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Original scientific article

GENOTYPE × YEAR INTERACTION ON RYE PRODUCTIVITY PARAMETERS CULTIVATED ON SANDY CHERNOZEM SOIL

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Rye is a dual-purpose crop, for nutrition but also for bioenergy. The selection of rye is aimed at its improvement as a plant for human and animal consumption, but also it is interesting for bioenergy production as it combines high biomass production with low environmental impact. There is a growing demand for sustainable sources of biomass worldwide. Directions for achieving rye selection for energy purposes include selection to increase biomass yield and corresponding physiological properties. During three years (2019-2021), four rye genotypes were examined. The aim of this study was to examine the influence of genotype (G), year (Y) and their interaction (G×Y) on rye productivity parameters: plant height (PH), spike length (SL), 1000-grain weight (TGW), hectoliter mass (HM), green biomass yield (GBY), biogas yield (BGY) as well as the possibility of using rye as an alternative fuel. Rye is an excellent raw material for the production of healthy food, but also for the production of biofuels. The study discussed the potential use of four high yielding genotypes for biofuel production. Genotype G1 (25.29 t ha^{-1}) had a statistically significantly higher average green biomass yield compared to genotypes G2, G3 and G4 (22.98 t ha^{-1}, 23.56 t ha^{-1} and 23.76 t ha^{-1}). Significant G×Y interactions demonstrate differences between rye genotypes in response to environmental conditions. Plant height was directly proportional to biomass yield. As one of the targets in breeding programs, to develop taller cultivars as biofuel feedstock. Screening and selection of appropriate rye varieties for each region is critical for optimum results.

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INTRODUCTION

Rye (*Secale cereale* L.) is an annual cereal of the *Triticeae* tribe within the *Pooideae* subfamily. The cultivated forms of *S. cereale* ssp. are mainly grown in North America, Northern and Eastern Europe, Russia and China, where the grain is used for animal feed or production of bread and alcoholic beverages. Rye can also be grown for biomass used as forage, green manure, or production of bioenergy (NEWEL and BUTLER, 2013; HAFFKE *et al*., 2014; GLAMOČLIJA *et al*., 2015; JANKOVIC *et al*., 2016; LAKIĆ e*t al.,* 2018). Rye has a relatively high drought tolerance due to a well-developed root system and is therefore often cultivated on marginal land that is unsuitable for most other cereal crops (SCHLEGEL, 2014). The undemanding nature of rye is an important asset for future development of new varieties that will withstand the effects of climate change, as well as cultivation on devastated lands.

The world is growing the consumption of energy obtained from renewable origins. In the European Union (EU) for instance, the share of renewable energy is expected to be between 55 and 75% of the total energy consumption in 2050, and it will proportionally increase by higher use of biomass (EUROPEAN COMMISSION, 2011). Thanks to the development of new technologies for processing bio-waste into energy, the rate of increase in the use of alternative fuels is growing significantly. According to estimates by experts in the field of energy, it is about 15% per year in highly developed countries (POPOVIĆ *et al.,* 2020a). Secondary biomass, which would be used to produce biofuels, is one of the ways in which countries could meet their obligations under the Kyoto Protocol on Climate Change, because they would, in general, reduce emissions of harmful gases and greenhouse effect as a fundamental factor of global temperature rise. By improving the technological process of obtaining biofuels from secondary products, energy sources would be obtained, which have a much wider application. The advantage of these energy sources is the fact that they come from renewable sources, which significantly reduces the dependence on the import of fossil fuels which a large number of countries do not have. In addition to economic ones, there are also problems with environmental protection, because the increasing use of fossil fuels significantly increases the amount of harmful gases in the atmosphere, while by using of bio-fuel significantly lower emissions of harmful gases. The consequence of increasing the concentration of these gases in the atmosphere (especially carbon dioxide) affects climate change, which is manifested by global warming due to the greenhouse effect (POPOVIĆ *et al.,* 2020a; 2020b; RAKAŠČAN *et al*., 2021).

Drought is the most common environmental stress affecting rye cultivation both in developing as well as developed countries. Water and heat are the two main causes of drought stress. When choosing genotypes, it should be borne in mind that precipitation is the biggest factor limiting the success of production in the continental climate, what are the production conditions in our country. A good schedule and a sufficient amount of precipitation are prerequisites for a more optimal crop density, and thus a higher yield. Changed climatic conditions and their greater variability will affect the state of agricultural production in Serbia in the future. Changed climatic conditions mean, primarily, an increase in the average temperature and changes in the regime and amount of precipitation. Greater variability means more frequent and intense extreme weather events such as heat waves, droughts and episodes of heavy rainfall. Both drought and heat stress are responsible for decline in cereals production in many regions of the world. Landraces are unexploited genetic resources for various agronomic traits contributing tolerance to abiotic stress.

Among the small-grain cereals, winter rye (*Secale cereale* L.) stands out for its vigorous growth and enhanced tolerance to abiotic and biotic stress factors. Europe is the largest rye grower worldwide and covers about 81% of world`s cultivation area, with Russia, Poland, and Germany being the main producers (FAO, 2019). The use of stable genotypes could be a source of yield enhancement in across environments. However, the genotype × environment interaction (GEI) is a significant feature of plant breeding program as well as the introduction of new crop varieties. Different genotypes of different crop varieties are sensitive to changing soil, climate, and biotic factors as a result of their unique response to each of these factors (TREVASKIS *et al.*, 2003). It is therefore imperative that the analysis of GEI takes center stage when evaluating varieties for adaptation. Assessment of the stability of grain yield and its associated traits across growing regions is a requirement in breeding for varieties for specific or common environments for high production and productivity. This calls for the development of varieties that would give stable production from year to year and from location to location even under varied conditions of cultivation. It should be noted that selection of varieties based on grain yield alone may not be adequate when GEI is significant (YAN *et al.*, 2003; 2004; JOVANOVIĆ-TODOROVIĆ *et al.*, 2020), especially where these have had frequently changing ranks due to cross interaction in different environments. It is therefore an indispensable fact that the GEI was taken into account, properly understood and analyzed. The main characteristic of Serbian domestic varieties of rye is excellent stability and adaptability to our climatic and soil conditions and high genetic potential of fertility.

The aim of the present study was to observe the genetic variability of different rye genotypes, the influence of year and genotype on rye productivity parameters, correlations between them, and the possibility of using rye cultivated on sandy chernozem soil as an alternative fuel.

MATERIAL AND METHODS

Experiment with rye genotypes, cultivated on sandy chernozem soil, were performed in Ilandža (44° 10' 0.6" N, 20° 55' 0.6" E, 59 m a.s.l.) during the three-year research (2019-2021). In this study examined the influence of genotype (G), year (Y) and their interaction (G×Y) on following rye productivity parameters: plant height (PH), spike length (SL), weight of 1000 seeds (TGW), hectoliter mass (HM), green biomass yield (GBY) and biogas yield (BGY). The experiment were performed as a two-factorial, by the method of completely randomised block system in three replications, with genotypes: G1 - Propower, G2 - Tayo, G4 - Serafino (KWS) and G3 - NS Savo (Institute of Field and Vegetable Crops, Novi Sad). Elementary plots were 10 m^2. In all three years of research, the pre-crop was soybean. During the experiment, standard cultivation technology for rye production was applied. In the pre-sowing preparation, 15:15:15 NPK nutrients (350 kg ha^{-1}) were introduced. Sowing was done in the optimal autumn term, 20 September in 2019 and 2021 and 18 September in 2020. During the vegetation period, mechanical and chemical measures of crop care were applied. Mowing was done at wax maturity, and then samples were taken from each elemental plot for the examined morphological-productive parameters. Plant height was measured in cm, and then whole plants were cut on all basic plots, in order to obtain the yield of aboveground biomass (t ha^{-1}) and total grain yield (t ha^{-1}). When the morphological parameters been measured, the rye was chopped and placed in silo trenches, covered to stand for 40 days, for each genotype separately, after which the silage was placed in a fermenter from which biogas was obtained (RICHARDS *et al.*, 1994; POPOVIĆ *et al.*, 2020a).

In Germany, only 4 rye varieties are currently registered for whole plant silage (BUNDESSORTENAMT, 2019). Higher gains in selection have been reported when plant height (PH) was used as a secondary trait instead of grain yield (GY) to indirectly estimate dry mass yield (DMY) in hybrid rye (HAFFKE *et al.*, 2014; GALÁN *et al.*, 2020). Rye is mainly bred for grain yield (in our study - G2, G3 and G4) while G1 is the silage genotype (selected on GBY).

Meteorological data

Meteorological conditions have a significant impact on biomass production and grain yield of plants (BOJOVIĆ *et al.*, 2019; POPOVIC *et al.*, 2012; JANKOVIC *et al.*, 2016; ŽIVANOVIĆ and POPOVIĆ, 2016; TERZIĆ *et al.*, 2019; MARKOVIĆ *et al.*, 2020; RAJIČIĆ *et al.*, 2020a; 2020b; LAKIĆ e*t al.*, 2020; KOSTIĆ *et al.*, 2021; LJUBIČIĆ *et al.*, 2021; UGRENOVIĆ e*t al.*, 2021). For the analysis of the amount and distribution of precipitation, as well as thermal conditions during the vegetation period of rye, the data of the Republic Hydrometeorological Service of Serbia (https://www.hidmet.gov.rs/index_eng.php) were used, for the Ilandža locality for all years of research (Figure 1). Ilandža is a populated place in the municipality of Alibunar, in the South Banat district of Serbia. Meteorological conditions in the examined years had a significant impact on the growth and development of rye plants, Figure 1.

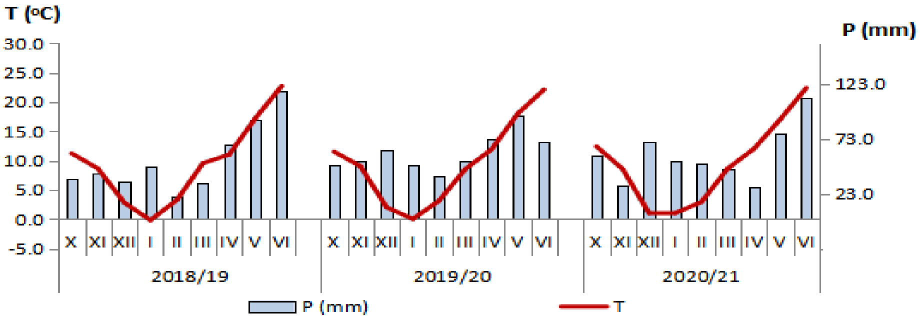


Figure 1. Precipitation sum (mm) and average air temperature (ºC) during the vegetation period of rye in micro-trials, Vršac, Serbia.

The average temperature during the vegetation period of rye was approximately the same in all three years of research (9.5ºC). The analysis of average monthly temperatures indicates that March in 2020 and 2021 were colder (8.5ºC) compared to 2019 (9.5ºC). The monthly water regime in the winter period in all years of research was favourable. The average amount of precipitation during the vegetation period of rye was the highest in the second year of research (538 mm), lower in the third (523 mm), and the lowest in the first year (484 mm). The monthly water regime in the second year was favourable, while in the first in February and March (20.3 mm and 32.6 mm), and in the third in April (29.2 mm) there was a lack of precipitation (Figure 1).

Soil conditions

The soil where the trial was set up is Sandy Chernozem (according to the Serbian soil classification system), while according to WRB classification (2014) this soil type is classified as Arenic Chernozem. The chemical analysis of agrochemical characteristics of the soil in the municipality of Ilandža presented in Table 1, was performed with the use of methods described by BOGDANOVIĆ and UBAVIĆ (1995). We have analyzed the basic parameters of soil fertility (pH in H_2O and in KCl – potentiometric (SRPS ISO 10390:2007 method); $CaCO_3$ - using Scheibler calcimeter, easily available P_2O_5 and K_2O – by Egner-Riehm – AL method), with sampling depths (0-30 cm). Analysis of the results obtained in soils have shown that pH in H_2O is of weakly-alkaline reaction, pH in KCl is of neutral reaction, content of $CaCO_3$ and total nitrogen is medium, and very low content of available P_2O_5 and K_2O (Table 1).

*Table 1. Agrochemical properties of soil**

Soil depth, 0-30 cm	pH		C_{org}	Total N	$CaCO_3$	Available	
	in KCl	in H_2O	%	%	%	P_2O_5 mg/100 g	K_2O mg/100 g
Ilandža	6.95±0.30	7.8±0.40	3.62±1.65	0.14±0.04	2.04±0.46	0.54±0.20	0.40±0.22

*Agrochemical analyses of soil samples from the experimental fields were performed in the laboratory of FINS in Novi Sad, 2020.

The soil on which the experiment was performed was poor in total nitrogen content and available phosphorus and potassium. In order for the soil to be a favourable environment for optimal agricultural production, it is necessary to have favourable physical and mechanical properties, i.e. not to show strong swelling, shrinkage, plasticity, stickiness, bonding and compaction and not to offer great resistance during cultivation and to development of roots and sprouts of cultivated plants. For successful production on lands of unfavourable physical and mechanical properties, it is necessary to carry out measures of repair and preservation of agronomical favourable structure. Proper, timely tillage at optimal humidity contributes to the maintenance and repair of soil structure. Application of organic fertilizers (manure, compost, peat) and regular fertilization with plant nutrition (mineral fertilizers) also indirectly contribute to repairing soil structure, because their use impact forming of strong root system, and after the removal of crops a significant amount of harvest residues remains. Using of gypsum is an ameliorative measure which, when applied to alkaline soils, has a positive effect on the aggregation of soil mass and on the stabilization of the soil structure.

Based on the analyses in non-irrigated and irrigated conditions, dependent of climate change, a possible benefit for crops is observed. The analyzed yield, net irrigation, and results showed potential prosperity applying irrigation under climate change (MARKOVIĆ *et al.*, 2020). Some small-scale irrigation programs introduced by the government could assist the sustainable crop production in the studied area.

Statistical analysis

The experimental data obtained were analyzed using the statistical package STATISTICA 12 for Windows (TIBCO Software Inc., Palo Alto, CA, United States). Significance testing of differences between the calculated mean values of the examined factors (genotype and years) was performed using a two-factorial model of analysis of variance (ANOVA). All significance ratings were based on the F-test. The statistical significance of the difference among the means was determined using Fisher's least significant difference (LSD) *post hoc* test at the 0.05% and 0.01% probability level. The relative dependence was determined by the method of correlation analysis (Pearson's correlation coefficients), and the obtained coefficients tested by t-test for significance levels of 0.05% and 0.01%.

RESULTS AND DISCUSSION

In this study, productivity rye genotypes was studied during three years of field - tests. All parameters studied showed significant effects of genotype (G) as revealed by an ANOVA analysis (Tables 2 and 3). Based on the analysis of variance, there is highly significant differences of plant height in regard to the genotype (F_{exp}=9.91**).

Highly significant differences are also noted for biomass yield (F_{exp}=35.57**), biogas yield (F_{exp}=217.30**), hectoliter mass (F_{exp}=10.38**) and 1000 grain mass (F_{exp}=38.18**), in regard to the genotype (Table 2). Significant differences in regard to the year are noted for biomass yield (F_{exp}=5.72**), biogas yield (F_{exp}=8.30**), hectoliter mass (F_{exp}=8.70***) and 1000 grain mass (F_{exp}=7.86**), (Table 2).

Plant height

The results of plant height of rye genotypes are presented in Table 3. The average rye plant height of all genotypes and in all three years of research was 138.25 cm, and it varied from 133.89 cm to 145.90 cm, Figure 2a. Genotype G1, in 2021 year, had a significantly higher value of plant height relative to all genotypes, in all years, 152.03 cm, Table 3.

Genotypes had a statistically significant effect on plant height. Genotype G1 had statistically significantly more plants height compared to genotypes G2, G3 and G4, Table 3. The highest average value established at G1 genotype (145.90 cm), which had the highest values in 2021 year. The lowest average plant height established at G4 and G2 genotypes (133.89 cm and 134.26 cm), which had the lowest values in all investigated years (Figure 2a).

The year factor non-significantly affected this trait. Higher values are established in the third year (139.62 cm) compared to the first and second year of investigation (136.42 and 138.70 cm, respectively). The genotypes have shown their own genetic peculiarity for plant height. Year and genotype interactions significantly affected this productivity parameter, Table 3, Figure 2b.

Table 2. Analysis of variance for tested parameters

Effect	SS	Deg. of Freed.	MS	F	p
Plant height					
Intercept	688015.11	1	688015.11	2484.21**	0.0000
Genotype	845.71	3	281.90	9.91**	0.0002
Year	65.2	2	32.60	1.15	0.3349
G × Y	247.71	6	41.30	1.45	0.2369
Error	682.80	24	28.40		
Spike length					
Intercept	5121.79	1	2121.79	8450.25**	0.0000
Genotype	26.03	3	8.68	14.32**	0.0000
Year	1.23	2	0.62	1.02	0.3764
G × Y	4.02	6	0.67	1.11	0.3882
Error	14.55	24	0.61		
1000 grain mass					
Intercept	76858.32	1	76858.32	71165.11**	0.00000
Genotype	123.70	3	41.23	38.18**	0.00000
Year	16.99	2	8.49	7.86**	0.00236
G × Y	20.65	6	3.44	3.19*	0.01912
Error	25.92	204	1.08		
Hectolitre mass					
Intercept	180228.21	1	180228.10	318050.05**	0.00000
Genotype	17.20	3	5.70	10.38**	0.00017
Year	9.80	2	4.90	8.70**	0.00148
G × Y	4.06	6	0.77	1.22	0.35648
Error	13.60	24	0.67		
		35			
Green biomass yield					
Intercept	20558.78	1	20558.78	83913.39**	0.00000
Genotype	26.14	3	8.71	35.57**	0.00000
Year	2.81	2	1.40	5.72**	0.00000
G × Y	3.00	6	0.50	2.04*	0.01814
Error	5.88	204	0.25		
Biogas yield					
Intercept	1984248.05	1	1984248.05	103870.71**	0.00000
Genotype	12453.20	3	4151.10	217.30**	0.00000
Year	319.20	2	159.01	8.30**	0.00177
G × Y	406.50	6	68.06	3.52*	0.01174
Error	458.20	24	19.10		

*G-Genotype; Y-Year; G x Y -Genotype x Year

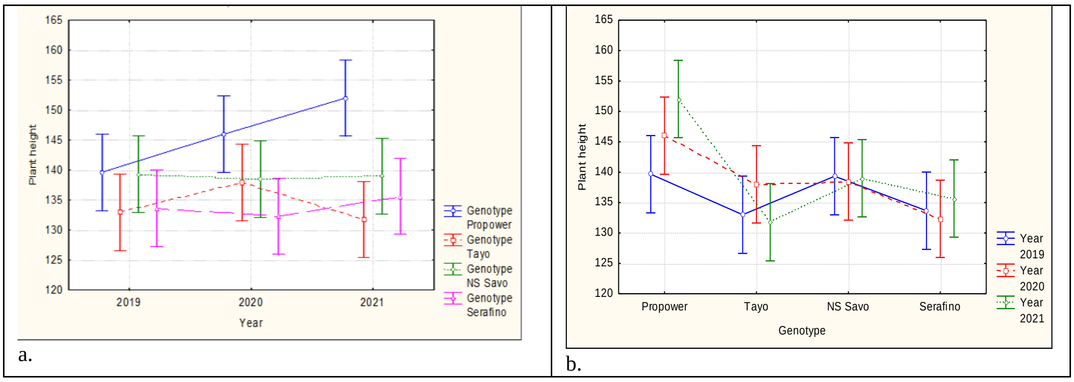
Table 3. Average value and Stand. Dev. of rye parameters, 2019-2021.

Effect	Level of factor	Plant height, cm	Spike length, cm	1000 grain weight, g	Hectoliter mass, kg	Green biomass yield, t ha^{-1}	Biogas yield, m^{3}kg^{-1}
Total		138.25± 7.25	11.93± 1.14	46.20± 2.31	70.75±1.13	23.89± 1.04	234.72±19.74
G1	Propower	145.90± 6.62	13.21± 0.83	49.11± 2.47	71.58±0.98	25.29± 0.78	265.13± 4.56
G2	Tayo	134.26± 4.81	11.46± 0.75	43.97± 0.77	70.29±0.66	22.98± 0.72	220.22± 7.36
G3	NS Savo	138.93± 6.1	12.11± 0.74	45.69± 0.85	71.27±1.19	23.56± 0.40	218.96± 5.19
G4	Serafino	133.89± 4.51	10.93± 0.82	46.06± 0.72	69.89±0.78	23.76± 0.41	234.78± 6.78
Y	2019	136.42± 6.34	12.07± 1.16	45.78± 1.63	70.95±0.71	23.82±1.08	230.57±19.52
Y	2020	138.70± 6.12	12.04± 1.06	45.67± 2.08	70.04±0.99	23.60±0.82	237.00±19.60
Y	2021	139.62± 9.15	11.66± 1.2	47.18± 2.91	71.27±1.29	24.27±1.17	236.75±21.11
G × Y	G1, 2019	139.67±4.51	13.56± 0.51	47.33± 2.52	71.67±0.58	25.23±0.21	260.40± 0.53
G × Y	G1, 2020	146.00±5.29	13.06± 1.10	48.33± 1.53	70.74±1.11	24.60±0.87	264.67± 2.52
G × Y	G1, 2021	152.04± 3.43	13.00± 1.01	51.67± 0.58	72.33±0.58	26.03±0.35	270.33± 1.53
G × Y	G2, 2019	133.00± 7.00	10.83± 0.2	44.43± 0.51	70.50±0.50	22.42±0.31	214.00± 1.00
G × Y	G2, 2020	138.00±1.73	12.03± 0.55	43.27± 0.65	70.00±1.00	22.90±0.50	226.00± 4.58
G × Y	G2, 2021	131.76± 2.80	11.50± 0.86	44.20± 0.72	70.36±0.55	23.63±0.80	220.67± 9.29
G × Y	G3, 2019	139.33± 8.50	12.50± 0.50	45.33± 0.58	71.30±0.30	23.77±0.49	215.87± 0.61
G × Y	G3, 2020	138.47± 3.09	12.00± 1.00	45.07± 0.11	70.10±0.30	23.37±0.32	216.00± 0.50
G × Y	G3, 2021	139.00± 8.18	11.83± 0.76	46.67± 0.58	70.10±1.53	23.55±0.39	225.00± 5.00
G × Y	G4, 2019	133.67± 4.72	11.40± 0.5	46.00± 1.00	72.40±0.53	23.86±0.15	232.00± 4.36
G × Y	G4, 2020	132.33± 4.93	11.06± 1.10	46.00± 1.01	69.33±0.58	23.53±0.49	241.33± 8.14
G × Y	G4, 2021	135.67± 5.13	10.33± 0.57	46.17± 0.28	70.00±1.00	23.87±0.51	231.00± 1.00

*G-Genotype; Y-Year; G x Y -Genotype x Year

Parameter	Plant height		Spike length		1000 grain weight		Hectoliter mass		Biomass yield		Biogas yield	
LSD	0.5	0.1	0.5	0.1	0.5	0.1	0.5	0.1	0.5	0.1	0.5	0.1
G	5.193	7.037	0.758	1.027	1.012	1.371	0.733	0.993	0.4818	0.653	4.255	5.766
Y	4.497	6.094	0.656	0.889	0.876	1.187	0.770	0.860	0.4174	0.618	3.468	4.994
G × Y	8.994	12.188	1.313	1.779	1.752	2.375	1.269	1.720	0.8345	1.131	7.370	9.987

The plant height is a variable trait and its expression highly depends on the environmental factors. To achieve high plant height the rye crop still needs favourable agroecological conditions for optimal growth (LAKIĆ *et al.,* 2018). Variability of plant height depended on both investigated genotypes and years, what are in agreement with previous study (KHAN *et al.*, 2004). By selecting plants with a better above-ground growth it is possible to predict a better development of the root system. Genotypes with faster early vigour have produced higher biomass and grain yield (BLAŽIĆ *et al.*, 2021).



a.

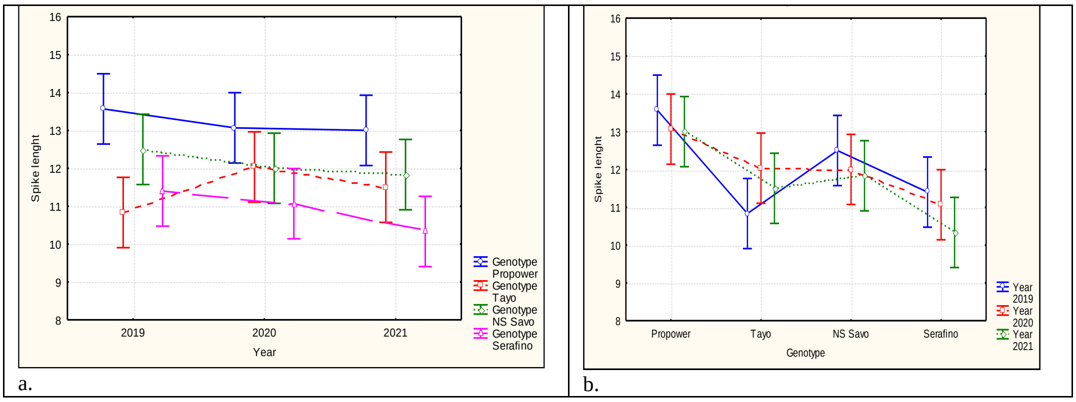
b.

Figure 2. Effects of genotype × year interaction on plant height.

Spike length

Spike length is genetically controlled, but also depends on environmental factors. The highest average value for spike length has shown G1 genotype (13.21 cm), and the lowest G4 genotype (10.93 cm). Genotype G1, in 2019 year, had a significantly higher value of spike length relative to all genotypes, in all years, Table 3.

The most favourable year for the examined parameter was 2019. The genotypes had higher average values of spike length in the first and second years (12.07 cm and 12.04 cm) than in the third investigated year (11.66 cm), Figure 3a.



a.

b.

Figure 3. Effects of genotype x year interaction on spike length.

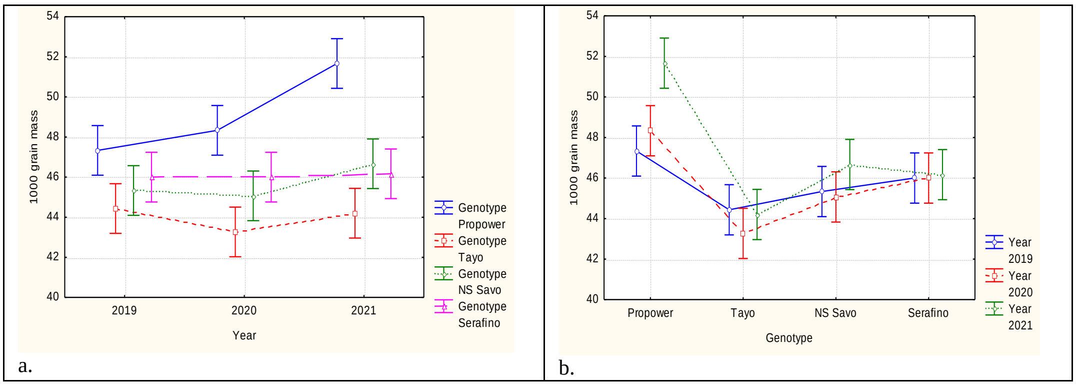
Genotype and genotype × year interaction was not significant for tested trait. The genotypes showed significant differences in the average values of spike length that indicated diversity of investigated genotypes, Figure 3b. Variability of spike length depended on both investigated genotypes, what are in agreement with previous study (KHAN *et al.*, 2004).

1000-grain weight

Genotype has significant effect on 1000-grain weight. According to the obtained results, the G1 genotype had a statistically significantly higher 1000-grain weight (49.11 g) compared to the G2, G3 and G4 genotype in all production years (Tables 2 and 3).

The genotype has shown its own genetic specificity for 1000-grain weight. The highest average value established at G1 genotype u 2021 (51.67 g). The lowest average 1000--grain weight established at G2 genotypes (43.97 g). G2 genotype had the significantly lowest values in all investigated years compared to the genotypes G1, G3 and G4 (49.11 g, 45.69 g and 46.06 g, respectively), Figure 4a.

The year factor also significantly affected this trait. Higher values are established in the third year (47.18 g) compared to the first and second year of investigation (45.78 and 45.67 g, respectively), Table 2. Genotype and year interaction significantly affected this productivity parameter, Figure 4b.



a. b.

Figure 4. Effects of genotype x year interaction on 1000- grain weight.

The 1000-grain weight is the marketing importance traits. The 1000-grain weight is defined as the absolute mass of absolutely dry and undamaged grains. It is used as a measure of quality, because with the same grain size, those who are heavier will indicate the possibility of higher utilization in processing. The 1000- grain weight can vary between genotypes depending on agro-meteorological conditions and the amount of applied nutrients (POPOVIĆ *et al.*, 2020a).

Hectolitre mass

Table 2 shows the value of hectoliter mass of rye grain depending on the genotype and production year. The average value of hectoliter mass for all genotypes in the studied period was 70.75 (kg hl^{-1}). Between the examined years, for all genotypes, there were statistically significant differences in the value of hectoliter mass, Tables 2 and 3, Figure 5a.

The year factor significantly affected this hectoliter mass. Higher values are established in the third year (71.27 kg hl^{-1}) compared to the first and second year of investigation (70.95 kg hl^{-1} and 70.04 kg hl^{-1}, respectively), Figure 5a. Genotype and interaction genotype × year had significantly affected hectoliter mass. The tested genotypes showed significant differences in the average values of hectoliter mass, which indicated diversity of investigated genotypes, Figure 5b. According to the obtained results, genotypes G1 and G3 (71.58 kg hl^{-1} and 71. 27 kg hl^{-1}) had a statistically significantly higher average hectolitre mass compared to genotypes G2 and G4 (70.29 kg hl^{-1} and 69.89 kg hl^{-1}), Tables 2 and 3, Figure 5b.

Absolute grain mass is a characteristic of the variety and therefore there are greater variations between different genotypes than between years and variants of mineral nutrition (LALEVIĆ *et al.*, 2012).

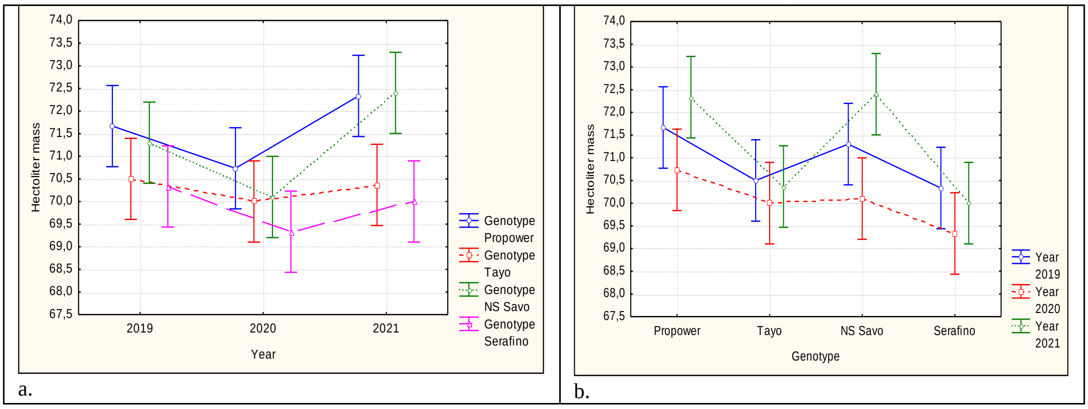


Figure 5. Effects of genotype x year interaction on value of hectoliter mass.

Green biomass yield

The values of green biomass yield of rye depending on the genotype and production year are given in Table 2. The average value of green biomass yield for tested genotypes in the study period was 23.89 t ha^{-1}. Genotype, year and genotype × year interaction were significant for green biomass yield. Between the examined years, in the tested genotypes, there were statistically significant differences in the value of green biomass. Biomass yields for years ranged from 23.60 t ha^{-1} (2020) to 24.27 t ha^{-1} (2021), Tables 2 and 3, Figure 6a. Genotype G1 (25.29 t ha^{-1}) had a statistically significantly higher average green biomass yield compared to genotypes G2, G3 and G4 (22.98 t ha^{-1}, 23.56 t ha^{-1} and 23.76 t ha^{-1}), Tables 2 and 3, Figure 6b. G×Y interactions demonstrate rye genotype differences as response to environmental conditions, Figure 6b. The analyzed yield components are variable traits and their expression highly depended on the environmental factors. The investigated genotypes showed significant differences in the average values of green biomass yield. It indicated diversity of examined genotypes. To achieve the rye crop high biomass yields, still needs favorable agro-ecological conditions for optimal growth.

In the study GALÁN *et al.* (2020) rye demonstrated its high dry matter yield (DMY) potential on sandy soils and under drought stress. Under these conditions, rye yielded 8.4 t dry matter ha^{-1}, and under better environmental conditions, yields were up to 14.7 t dry matter ha^{-1}. Rye can, therefore, represent a suitable alternative for biomass production in a variety of agroecological conditions, including areas where the cultivation of other cereal crops would not be competitive (GEIGER and MIEDANER, 2009).

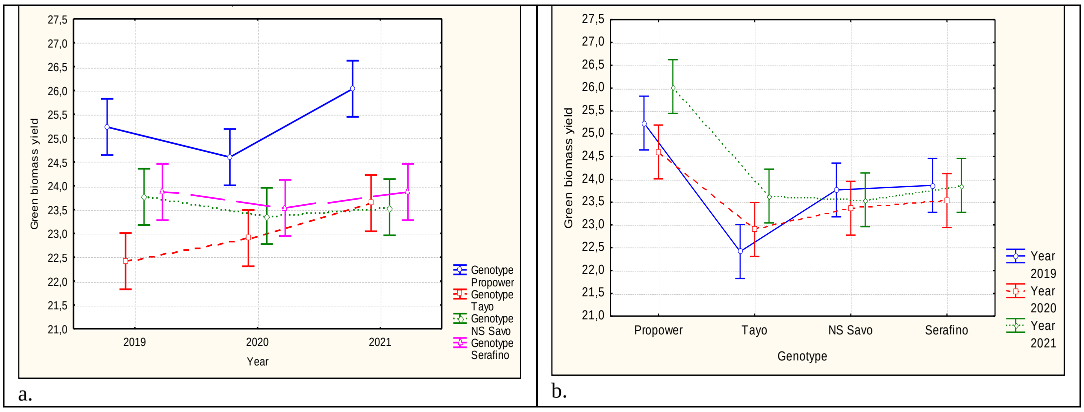


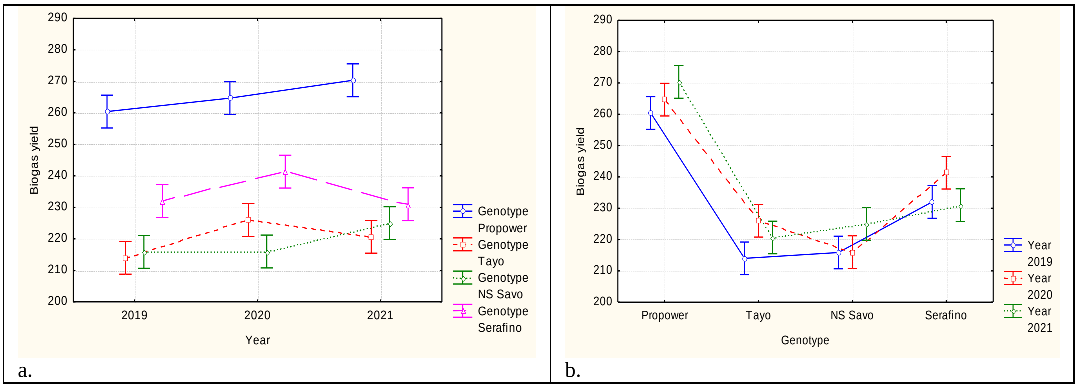
Figure 6. Effects of genotype x year interaction on value of green biomass yield.

Considering that three quarters of the rye harvest is used for non-food purposes, rye appears as a sustainable alternative source of biomass (GEIGER and MIEDANER, 2009). In general, biomass takes the fourth place among all fuel which is applied in the world. It gives about 2 billion t of the conditional fuel per year that makes about 14% of the common consumption of primary energy supplies in the world (DUBOVIN *et al.*, 2007). Literary data demonstrate that the main indicators for a bio-energetic rye, on which the breeder has to pay attention, are fresh and dry matter yield (HÜBNER *et al.*, 2011; GOTTWALD, 2014). It is established that the highest amount of biomass from rye plants can be reached at the milk-maturity (MIEDANER *et al.*, 2010), but an quantity of biomass depends on the soil and climatic conditions: in some regions of the world, the yield can be five times higher, than, for example, in Germany (DEUBLEIN *et al.*, 2008).

Biogas yield

The average value for biogas yield, for tested genotypes in the studied period was 234.72 m^3t^{-1}. Genotype, year and genotype × year interaction were significant for green biomass yield. Between the years examined, genotypes had significant differences in average biogas yield values. The most favourable year for the examined parameter was 2021. Biomass yields for years ranged from 230.57 m^3t^{-1} (2020) to 237.00 m^3t^{-1} (2021), Tables 2 and 3, Figure 7a. Genotype G1 (265.13 m^3t^{-1}) had a statistically significantly higher average value for biogas yield compared to genotypes G2, G3 and G4 (220.22 m^3t^{-1}, 218.96 m^3t^{-1} and 234.78 m^3t^{-1}), Tables 2 and 3, Figure 8b. Year and genotype interaction significantly affected of biogas yield. The investigated genotypes showed significant differences in the average values of biogas yield. It indicated diversity of investigated genotypes.

The results of this study confirm the findings of many authors that the genetically determined productivity of cultivated plants is strongly modified by agroecological conditions and genetic factor (COLLINS *et al.*, 2014; MILANOVIĆ *et al.*, 2020). When considering the productivity of rye, in addition to grain yield, as the most important characteristics the yield of the aboveground biomass should be especially emphasized.



a. b.

Figure 7. Impact of genotype x year interaction on value of biogas yield.

The silage of the rye, in two different DM - dry matter content, is supplementary biomass for biogas plants based on traditional inputs (maize silage) and thus contributes the overall biogas production. In order to obtain maximum biogas yield, some parameters have to be considered when selecting a catch crop for biogas production, namely the crop species, the soil characteristics, the weather conditions, harvest time, the dry matter content, and the nitrogen application. All these parameters have direct impact on maximum biogas yield per kg of ODM (VÍTĚZ *et al.*, 2015).

Correlation of rye tested traits

The relationship between biomass yield and 1000 grain mass, then spike length, biogas yield, as well as biomass yield and hectolitre mass was investigated using the Pearson linear correlation coefficient (Table 4).

Table 4. Correlation coefficients between examined traits

Parameter	PH	SL	GBY	BY	HGM	HM
Plant height - PH	1.00	0.50*	0.58*	0.57*	0.59*	0.48*
Spike length - SL	0.50*	1.00	0.57*	0.49*	0.44^{ns}	0.45*
Green biomass yield - GBY	0.58*	0.57*	1.00	0.74**	0.75**	0.47*
Biogas yield - BY	0.57*	0.49*	0.74**	1.00	0.79**	0.30^{ns}
1000 grain mass - HGM	0.59*	0.44^{ns}	0.75**	0.79**	1.00	0.54*
Hectoliter mass - HM	0.48*	0.45*	0.47*	0.30^{ns}	0.54*	1.00

^{ns}–not significant; * and **significant at the level of probability 0.05% and 0.01%.

Correlation between the tested parameters was significant, but not particularly high. Plant height is also directly proportional to biomass and is one of the targets in breeding programs for obtaining taller cultivars as bio-fuel feedstock. A strong positive correlation was calculated between biomass and biogas yield (r =0.74**), biogas yield and 1000 grain mass (r

=0.79**), and green biomass yield was in strong positive correlation with 1000 grain mass (r =0.75*), Table 4. Overground green biomass yield was in positive correlation with spike length (r=0.57*), plant height (r=0.58*) and hectolitre mass (r=0.47*), Table 4.

Biogas yield was in positively correlated with plant height (r=0.57*) and spike length (r=0.49*), Table 4. The analysis of the impact of agroecological conditions on the productivity of rye should answer the questions of the possibility of its use, in a certain area. Biotic and abiotic stresses adversely impact the crop productivity and traits important for biofuel production. Adaptation and tolerance towards abiotic and biotic stresses is critical for the survival of a plant under suboptimal conditions. Drought stress is major cause for limiting rye potential in tropical regions, whereas in temperate environments, early season cold stress is the major constraint (LAKIĆ *et al.,* 2018). Observing the average during the previous three years in experiments in Vojvodina significantly higher grain yields are observed achieved in 2021. Rye genotype, NS Savo had a grain yield of 6.25 t ha^{-1}. In addition to the most important agronomic characteristics such as yield, height and resistance to lodging, genotypes are also assessed for technological quality and disease resistance. Genotype NS Savo achieved significantly higher grain yield and better quality compared to the standard variety, which indicates its high fertility potential (JOCKOVIĆ *et al.,* 2022). To achieve high and stable yields in intensive agricultural production, it needs to be proper and timely application of agro-technical measures, and selection of high-yielding varieties, which will under certain conditions of production achieve maximum yield (POPOVIĆ *et al.,* 2012; 2020a, 2020b).

MILANOVIĆ *et al*., 2020 point out that the following types of alternative bio-fuels can be found: methanol, bio-methanol, bio-ethanol, biodiesel, natural gas, hydrogen, etc. As raw materials for biomass, from agriculture it can be used: sugar cane, sugar beet, sorghum, maize, wheat, rye, oilseed rape, sunflower, potatoes, barley, olives, palm and other exotic products. The main advantages of bio-fuels are that it is a renewable and inexhaustible source of energy-fuel, which emits less pollution into the atmosphere than conventional fuels. In addition, these fuels are CO_2 neutral, i.e. they emit but also consume CO_2. It is also very important that they use waste materials that would most often be disposed of, and in that way, even in a minimal percentage, they would participate in the substitution of fossil fuels, which will be especially important in the coming decades.

JANKOVIĆ *et al.* (2017) point out that the selection of rye is aimed at its improvement as a plant for human and animal consumption, and lately work has been done on obtaining genotypes suitable for fuel production. Directions that achieve this include increasing the yield of plant mass, improving the structure of the cell wall and selection for appropriate physiological properties. Biomass production can be increased by intensive shrubbing, more efficient absorption of nutrients and water by accumulating reserve substances. Regarding the selection for physiological properties and ecological suitability of rye, it must be pointed out that its important advantage over other bio-energy crops is resistance on drought and withstand on high temperatures. The techniques used for rye breeding are constantly being developed and improved.

A prerequisite condition for successfully increasing yield potential through breeding is the availability of a variety of initial material that have proven to be highly productive. Genetic diversity among plant species offers prospects for improving the plant characteristics. Its assessment is necessary to help tackle the threats of environmental fluctuations and for the effective exploitation of genetic resources in breeding programmes (KHAN *et al.,* 2015). The controlled selection of varieties suitable for the breeder interest to the environment conditions, as well as the study of the relationships between the yield and the components that determine its formation, is a guarantee for the upward development of productivity breeding (STOEVA *et al.,* 2009; IKANOVIĆ and POPOVIĆ, 2020; DIMITROV *et al.,* 2021).

CONCLUSION

Genotype, year and genotype x year interaction were significant for green biomass yield. Genotype G1 (25.29 t ha^{-1}) has statistic higher average green biomass yield compared to genotypes G2, G3 and G4. G×Y interactions demonstrate genotype rye differences in response to environmental conditions. Correlation between the tested parameters was significant, but not particularly high. A strong positive correlation was calculated between biomass and biogas yield (r = 0.74**), biogas yield and 1000 grain mass (r = 0.79**), and green biomass yield was in strong positive correlation with 1000 grain mass (r = 0.75**).

Rye, with its of adaptive features and low input requirements, is one of the important candidates for biofuel feedstock. It can play a significant role in addressing the growing need for renewable energy. Plant height is also directly proportional to biomass and is one of the targets in breeding programs with an aim to develop taller cultivars as biofuel feedstock. Screening and selection of appropriate rye varieties for each region is critical for optimum results.

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INTERAKCIJA GENOTIP × GODINA NA PARAMETRE PRODUKTIVNOSTI RAŽI GAJENE NA PESKOVITOM ČERNOZEMU

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Izvod

Raž je usev dvostruke namene, za ishranu i za bioenergiju. Selekcija raži ima za cilj, unapređenje biljke za ishranu ljudi i životinja, ali je interesantna i za proizvodnju bioenergije, jer kombinuje veliku proizvodnju biomase sa malim uticajem na životnu sredinu. Širom sveta postoji rastuća potražnja za održivim izvorima biomase. Pravci kojima se postiže selekcija raži u energetske svrhe obuhvata selekciju na povećanje prinosa biomase i odgovarajućih fizioloških svojstava. U trogodišnjim mikroogledima (2019-2021.) ispitivana su četiri genotipa raži. Cilj ove studije bio je da se ispita uticaj genotipa (G), godine (Y) i njihove interakcije (G×Y) na parametre produktivnosti raži: visinu biljaka (PH), dužinu klasa (SL), masu 1000 semena (TGW), hektolitarsku masu (HM), prinos zelene biomase (GBY), i prinos biogasa (BGY). Raž je odlična sirovina za proizvodnju zdravstveno bezbedne hrane ali i za proizvodnju biogoriva. Studija razmatra potencijalnu upotrebu visokoprinosnih genotipova za proizvodnju biogoriva. Genotip G1 (25.29 t ha^{-1}) imao je statistički značajno veći prosečni prinos zelene biomase u odnosu na genotipove G2, G3 i G4 (22.98 t ha^{-1}, 23.56 t ha^{-1} i 23.76 t ha^{-1}). Interakcija G × Y pokazuje razliku između genotipova raži, kao odgovor na uslove životne sredine. Korelacija između testiranih parametara bila je značajna, ali ne posebno visoka. Visina biljaka bila je direktno proporcionalna prinosu biomase. Kao jedan od ciljeva u programima oplemenjivanja je da se kao sirovina za biogorivo stvaraju više sorte. Selekcija i odabir odgovarajućih sorti raži za svaki region je od ključnog značaja za postizanje optimalnih rezultata.

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