CIRCULATION OF PLANT NUTRIENTS IN BIOENERGY PRODUCTION

Sarmite Rancane[1], Aldis Karklins[1], Dagnija Lazdina[2]
[1]Latvia University of Life Sciences and Technologies, Latvia;
[2]Latvian State Forest Research Institute "Silava", Latvia
sarmite.rancane@llu.lv , aldis.karklins@llu.lv, dagnija.lazdina@silava.lv

Abstract. In order to achieve the goals, set within the EU Green Course, it is necessary to increase the share of renewable resources, as well as to change the resource use habits, including greater emphasis on the re-use of plant nutrients. Taking into consideration political objectives, it can be expected that energy production from plant biomass obtained from agricultural land will increase in the near future. Perennial grasses are more perspective for bioenergy production in temperate climate conditions, taking into account their growing conditions, productivity, biomass quality, and productive longevity. In order to facilitate the achievement of these objectives, a research was carried out to study the possibilities of the cultivation of reed canary grass (RCG) (*Phalaris arundinacea* L.) and festulolium (×*Festulolium*) by using the waste products from bioenergy production – biogas fermentation digestate and wood ash – as fertilisers. A field experiment was set up where an equivalent amount of plant nutrients (100 N; 80 P_2O_5; 160 K_2O, $kg \cdot ha^{-1}$) by different fertilisers was provided, compensating for the missing elements with mineral fertilisers. Two mowing regimes for grass harvesting were used: two-cut and one-cut. The results obtained showed that in this way, partial re-use of plant nutrients can be ensured: waste products provided a significant increase in grass dry matter yield (DMY) for both species. Furthermore, harvest analyses showed that when mowing at plant senescence, part of nutrients had already been transformed from the above-ground parts to the roots, ensuring plant nutrient re-use in the following seasons. Nutrient removal by yield using the two-cut mowing regime, especially for RCG, was significantly higher, compared to the one-cut regime. The highest removal was obtained for potassium: in the two-cut mowing regime, the removal with RCG was two times higher (202.3 $kg \cdot ha^{-1}$ K_2O) compared with the one-cut regime (92.5 $kg \cdot ha^{-1}$ K_2O). Similar tendencies were observed also for nitrogen and phosphorus, showing the ability of grasses to efficiently transfer the plant nutrients from aboveground biomass to roots during plant senescence, especially for RCG.

Keywords: festulolium, reed canary grass, biogas fermentation digestate, wood ash.

Introduction

Depletion of non-renewable energy resources along with increasing environmental pollution has a global impact on the climate. It forces immediately to change the currently applied methods for the use, consumption, and disposal of biological resources, focussing on their recycling. Fossil fuel and mineral resources, including those necessary for fertilisation production, are limited, they are irreversibly running out; therefore, they should be used as sustainably as possible. One of the options to limit the external agricultural inputs is to use the waste products (wood ash and biogas fermentation digestate) for fertilisation of crops used for bioenergy production. Instead of disposing digestate or ash from the boiler houses in landfills, it is necessary to find ways to use them effectively for fertilisation of field and forest crops, which allows reducing the utilisation costs as well as diminishing the environmental impacts. As a result, a partly closed plant nutrient cycle is formed, e.g., circulation of nutrients from the system "soil – energy crops – waste products – soil – energy crops etc.". The Action plan within the Green Deal of the EU includes an effective use of resources by the realisation of climate-neutral economy, the restoration of biological diversity, and a substantial decrease in pollution. Until 2030, it is envisaged to decrease plant nutrient losses by 50%, at the same time ensuring that soil fertility does not decline [1]. This means reducing fertiliser use by at least 20% by 2030. The European Commission has set a target of a 30% reduction in the use of non-renewable resources in fertiliser production [2], because a great amount of fossil energy for this purpose is used. That is why as much as possible should be done to find the ways for substituting plant nutrients in mineral fertilisers with those in waste products. More attention should be paid to the fact that waste products are returned back to the crop growing cycle, to the field from where they were taken away with the harvest.

It is recognized that wood ash and digestate are rich in plant nutrients; therefore, they could be a good alternative to commercial fertilisers [3-6]. Digestate contains many micro- and macro-elements important for plant growth, including mineral nitrogen (more than 60% of total N), phosphorus and potassium, therefore it·has a great potential as an organic fertilizer with high bioavailability [7; 8]. Wood ash, on the other hand, contains all the macro and micro nutrients necessary for the physiological processes of plants, with the exception of nitrogen [6]. Many minerals in ash are in the form of oxides

DOI: 10.22616/ERDev.2022.21.TF107

and hydroxides, some of which are readily soluble in water and cause a strong alkaline reaction [9], so ash also acts as a liming agent. Due to the lack of information on the efficiency of fertilisation of waste products and their long-term effects on soil properties, studies are needed to determine the best fertiliser application methods, optimal application rates, and effects on grass yield and crop quality.

Rational use of plant nutrients as well as fertiliser planning includes the consideration of different aspects such as plant nutrient uptake specifics by particular crops, removal with harvest, "crop – soil – fertiliser" interactions, etc. Tall growing perennial grasses such as reed canary grass (*Phalaris arundinacea* L.) and festulolium (×*Festulolium*) have a wide range of use – they can be used both for fodder production and bioenergy, as well as for ecological and social purposes.

The aim of the experiments was to find the possible use of wood ash and digestate in grass fertilisation, to compare their fertilisation efficiency with commercial fertilisers, assessing the possibility of partially replacing them, as well as to evaluate the differences in plant nutrient removal from soil with above-ground grass biomass under different fertiliser treatments using different grass mowing regimes.

Materials and methods

The research was carried out at Skriveri Research Institute of Agriculture of the Latvia University of Life Sciences and Technologies during 2012-2016. The soil in the experimental field was Endocalcaric Katostagnic Glossic Retisol [10], fine sandy loam. The main soil agrochemical parameters: medium organic matter content (29.1-34.3 $g \cdot kg^{-1}$), pH KCl 5.9-6.5, very high phosphorus content (235.3-352.3 $mg \cdot kg^{-1}$ P_2O_5), and medium plant-available potassium content (127.5-155.9 $mg \cdot kg^{-1}$ K_2O).

Five different treatments for reed canary grass (*Phalaris arundinacea* L.) 'Bamse' and festulolium (×*Festulolium*) 'Felina' were compared using a randomised block design in four replicates. The same amount of plant nutrients (100 $kg \cdot ha^{-1}$ N; 80 $kg \cdot ha^{-1}$ P_2O_5; 160 $kg \cdot ha^{-1}$ K_2O) by different fertilisers was provided using: commercial or mineral fertilisers (MF), wood ash (WA), biogas fermentation residue or digestate once (D1), and biogas fermentation residue or digestate twice (D2) a season. In the sowing year, fertiliser rates were halved and only 50 $kg \cdot ha^{-1}$ N, 40 $kg \cdot ha^{-1}$ P_2O_5, and 80 $kg \cdot ha^{-1}$ K_2O were applied. No-fertiliser or control option was also included to compare the fertilisation efficiency. Full rate of fertilisers in early spring just after vegetation renewal was applied in the treatments MF, WA, and D1. In option D2, a half of the dose was used in spring, and the other half was used in fall after grass mowing. For balancing of nutrients in digestate and WA treatments, if necessary, mineral fertilisers (ammonium nitrate, single superphosphate, potassium chloride) were used (Table 1).

Table 1

Plant nutrients supplemented with mineral fertilisers to reach NPK 100:80:160

Option	Sowing year, $kg \cdot ha^{-1}$			Years of use (1^{st}-3^{rd}), $kg \cdot ha^{-1}$		
	N	P_2O_5	K_2O	N	P_2O_5	K_2O
Wood ash (WA)	50	22	–	99	61	–
Digestate (D1, D2)	–	–	13	–	38–66	54–87

In the sowing year, fertilisers were incorporated into the soil before grass sowing. Afterwards, in the following years, all kinds of fertilisers were top-dressed without incorporation. The grasses were sown using a "Nordsten NS-1025" seeder; the sowing rate was 12 $kg \cdot ha^{-1}$ for RCG and 15 $kg \cdot ha^{-1}$ for festulolium. The total area of one plot – 43 m^2; of the harvest check plot – 10 m^2.

The one-cut and two-cut mowing regimes were used for grass dry matter yield (DMY) determination. If the one-cut regime was used, the biomass was harvested at plant senescence (the end of September or the beginning of October). If two cuts were used, then the first cut was done at the stage of full panicle/spike development (middle of June), and the second cut was at the stage of plant senescence.

The chemical analysis of grass dry matter was performed in the Laboratory of Forest Environment of the Latvia State Forest Research Institute "Silava". The following methods (according to the LVS ISO standard) were employed: total nitrogen – by the Kjeldahl method (LVS ISO 11261); phosphorus – in 0.2 M HCl extract, spectrophotometrically; potassium – in 0.2 M HCl extract after dry combustion. Plant nutrient (NPK) removal was calculated based on the grass dry matter yield and its chemical composition.

ANOVA was used for data processing (Microsoft Office Excel software), and F-test was used for the assessment of the significance of means at $LSD_{0.05}$.

Results and discussion

The application of all fertilisers produced considerably higher dry matter yields compared to the yield of control (without fertilisers). In the two-cut mowing regime, DMY varied from 5.64 $t \cdot ha^{-1}$ to 8.14 $t \cdot ha^{-1}$ for reed canary grass (RCG), and from 3.63 $t \cdot ha^{-1}$ to 5.34 $t \cdot ha^{-1}$ for festulolium (three-year average). In the one-cut mowing regime, DMYs were higher – they varied from 6.24 $t \cdot ha^{-1}$ to 8.11 $t \cdot ha^{-1}$ for RCG, and from 3.98 $t \cdot ha^{-1}$ to 7.02 $t \cdot ha^{-1}$ for festulolium (Table 2). Significantly higher DM yields in both mowing regimes for both species were obtained using mineral fertilisers (MF) and wood ash (WA).

Table 2

Dry matter yield ($t \cdot ha^{-1}$) in different mowing regimes (three-year average)

Treatment/ Option	*Phalaris arundinacea* L.		×*Festulolium*	
	two-cut regime	one-cut regime	two-cut regime	one-cut regime
Control (C)	3.87 ± 0.17	4.6 ± 0.33	2.09 ± 0.24	2.43 ± 0.18
Mineral fertilisers (MF)	**7.91** ± 0.38	**8.11** ± 0.19	**5.06** ± 0.31	**6.85** ± 0.19
Wood ash (WA)	**8.14** ± 0.67	**8.08** ± 0.40	**5.34** ± 0.41	**7.02** ± 0.52
Digestate 1× (D1)	5.71 ± 0.33	6.24 ± 0.31	3.63 ± 0.17	4.39 ± 0.34
Digestate 2× (D2)	5.64 ± 0.25	6.43 ± 0.29	3.80 ± 0.29	3.98 ± 0.25
$LSD_{0.05}$	1.37	0.98	0.92	1.11

Comparing the differences in DMY in both mowing regimes, it can be concluded that more productive grass swards were obtained using the one-cut mowing regime. The increase in DMY for RCG ranged on average from 0.2 $t \cdot ha^{-1}$ in the MF option to 0.79 $t \cdot ha^{-1}$, using the digestate twice a season (D2). The increase in DMY using the one-cut mowing regime for festulolium was found to be even higher – it ranged from 0.2 $t \cdot ha^{-1}$, using digestate twice a season, (D2) to 1.68 and 1.79 $t \cdot ha^{-1}$ in WA and MF options, respectively (Fig. 1).

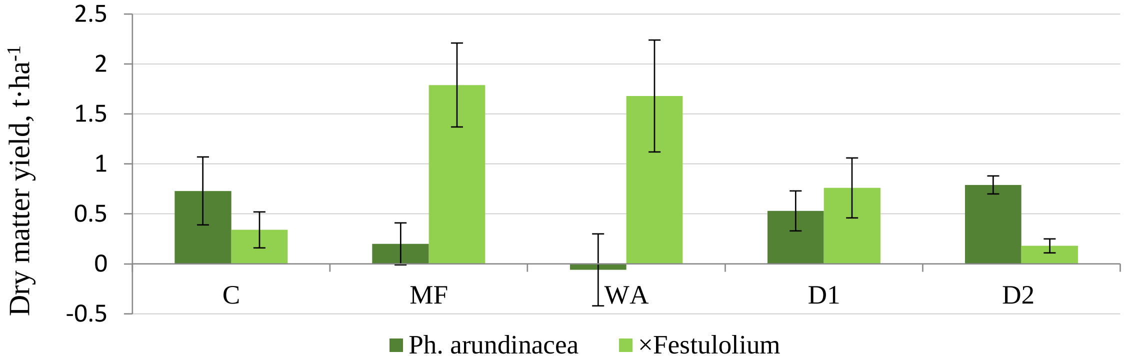

Fig. 1. **Differences in dry matter yield using one-cut mowing regime, compared to two-cut mowing regime, $t \cdot ha^{-1}$ (error bars indicate the standard errors)**

The nitrogen (N) content of grass dry matter varied depending on the species and the fertiliser type, as well as on the mowing regime. It ranged from 11.97 $g \cdot kg^{-1}$ N (RCG, D2) to 15.91 $g \cdot kg^{-1}$ N (festulolium, MF), using the two-cut mowing regime; and from 5.94 $g \cdot kg^{-1}$ N (RCG, D2) to 11.45 $g \cdot kg^{-1}$ N (festulolium, MF), using the one-cut regime. When mowing once a season during plant senescence, the N content in plant dry matter decreased significantly for both species: by 35-50% for RCG and by 15-30% for festulolium, depending on the treatment. A higher nitrogen content in both mowing regimes was found using wood ash (WA) and mineral fertiliser (MF) treatments (Table 3). No significant differences between species were found using the two-cut mowing regime; however, in the one-cut regime, a significantly lower N content was for RCG.

The phosphorus (P_2O_5) content in grass dry matter was comparatively low and varied on average from 4.28 $g \cdot kg^{-1}$ (festulolium, WA) to 6.73 $g \cdot kg^{-1}$ P_2O_5 (RCG, D2), using the two-cut mowing regime; and from 2.92 $g \cdot kg^{-1}$ (RCG, WA) to 4.85 $g \cdot kg^{-1}$ P_2O_5 (RCG, control), using the one-cut mowing regime. A significantly lower content of phosphorus for both species was found using the one-cut mowing regime, i.e., it decreased by 23-48% for RCG and by 7-32% for festulolium, depending on the treatment.

A comparison between species showed that a lower phosphorus content was for festulolium, especially in the two-cut mowing regime.

Table 3

Chemical composition of grass dry matter in different mowing regimes

Treatment/ Option	N, g·kg^{-1}		P_2O_5, g·kg^{-1}		K_2O, g·kg^{-1}	
	two-cut	one-cut	two-cut	one-cut	two-cut	one-cut
Phalaris arundinacea L.						
Control	13.23 ± 1.13	6.53 ± 0.35	6.29 ± 0.09	4.85 ± 0.39	21.04 ± 1.02	7.98 ± 0.55
MF	12.29 ± 0.07	8.05 ± 0.70	5.40 ± 0.09	3.07 ± 0.23	20.28 ± 0.34	8.34 ± 0.23
WA	14.04 ± 0.37	7.87 ± 0.89	5.43 ± 0.17	2.92 ± 0.07	20.21 ± 1.16	7.94 ± 0.60
D1	12.72 ± 0.85	6.75 ± 1.06	6.45 ± 0.41	3.88 ± 0.27	22.26 ± 1.07	8.83 ± 0.36
D2	11.97 ± 0.05	5.94 ± 0.66	6.73 ± 0.19	3.52 ± 0.16	21.90 ± 0.71	9.54 ± 1.30
×*Festulolium*						
Control	12.03 ± 0.33	9.38 ± 0.99	5.02 ± 0.10	3.62 ± 0.21	20.94 ± 0.80	12.65 ± 2.49
MF	15.91 ± 0.76	11.45 ± 0.53	4.63 ± 0.24	3.14 ± 0.19	26.53 ± 0.44	15.94 ± 1.02
WA	15.76 ± 0.79	11.10 ± 0.28	4.28 ± 0.16	3.97 ± 0.09	24.32 ± 1.03	17.61 ± 0.92
D1	13.24 ± 0.29	9.66 ± 0.51	4.83 ± 0.38	3.77 ± 0.05	26.13 ± 0.90	17.26 ± 0.05
D2	12.46 ± 0.48	10.69 ± 0.75	4.93 ± 0.27	3.92 ± 0.23	25.45 ± 1.68	14.63 ± 1.64

The potassium (K_2O) content varied from 20.21 g·kg^{-1} K_2O (RCG, WA) to 26.53 g·kg^{-1} K_2O (festulolium, MF), using the two-cut mowing regime; and from 7.98 g·kg^{-1} N (RCG, Control) to 17.61 g·kg^{-1} N (festulolium, WA), using the one-cut regime (Table 3). A significantly lower potassium (K_2O) content was found in the one-cut regime, where it was 57-62% lower for RCG and 28-43% lower for festulolium. In the two-cut mowing regime, a higher potassium content was found in the 1st cut. When mowing during plant senescence, the potassium content decreased on average 2-4 times compared to the 1st cut. The comparison of grass species showed that a lower potassium content in all cuts was for RCG. Although the results varied by mowings, a higher potassium content was observed when digestate fertiliser was used. It could have been affected by the high plant available potassium content in the digestate. Other researchers also reported higher potassium contents found in the grass fertilised with potassium [11-13].

The amount of plant nutrients which was removed from the field with harvested above-ground grass biomass depended on both the dry matter yield and the chemical composition. Therefore, using the one-cut mowing regime, NPK removal for RCG reduced on average two times compared to that of the two-cut mowing regime (Fig. 2). The main reason for these differences was the changes in the chemical composition of grass dry matter, as the differences in DMY of RCG between mowing regimes were less pronounced. This demonstrates the expressed specificity of RCG to transfer plant nutrients from above-ground biomass to the roots during plant senescence. Festulolium shows similar, though less pronounced, trends in nutrient transport. The obtained data demonstrate certain differences in NPK uptake and utilisation between both grass species.

Potassium removal was the highest for RCG: over a three-year period, it varied from 92.6 to 207.3 kg·ha^{-1} K_2O in the two-cut mowing regime and from 45.2 to 80.8 kg·ha^{-1} K_2O in the one-cut mowing regime. Whereas for festulolium, similar amounts of potassium were removed in both mowing regimes: 43.4–115 kg·ha^{-1} K_2O in the two-cut mowing regime and 38.6–134.6 kg·ha^{-1} K_2O in the one-cut mowing regime. This can be explained by the fact that festulolium had a significantly higher DMY when the one-cut mowing regime was used. The nitrogen removal was slightly lower compared with potassium removal: 54.0–142.9 kg·ha^{-1} N and 39.0–69.1 kg·ha^{-1} N for RCG in the two-cut and one-cut mowing regime, respectively; and 23.2–73.3 kg·ha^{-1} N and 22.1–78.7 kg·ha^{-1} N for festulolium in the two-cut and one-cut mowing regime, respectively.

The removal of phosphorus, compared to the nitrogen and potassium removal, was notably lower: 24.2-48.0 kg·ha^{-1} P_2O_5 and 21.0-26.5 kg·ha^{-1} P_2O_5 for RCG in the two-cut and one-cut mowing regime, respectively; and 9.4-19.8 kg·ha^{-1} P_2O_5 and 6.0–12.9 kg·ha^{-1} P_2O_5 for festulolium in the two-cut and one-cut mowing regime, respectively.

The data obtained show the characteristic pattern of grass species in the consumption and re-use of plant nutrients. Studies elsewhere have also shown that in the autumn most of the plant nutrients from aboveground biomass of RCG move to the roots, thus largely providing plants with nutrients needed for the growth in the next season [14-16]. Being aware of that, it is possible to calculate more precise fertiliser doses to a specific grass species under specific conditions of use and thus help more efficiently achieve resource saving and re-use targets.

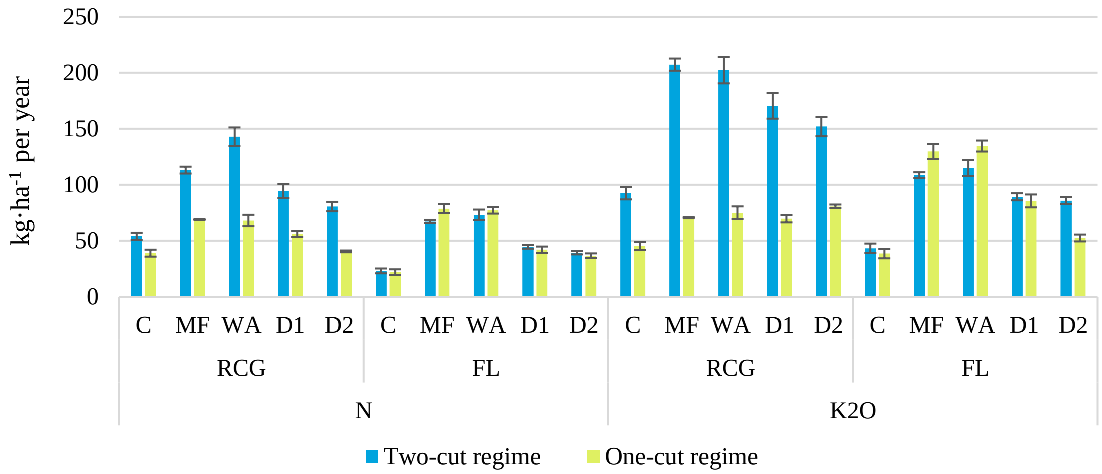

Fig. 2. **Nitrogen (N) and potassium (K_2O) removal on average per year, kg·ha^{-1}:** error bars indicate the standard errors

Conclusions

The fertilisers applied and the mowing regime used demonstrated a significant effect on the dry matter yield of grass and the removal of plant nutrients. The highest yields were obtained using wood ash and mineral fertilisers. Digestate also provided a significant increase in the yield compared to the non-fertilised option.

It was found that the grass species and the mowing regime had the greatest effect on the amount of plant nutrients removed: in the one-cut mowing regime of RCG, about two times less plant nutrients were removed than in the two-cut mowing regime. The research suggests that this was mainly dependent on the differences in the chemical composition of biomass: at plant senescence, NPK content decreased by 30-60% for RCG and by 20-40% for festulolium.

Differences in the dry matter content showed that grasses at plant senescence efficiently transferred plant nutrients from the plant aboveground parts to the roots; this process was more intense for RCG than for festulolium.

The use of grasses for bioenergy production and the subsequent use of waste products in fertilisation can contribute to the implementation of circular bioeconomy principles and the achievement of ecological goals. Postponing grass harvesting to later terms allows considerably saving the fertiliser use in the following years.

Acknowledgements

The research was supported by the ESF project No. 8.2.2.0/20/I/001 “LLU Transition to a new funding model of doctoral studies”.

Author contributions

Conceptualization, S.R., A.K. and D.L.; methodology, S.R. and A.K.; investigation, S.R. and D.L.; data collection and processing, S.R.; writing – original draft preparation, S.R.; writing – review and editing A.K. and D.L. All authors have read and agreed to the published version of the manuscript.

References

[1] Communication from the Commission to the European Parliament. [online] [20.01.2021]. Available at: https://www.greenpeace.org/static/planet4-eu-unit-stateless/2020/05/3c9842bb-may2020-farm-to-fork-leak.pdf

[2] Chojnacka K., Moustakas K., Witek-Krowiak A. Bio-based fertilizers: A practical approach towards circular economy. Bioresource Technology, Vol. 295, 2020, pp. 1-11.
[3] Möller K., Müller T. Effect of anaerobic digestion on digestate nutrient availability and crop growth: A review. Engineering in Life Sciences, Vol. 12, 2012, pp. 242-257.
[4] Vassilev S.V., Baxter D., Andersen L.K., Vassileva C.G. An overview of the composition and application of biomass ash. Part 1. Phase-mineral and chemical composition and classification. Fuel. Vol. 105, 2013, pp. 40-76.
[5] Risberg K., Cederlund H., Pell M., Arthurson V., Schnürer A. Comparative characterization of digestate versus pig slurry and cow manure - chemical composition and effects on soil microbial activity. Waste Management, Vol. 61, 2017, pp. 529-538.
[6] Lazdiņa D., Bebre I., Dūmiņš K., Skranda I., Lazdins A., Jansons J., Celma S. Wood ash – green energy production side product as fertilizer for vigorous forest plantations. Agronomy Research, Vol. 15, 2017, pp. 468-477.
[7] Dubrovskis V., Adamovičs A. Bioenerģētikas horizonti (Bioenergy horizons). Jelgava: LLU, 2012, p. 352 (In Latvian).
[8] Kataki S., Hazarika S., Baruah D.C. Assessment of by-products of bioenergy systems (anaerobic digestion and gasification) as potential crop nutrient. Waste Management. Vol. 59, 2017, pp. 102-117.
[9] Ljung A., Nordin A. Theoretical feasibility for ecological biomass ash recirculation: chemical equilibrium and heavy metals during combustion. Environmental Science & Technology, Vol. 31, 1997, pp. 2499-2503.
[10] WRB 2014. World reference base for soil resources. World Soil Resources Reports No. 106. FAO, 2015, 189 p.
[11] Bērziņš P., Antonijs A., Rumpāns J. Minerālmēslu efektivitāte daudzgadīgo zāļu zelmenī (Efficiency of mineral fertilizers on perennial grasses). Latvian Journal: Agronomijas Vēstis. Nr. 1, 1999, pp. 24-29 (In Latvian).
[12] Kayser M., Isselstein J. Potassium cycling and losses in grassland systems: A review. Grass and Forage Sciences, Vol. 60, 2005, pp. 213-224.
[13] Adamovics A., Platace R., Gulbe I., Ivanovs S. Influence of fertilisers on chemical content of energy grass biomass. Proceedings of International Scientific Conference "Engineering for Rural Development", Jelgava, 2017, p. 98-102.
[14] Partala A., Mela T., Esala M., Ketoja E. Plant recovery of 15N-labelled nitrogen applied to reed canarygrass grown for biomass. Vol. 61, 2001, pp. 273-281.
[15] Lindvall E., Gustavsson A.M., Samuelson R., Magnusson T., Palmborg C. Ash as a phosphorus fertilizer to reed canary grass: effects of nutrient and heavy metal composition on plant and soil. GCB Bioenergy, Vol. 7, 2015, pp. 553-564.
[16] Rancane S., Karklins A., Lazdina D., Berzins P., Bardule A., Butlers A., Lazdins A. Biomass yield and chemical composition of Phalaris arundinacea L. using different rates of fermentation residue as fertiliser. Agronomy Research, Vol. 15, 2017, pp. 521-529.