO – impact order, an order based on F-ratio

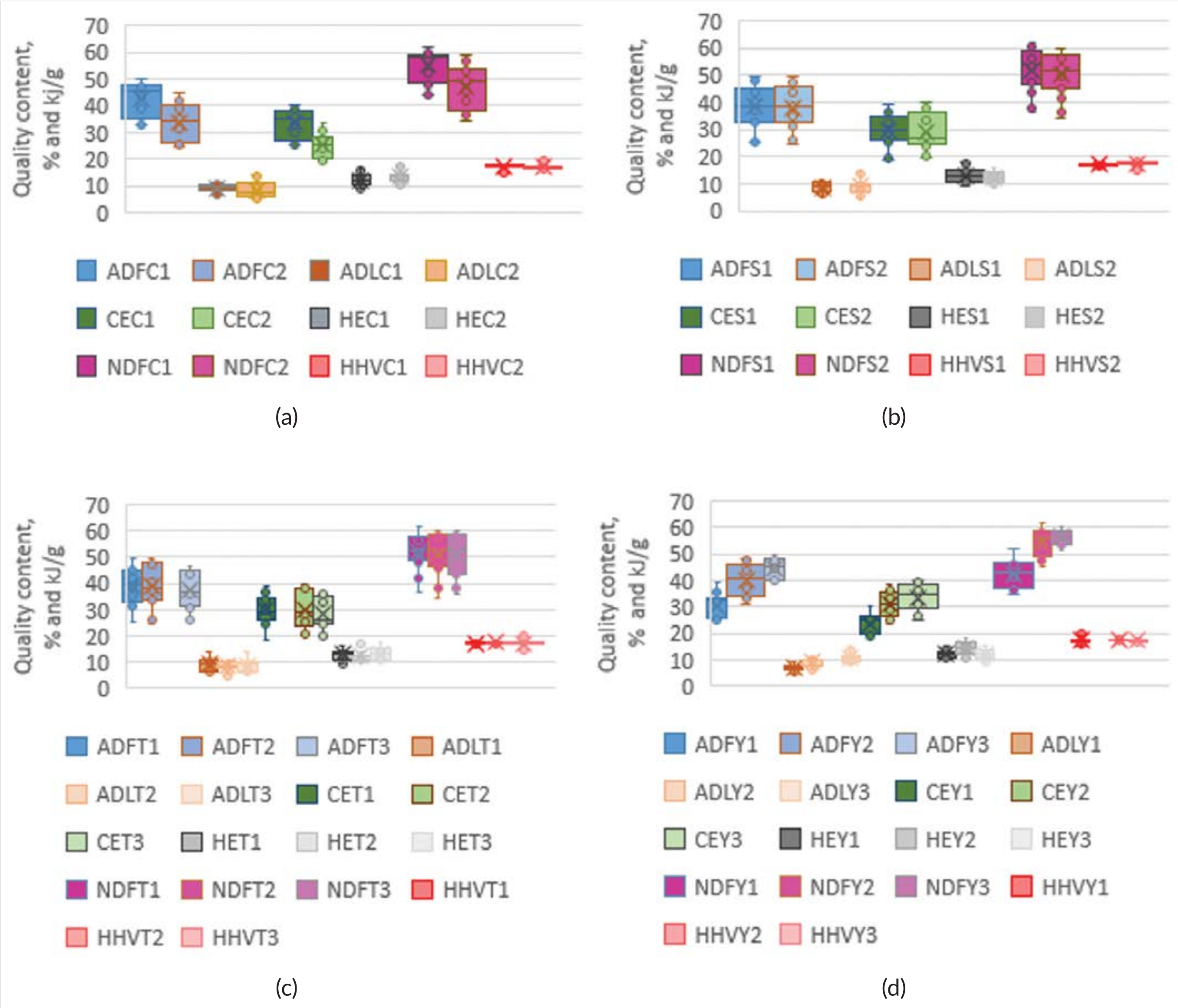

Figure 2. Box plot for quality content, according to harvests: C1 – first harvest, C2 – second harvest (a), sites: S1 – Site 1, S2 – Site 2 (b), nutrition treatments: T1 – intensive, T2 – semi-intensive, T3 – untreated control (c), and years: Y1 – 2018, Y2 – 2019, Y3 – 2020 (d), displaying the minimum, first quartile, median, mean, third quartile, and maximum of ligno-cellulose indicators (ADF – ADL – CE – HEM – NDF) and calorific value (HHV), counting the cuts separately

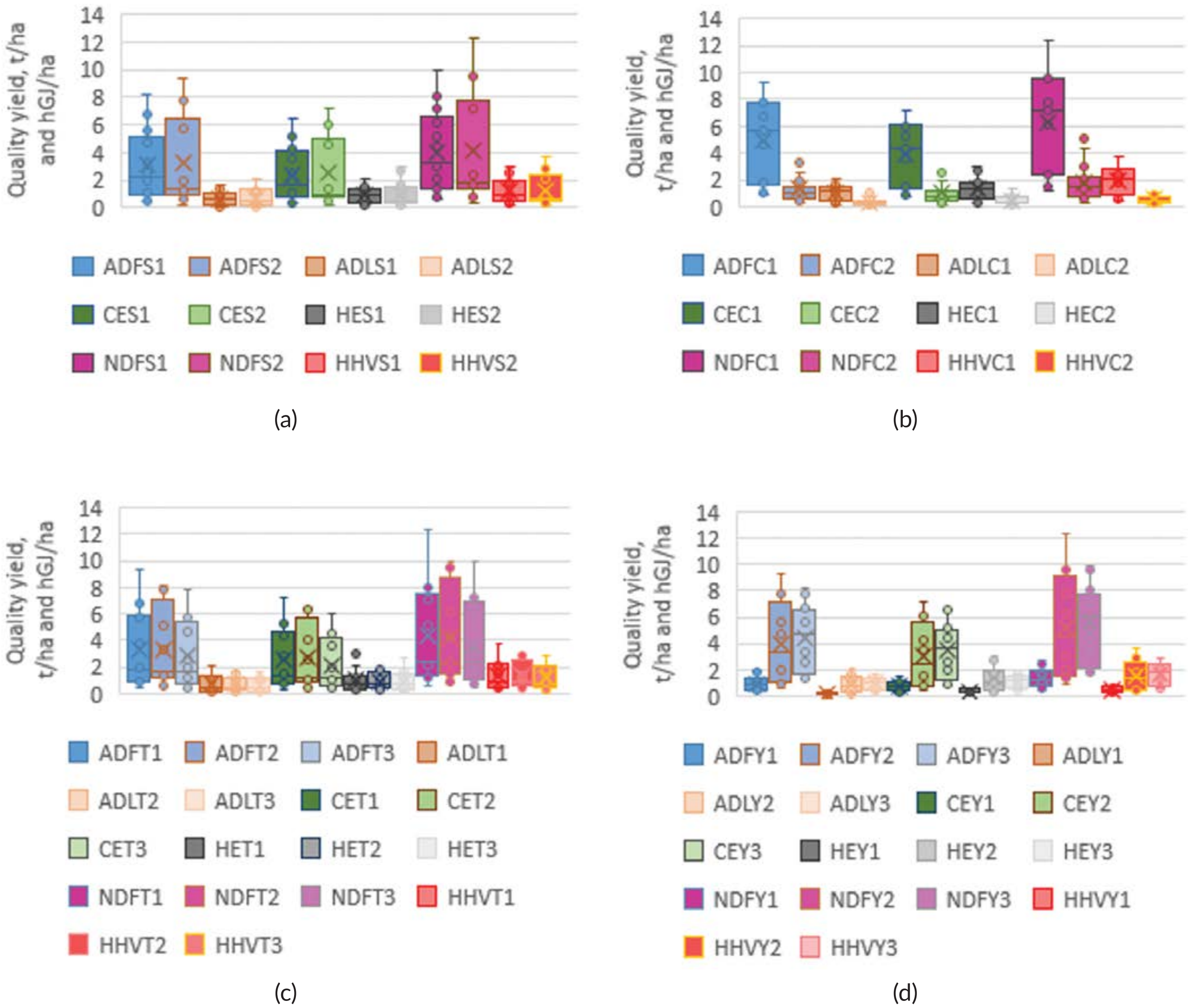

Figure 3. Box plot for quality yield, according to harvests: C1 – first harvest, C2 – second harvest (a), sites: S1 – Site 1, S2 – Site 2 (b), nutrition treatments: T1 – intensive, T2 – semi-intensive, T3 – untreated control (c), and years: Y1 – 2018, Y2 – 2019, Y3 – 2020 (d), displaying the minimum, first quartile, median, mean, third quartile, and maximum of lignocellulose indicators (ADF – ADL – CE – HEM – NDF) and calorific value (HHV), counting the cuts separately

Table 4. Homogeneous groups (H) and parameters of statistical analyses of variance for the dataset of quality content within the levels of main effects, quality indicators in % (ADF, ADL, CE, HEM, NDF) or J/g (HHV), counting the harvests separately

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
Sites																		
Site 1	a	38.438	0.5496	a	8.789	0.3679	a	29.6489	0.5383	a	13.288	0.4581	a	51.345	0.6525	a	17150.	187.974
Site 2	a	38.131	0.5496	a	8.982	0.3679	a	29.1483	0.5383	a	12.366	0.4581	a	50.877	0.6525	a	17499.	187.974
Years																		
2018	c	30.485	0.6731	c	6.850	0.4506	c	23.635	0.6593	b	12.001	0.5611	b	42.273	0.7992	a	17282.	230.22
2019	b	39.987	0.6731	b	9.011	0.4506	b	30.976	0.6593	a	14.412	0.5611	a	54.588	0.7992	a	17247.	230.22
2020	a	44.381	0.6731	a	10.796	0.4506	a	33.585	0.6593	b	12.060	0.5611	a	56.417	0.7992	a	17444.	230.22
Harvests																		
First harvest	a	42.685	0.5496	a	9.241	0.3679	a	33.444	0.5383	a	12.342	0.4581	a	54.876	0.6525	a	17306.	187.974
Second harvest	b	33.883	0.5496	a	8.531	0.3679	b	25.353	0.5383	a	13.312	0.4581	b	47.347	0.6525	a	17344.	187.974
Nutrition																		
Intensive	a	38.848	0.6731	a	9.229	0.4506	a	29.619	0.6593	a	12.843	0.5611	a	51.918	0.7992	a	17214.	230.22
Semi-int.	a	38.673	0.6731	a	8.553	0.4506	a	30.119	0.6593	a	12.159	0.5611	a	50.832	0.7992	a	17450.	230.22
Control	a	37.332	0.6731	a	8.874	0.4506	a	28.458	0.6593	a	13.479	0.5611	a	50.584	0.7992	a	17310.	230.22

H – homogenous group (MANOVA determines which means are significantly different from which others at the statistical 95.0% confidence level, $P < 0.05$, respectively)

Table 5. Homogeneous groups (H) and parameters of statistical analyses of variance for a dataset of quality yield within the levels of main effects, quality indicators in t/ha (ADF, ADL, CE, HEM, NDF) or GJ/ha (HHV), counting the harvests separately

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
Sites																		
Site 1	a	3.0499	0.3500	a	0.6927	0.0735	a	2.3573	0.2805	a	0.9232	0.1101	a	3.9789	0.4410	a	122.71	12.563
Site 2	a	3.2208	0.3500	a	0.7028	0.0735	a	2.5180	0.2805	a	0.9274	0.1101	a	4.1245	0.4410	a	129.57	12.563
Years																		
2018	b	0.9762	0.4287	b	0.2198	0.0900	b	0.7564	0.3436	b	0.3728	0.1348	b	1.3446	0.5401	b	52.18	15.386
2019	a	3.9466	0.4287	a	0.8805	0.0900	a	3.0660	0.3436	a	1.1080	0.1348	a	5.2152	0.5401	a	156.25	15.386
2020	a	4.4835	0.4287	a	0.9929	0.0900	a	3.4906	0.3436	a	1.2949	0.1348	a	5.5954	0.5401	a	169.98	15.386
Harvests																		
First harvest	a	4.9377	0.3500	a	1.0553	0.0735	a	3.8824	0.2805	a	1.3479	0.1101	a	6.2620	0.4410	a	189.60	12.563
Second harvest	b	1.3331	0.3500	b	0.3401	0.0735	b	0.9929	0.2805	b	0.5026	0.1101	b	1.8415	0.4410	b	62.68	12.563
Nutrition																		
Intensive	a	3.2878	0.4287	a	0.7696	0.0900	a	2.5183	0.3436	a	0.9827	0.1348	a	4.2792	0.5401	a	132.54	15.386
Semi-int.	a	3.3457	0.4287	a	0.6895	0.0900	a	2.6562	0.3436	a	0.8790	0.1348	a	4.2247	0.5401	a	132.39	15.386
Control	a	2.7727	0.4287	a	0.6341	0.0900	a	2.1386	0.3436	a	0.9141	0.1348	a	3.6513	0.5401	a	113.48	15.386

H – homogenous group (MANOVA determines which means are significantly different from which others at the statistical 95.0% confidence level, $P < 0.05$, respectively)

Table 6. Homogeneous groups (H) and parameters of statistical analyses of variance for a dataset of quality yield within the levels of main effects, quality indicators in t/ha (ADF, ADL, CE, HEM, NDF) or GJ/ha (HHV), counting the harvests together

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
Sites																		
Site 1	a	6.0999	0.4802	a	1.3854	0.1086	a	4.7146	0.3791	a	1.8463	0.1603	a	7.9579	0.6125	a	245.41	18.354
Site 2	a	6.4416	0.4802	a	1.4056	0.1086	a	5.0361	0.3791	a	1.8547	0.1603	a	8.2491	0.6125	a	259.14	18.354
Years																		
2018	b	1.9523	0.5881	b	0.4395	0.1331	b	1.5128	0.4643	b	0.7456	0.1963	b	2.6892	0.7502	b	104.37	22.478
2019	a	7.8931	0.5881	a	1.7611	0.1331	a	6.1321	0.4643	a	2.5899	0.1963	a	10.430	0.7502	a	312.50	22.478
2020	a	8.9669	0.5881	a	1.9858	0.1331	a	6.9811	0.4643	a	2.2161	0.1963	a	11.191	0.7502	a	339.60	22.478
Nutrition																		
Intensive	a	6.5757	0.5881	a	1.5391	0.1331	a	5.0365	0.4643	a	1.9653	0.1963	a	8.5584	0.7502	a	265.07	22.478
Semi-int.	a	6.6914	0.5881	a	1.3790	0.1331	a	5.3124	0.4643	a	1.7581	0.1963	a	8.4495	0.7502	a	264.79	22.478
Control	a	5.5453	0.5881	a	1.2682	0.1331	a	4.2771	0.4643	a	1.8282	0.1963	a	7.3025	0.7502	a	226.97	22.478

H – homogenous group (MANOVA determines which means are significantly different from which others at the statistical 95.0% confidence level, $P < 0.05$, respectively)

Impact of crop yield, plant height, and DM content at harvest

The impact of crop biometry on quality content and quality yield is evaluated by trend analyses, whereby plant height, DM yield, and DM content at harvest are involved (Figure 4). Within the trends, a second-order polynomic function is applied in general, since it is confirmed to be the most appropriate one according to the highest reliability index, which is also displayed in the figures being optimized to include the whole data cluster.

In terms of quality content, the following were found:

- weak reliability index of dependences on plant height, with R^2 ranging 0.004–0.106 (Figure 4A);
- weak to middle reliability index of dependence on the DM content at harvest, with R^2 ranging 0.012–0.461 (Figure 4C); and
- weak to strong reliability index of dependence on DM yield, with R^2 ranging 0.008–0.861 (Figure 4B).

The calorific value was less influenced by biometric parameters compared to the lignocellulose quality, since R^2 ranged 0.006–0.071 at HHV versus 0.004–0.861 at ADL–NDF. Among the indicators of lignocellulose quality, the content of cellulose appeared to be the most conditional (R^2 ranging 0.106–0.861), while the content of HEM was the most stable (R^2 ranging 0.004–0.012).

In accordance with the weak to strong reliability indexes in terms of quality content, a weak to strong reliability index was achieved concerning the dependencies of quality yield on biometric parameters, whereby the following were observed:

- weak reliability index on plant height, with R^2 ranging 0.076–0.119 (Figure 4D);
- middle reliability index on DM content at harvest, with R^2 ranging 0.257–0.306 (Figure 4F); and
- strong reliability index on DM yield, with R^2 ranging 0.905–0.999 (Figure 4E).

However, based on the correlation coefficient (*r*), all the evaluated dependencies were markedly more intense, since the reliability index corresponded to R^2 in the middle, and a strong correlation is given by R^2 values of 0.109 (r = 0.33) and 0.449 (r = 0.67), respectively. Therefore, the trend analysis clearly confirms that to achieve ideal ligno-cellulose quality and calorific value, in terms of quality content, the optimal plant height was 120–170 cm (Figure 4A), DM yield was 15–18 t/ha (Figure 4B), and DM content at harvest was 25% (Figure 4C), while in terms of quality yield, the optimal height and DM content at harvest were the same (Figure 4DF), but DM yield was 15–20 t/ha per harvest (Figure 4E) and even more of it was desirable. In the case of HHV content dependence on plant height (Figure 4A), the different course of the red polynomic line in comparison with the other ones seems to be affected by a single outlining point, which was not excluded from the evaluation. For the set of dependencies with the highest reliability indexes (quality yield dependence on DM yield, Figure 4E), a simple linear formula is displayed, with an adequate index of determination by the indicators, as shown in Table 7.

Table 7. Linear trend of quality yield dependence on dry matter yield, according to the indicators of ligno-cellulose quality and calorific value

Quality indicator	Linear formula	Index of determination
ADF	$y = 0.4945x - 0.4647$	$R^2 = 0.992$
ADL	$y = 0.1023x - 0.0469$	$R^2 = 0.974$
CE	$y = 0.3922x - 0.4178$	$R^2 = 0.988$
HEM	$y = 0.1238x + 0.0241$	$R^2 = 0.903$
NDF	$y = 0.6142x - 0.4199$	$R^2 = 0.997$
HHV	$y = 17.3784x - 0.3868$	$R^2 = 0.999$

Note: Linear formula of y = ax + b, where x = DM yield (t/ha); index of determination (R^2) is equal to r^2, where *r* = correlation coefficient

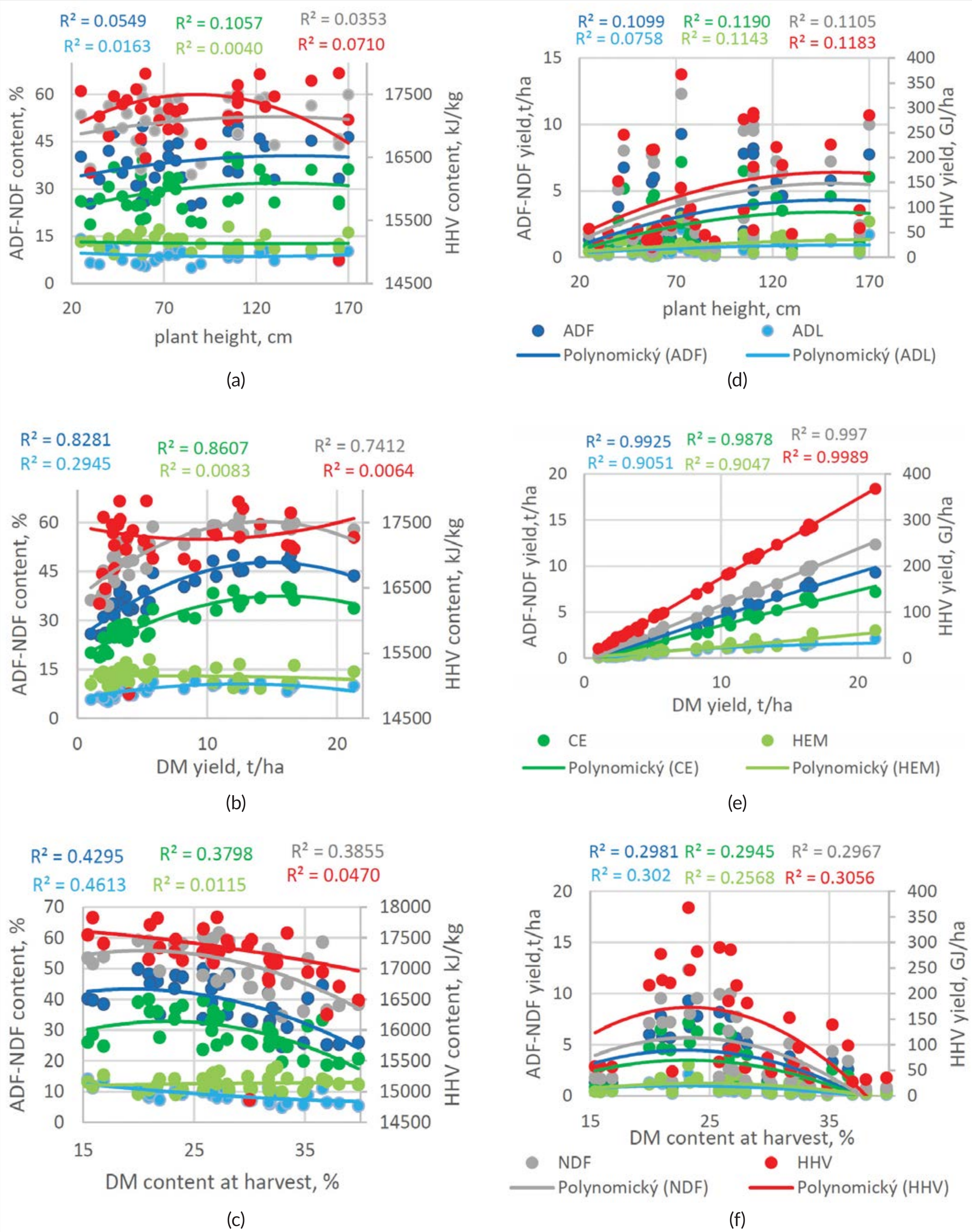

Figure 4. Dependence of quality content on plant height (a), dry matter yield (b), and dry matter content at harvest (c), and dependence of quality yield on plant height (d), dry matter yield (e), and dry matter content at harvest (f)

DISCUSSION

A recent extensive study by Cerempei et al. (2023), related to the quality of eastern galega, evaluates the crude protein content, DM digestibility, digestible energy load, metabolizable energy, net energy of lactation, relative feed value, and biochemical biomethane potential as well. At present, an absolute majority of research papers related to crop quality deal with the fodder quality focused on nutritive indicators, while some research includes biomethane potential (Ignaczak et al., 2022, 2021; Bushuyeva et al., 2014; Adamovics, 2014; Baležentiene and Spruogis, 2011; Moller et al., 1997, 1996). Regarding the energy purpose, Kintl et al. (2019) calculated the theoretical methane yield of eastern galega based on the results of a complex and similar set of indicators (proteins, fiber, ADF, NDF, starch, polysaccharide, lignin), which were determined after each harvest. According to the conclusions, each of the tested three species of Leguminosae (*Medicago sativa* L. and *Trifolium pannonicum* L. are the other two besides *Galega orientalis* L.) represents more satisfactory phytomass for biogas production in comparison to the tested five cultivars of three common field grasses species (*Lolium perenne* L., *Festulolium perseus*, *Dactylis glomerata* L.), which is valid for technologies of the first generation. An adequate comparative study on the crop suitability for second-generation technologies has not been published yet, since the applicable set of quality indicators for the technologies of second-generation differs.

Similar to this paper, the full set of ligno-cellulose quality key indicators was applied in a previous research, which evaluated the suitability of further energy crops for second-generation technologies (Tóth et al., 2023; Tóth, 2023, 2022). In comparison to earlier studied energy crops of *Elymus elongatus* L., *Secale cereanum*, *Silfium perfoliatum* L., and *Panicum virgatum* L., eastern galega also provides suitable phytomass, but certain specifics and differences are present as well. The mentioned plants are typical energy crops, and in general, they are characterized by a higher value of key indicators of ligno-cellulose quality than eastern galega. Due to the different agronomic benefits, eastern galega can be considered as an additional energy crop, which expands the biodiversity, which is in agreement with the findings of Symanowicz et al. (2019) and Żarczyńsk et al. (2021).

According to the study of Meripold et al. (2017), the content of NDF in DM of eastern galega varied from 49.5% to 55.9% depending on the year, cutting time, nitrogen nutrition, and accompanying grass component in the mixture. This is in agreement with the findings presented in the paper on average NDF content of 51.1%; however, the measured values were in a markedly wider range of 34.6%–61.7%. According to the results of Symanowicz and Kalembasa (2003), the high content of crude fiber (38.5%) was due to the later-than-normal harvesting of eastern galega. It agrees with the finding on ADF content of 42.7% and 33.9% for the first cut and second cut, respectively (Table 4), since the first cut was realized at a later phenophase than the second cut; more exactly, it was realized at the beginning of full flowering and beginning of flowering, respectively. However, according to trend analyses on dependencies of ADF content and yield on DM content at harvest, the harvest at 27% DM content seems to be optimal for the highest ADF content, as it is required for second-generation technologies, being even more appropriate than harvest at 35% DM content or higher ones (Figure 4 CF).

According to Jasinskas et al. (2008), the calorific value of DM of *Galega orientalis* ranged from 17.1 to 18.5 MJ/kg and depended on sward composition, growing conditions, and cutting time. Symanowicz et al. (2019) reported that the highest calorific values of 18.267 and 18.423 MJ/kg were found for eastern galega in the fifth year of cultivation under nutrition treatment only with K at a dose of 150/ha. These data are supporting the findings of this study on average HHV of 17.325 MJ/kg, while the wider range of 14.871–19.707 MJ/kg is connected to a single outlier at the minimum, which is evident from the box plot and the trend plots with the full original data cluster (Figures 2 and 4).

According to the conclusions of Dubis et al. (2020), the energy output of eastern galega stands peaked in utility years 4 and 5 at a level of 122.4–131.1 GJ/ha, whereby concerns DM yield of 14.7–15.3 t/ha, respectively. Presenting the results of an 11-year field experiment conducted in Poland, they found about 4.9 GJ/ha per year higher energy yield under high-input technology in comparison to the low-input technology. However, the energy productivity and efficiency were time dependent and differed under the technologies. The key importance is the fact that the maximum DM yield and energy yield were achieved 1 year later under high input, and the rate of decrease in the last 3 years of the experiment was 30% lower in comparison to that under low input. These findings are complementary to the findings of this study, since the long-term study has a wider timeframe regarding the lifetime of the crop stand. However, due to higher DM yields, higher differences were found in energy output according to the nutrition treatments, taking into account values of 132.54 – 132.39 – 113.48 GJ/ha per harvest in order to intensive – semi-intensive – untreated control, and even more higher as values of 265.07 – 264.79 – 226.97 GJ/ha per the harvests together, respectively.

CONCLUSIONS

Ligno-cellulose quality and calorific value of eastern galega depend on management practices and agro-environment conditions. The impact of nutrition, years, sites, and harvests was evaluated as the main effects on ADF, ADL, CE, HEM, NDF, and HHV, during introducing the crop into the new region of Central Europe with moderate continental climate and marginally heavy soil conditions. Two equal aspects of quality were followed in the research, the primary one being content-based quality (% or kJ/g) and the secondary one being yield-based quality (kg/ha or GJ/ha). The primary aspect is considered to be the general marker of phytomass quality, while the secondary aspect is important for conception of a sustainable supply chain since the area required depends on quality yields.

In regard to the quality content, eastern galega can be considered as an additional energy crop, which is complementary to the typical energy crops studied earlier. In terms of quality content, the impact of the sites and nutrition intensity was lower than the impact of harvests and years. In terms of quality yield, the harvests were confirmed to be the most important factor; even the years (with a great increase of phytomass yield by utility year approaching) were of lower importance, which was followed by nutrition and then by sites, which showed the least impact. The impact order of harvests < years < nutrition < sites was valid for each of the quality indicators, counting the harvests separately. In case of counting the cuts together, the similar impact order of years < nutrition < sites were confirmed.

Regarding the impact of plant biometry, the influence of plant height, DM yield, and DM content at harvest on quality was also evaluated. To achieve ideal ligno-cellulose quality and calorific value, in terms of quality content, the optimal plant height was in the range of 120–170 cm, DM yield was 15–18 t/ha, and DM content at harvest was 25%. In terms of quality yield, the optimal height and DM content at harvest were in the same range, but a DM yield of 15–20 t/ha per cut and even more is desirable.

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