ACTA UNIVERSITATIS AGRICULTURAE ET SILVICULTURAE MENDELIANAE BRUNENSIS

Volume 71 9 Number 3, 2023

INTERANNUAL EFFECT OF DIGESTATE FERTILIZATION ON YIELDS AND QUALITY OF WINTER RYE FORAGE

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Link to this article: https://doi.org/10.11118/actaun.2023.009

Received: 21. 2. 2023, Accepted: 3. 5. 2023

Abstract

In two-year pilot field experiments (harvest 2021–2022) we explored the interannual effect of digestate fertilization (30 t/ha prior to sowing) on yields and some qualitative parameters of winter rye (KWS Progas) forage silage. The yields of the aboveground biomass differed insignificantly on a year to year basis: 31.07 t/ha FM in 2021 and 25.17 t/ha FM in 2022 (4.9 t/ha DM in 2021 and 4.2 t/ha DM in 2022) although the dry matter content differed significantly: 15.6% in 2021 and 16.6% in 2022. Interannual differences in the qualitative parameters were significant for these characteristics (% of DM) – $N_{tot.}$: 2.2% (2021) versus 1.9% (2022); crude protein: 13.8% (2021) versus 11.7% (2022); ash matter: 6.5% (2021) versus 7.6% (2022); NDF: 63.8% (2021) versus 57.8% (2022). Differences of ADF were insignificant 37.0% (2021) versus 35.2% (2022). The results show that the applied dose of digestate (150 kg N/ha plus other nutrients) is sufficient to achieve an adequate yield and quality of winter rye forage. The influence of the year was significant for dry matter content and most of the monitored qualitative parameters, especially from the point of view of the intensity and distribution of air temperatures and rainfall. In addition, the residual nutrients in the soil after the winter rye forage harvest (N, K) will be utilized by the subsequently grown maize in the dual rye-maize system.

Keywords: winter rye, silage, quality, dry matter, crude protein (CP), ash content, acido-detergent fibre (ADF), neutral-detergent fibre (NDF)

INTRODUCTION

In the past, rye (*Secale cereale* L.) used to be the third most frequently grown cereal for fresh forage, after maize and oats (Petr *et al.*, 2008). Stoskopf (1985) recommended rye as a cover crop in cooler climates because rye is a winter-hardy crop and resumes growth quickly in early spring. Compared with similar small grain cover crops, rye is more cold-tolerant (Willick *et al.*, 2021), is higher-yielding (Haramoto, 2019), and may be more efficient at nitrogen uptake (Fisher *et al.*, 2011). Cereals, such as rye, are considered the best choice due to their winter hardiness and ability to scavenge nitrogen (Dabney *et al.*, 2001; Kaspar *et al.*, 2007; Lacey and Armstrong, 2015; Tewolde *et al.*, 2016). Since rye reaches the optimal harvest stage sooner than other cereals it can be harvested as a cover crop for spring crops (Maloney *et al.*, 1999). Stute *et al.* (2017) reported that rye grown as a cover crop prevented water and wind erosion and provided a sufficient amount of fodder in the case of drought. Rye provides a good ground cover and efficiently reduces soil erosion (Kaspar *et al.*, 2001); in addition, rye biomass helps to build organic matter in the soil (Kaspar *et al.*, 2006). Rye can also provide environmental benefits on the farm (Krueger *et al.*, 2011, 2012; Ramcharan and Richard, 2017) by improving soil (Blanco-Canqui *et al.*, 2017; Moore *et al.*, 2014) and water quality (Malone *et al.*, 2018). Rye can also generate agronomic benefits, including by increasing shading in spring and thus reducing weed competition for subsequent crops (Liebert *et al.*, 2017; Barnes and Putnam, 1983). Without doubt the greatest advantage of rye is that it guarantees high yields in early term and it can be grown on erosionendangered land (Jatkauskas *et al.*, 2022); it is also important that it diversifies the crop rotation and distributes seasonal work. Today however winter rye is grown as a catch crop and is harvested as silage at the end of the stem elongation stage or at the beginning of ear formation, in warmer regions usually from first third of May to early June (Petr *et al.*, 2008). Winter rye is one winter-hardy grain that farmers can double-crop. Harvested at the boot stage before flowering, rye is an animal feed that is comparable to corn silage (Osborne, 2011). In the course of time the production of silage from whole rye plants has increased, because of its extensive root system it can easily cope with drought and can thrive on infertile soil. Rye is with the right harvest timing definitely a nutritive feed, highly digestible and rich in protein (Bíro *et al.*, 2020). In terms of dry matter yields and energy from one unit of area, the optimal date of harvesting rye is considered to be the stage of milk to milk-dought maturity. As the plant continues to grow and the stalk grows taller, the proportion of stalk in the plant increases, and so does the content of fibre with a high degree of lignification (Doležal *et al.*, 2019). According to Šimek *et al.* (2019) and Bíra *et al.* (2020) the outcome is poorer nutrient digestion and thus the energy value.

Dabney *et al.* (2001) describe cover crops as a rich source of organic matter and minerals, but also as a protection against erosion. The cultivation of cover crops or the so-called “dual system” (winter rye - maize seed), which is used to protect the soil from erosion, to reduce soil water evaporation and nutrient losses from the soil, and to supply primary organic matter through stubble, roots and their excreta, is becoming increasingly important agri-environmentally (Krueger *et al.*, 2011; Herbstritt *et al.*, 2022). The use of dual cropping systems can generally be considered as a method to reduce N losses through leaching from the soil (Everett *et al.*, 2019), by 40–70% compared to winter fallow (Tonitto *et al.*, 2006). Smith (2019) reported that when winter rye was harvested as a pre-crop before planting silage maize, there was a reduction in silage maize yield compared to direct seeded maize. However, the combined yield and value of the two silage crops was greater than that of maize silage alone. The “dual system” is very beneficial for the environment as it increases soil cover, soil carbon accumulation and eliminates nitrate accumulation (Doran, 2018). However, winter rye in a dual cropping system can reduce profitability due to a decrease in silage yield (Thelen and Leep, 2002), especially depending on climatic conditions (Singer *et al.*, 2007). In the case of a decrease in silage yield after rye, Raimbault *et al.* (1991) cites reduced soil moisture, insufficient nitrogen (Tollenaar *et al.*, 1993), many post-harvest residues (Raimbault *et al.*, 1991), and allelopathic effects of rye on silage (Raimbault *et al.*, 1990; Tollenaar *et al.*, 1992). In the case of rye use as a cover crop, the environmental benefits are immediate and long-term economic benefits are obtained by conserving soil resources (Reicosky and Forcella, 1998), but the economic benefits of rye as a forage crop are not achieved. Reduced silage yields were observed in a dual winter rye-maize system compared to silage harvest alone, but total forage production was higher in a dual rye-maize system (Raimbault *et al.*, 1990; Tollenaar *et al.*, 1992), and thus the dual system offers the potential for increased profitability.

Winter rye is also a suitable substrate for fermenters of bio-gas plants (so-called energy rye). Harvested at full plant growth rye supplies high biomas yield, that is why stands of rye intended for the production of biogas are harvested no sooner then after ear emergence (Skládanka *et al.*, 2014). Alternatively, rye can be used in bioenergy systems to co-produce energy as well as byproducts that may have value as animal feed (Shao *et al.*, 2015; Heggenstaller *et al.*, 2008).

Digestate from biogas plants (BGP) applied prior to sowing or during vegetation is a suitable organic fertilizer for the nutrition and fertilization of rye because it contains all macro- and micro-biogenic elements, particularly N and K. It is a fertilizer rapidly releasing nitrogen and its C:N ratio is lower than 10 (Lošák *et al.*, 2013, 2014). Since the prices of fertilizers have increased sharply in the past year or fertilizers have become scarce (or a combination of both) digestates are now highly valued in many farms (Lošák *et al.*, 2022). Digestates (fugates) contain more mineral nitrogen (usually 5–6% in dry weight) and less organic carbon than the non-digested input materials (Johansen *et al.*, 2013), and C/N ratio in digestate can be ten times lower than that of farmyard manure (Alburquerque *et al.*, 2012). Digestate has the capacity to compete favorably with inorganic fertilizers for better crop productivity, yield, and enhancement of soil health (Odlare *et al.*, 2011; Verdi *et al.*, 2019). Digestate hold multiple functions in their beneficial roles to both the soil and the plants/crops. In the first instance, digestate is known to have fertilizing attributes that help in the productivity of the plants due to the availability of important nutrients necessary for plant growth. Secondly, their influence on soil health cannot be overemphasized as they play huge roles that promote soil efficiency through nutrient cycling in the soil, carbon transformation, and soil structure maintenance (Przygocka-Cyna and Grzebisz, 2018). However, studies published so far have shown that digestate can be a good source of quickly available nitrogen and other macro- and micro- nutrients for plants and can partly replace cattle slurry application or mineral fertilization (Garfí *et al.*, 2011; Alburquerque *et al.*, 2012; Šimon *et al.*, 2015). Eickensheidt *et al.* (2014) and Vázquez-Rowe *et al.* (2015) also recommend the use of digestate as a fertilizer instead of mineral fertilizers. Liu *et al.* (2009) and Chiew *et al.* (2015) reported that the application of digestate can increase soil fertility and improve the nutritional status of plants, especially macronutrients (N, P, K), and also some micronutrients. Chiew *et al.* (2015) are of the opinion that the use of digestate as a fertilizer can increase the content of macro- and microelements in the soil and in plants. Rodhe *et al.* (2006), Kapuinen *et al.* (2007) and Bermejo *et al.* (2010) point out that the application of digestate must be properly timed to avoid nitrogen losses due to the fact that organically fixed nutrients in digestate are released and thus available to plants after mineralization of organic matter. The addition of digestate to the soil must be adapted to the requirements of the plants and the climatic conditions in order to achieve maximum nutrient efficiency, the sufficient content of which then leads to higher crop yields. When fertilising with digestates it is therefore necessary to apply to the soil at the same time other sources of primary (labile) organic matter of good quality – by ploughing down all post-harvest residues, fertilising with farm manure, compost and straw (Cigánek *et al.*, 2010). Field and pot trials to date report positive effects of digestate application to arable land in terms of yields (Stinner *et al.*, 2008; Arthurson, 2009; Gunnarsson *et al.*, 2010) or no significant effects (Ross *et al.*, 1989; Båth and Elfstrand, 2008). Makádi *et al.* (2012) confirmed that due to the high available nutrients content, digestate application resulted in significantly higher aboveground biomass yields in the case of winter and spring wheat than the farmyard manure and undigested slurry treatment.

The objective of the present study was to investigate the year-to-year impact of an application of a constant amount of digestate as a fertilizer on yields and some qualitative parameters of winter rye silage in two-year pilot field experiments.

MATERIALS AND METHODS

The field experiments were established on plots of the Agricultural Enterprise Nové Město na Moravě (Czech Republic) farming on 3 800 ha of agricultural land (1 500 ha permanent grassland, 2 300 ha arable land) in the Žďár nad Sázavou district. The altitude ranges between 550 and 730 m above sea level, the altitude of the experimental locality is 594 m above sea level.

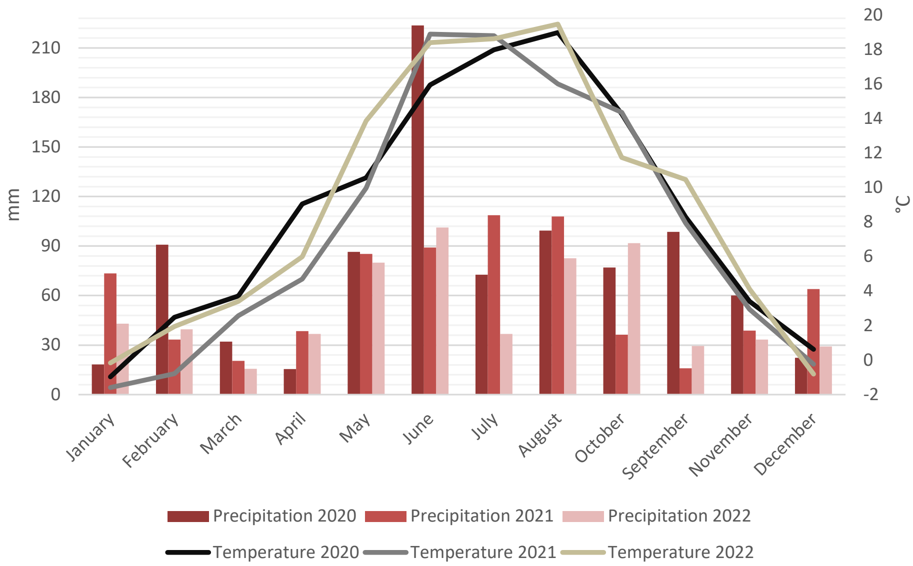
Fig. 1 shows the average monthly temperatures and total precipitation in the two years of the experiment. In both years the digestate was applied to the soil surface prior to sowing rye (11 September 2020; 23 September 2021) at an amount of 30 t/ha using a hose applicator and was then ploughed in (the depth of tillage was 30 cm – normal winter ploughing with organic fertiliser). Deeper incorporation (15–25 cm) is recommended to increase the nitrogen utilization efficiency and to reduce N losses (Maucieri *et al.*, 2016). The chemical composition of the digestate was as follows: dry matter content 6.52%, combustible substances content 72.54% in DM, pH 7.66, nutrients (% in FM): N_{tot} 0.50%, $N\text{-}NH_4^+$ 0.291%, P 0.063%, K 0.569%, Ca 0.183%, Mg 0.049%. Tab. I shows a positive nutrient balances for N and K after application of digestate, which will be used by subsequently grown maize.

The soil type of the locality is cambisol with cambic brown (braunified) horizon. Tab. II shows the basic agro-chemical soil characteristics before the establishment of the experiment (digestate application). Winter rye, variety KWS Progas, was sown out on 18 September 2020 and 29 September 2021 using a sowing rate of 100 kg/ha. In both years we used the pneumatic sowing machine Väderstad Rapid A 800S. In both years winter rye was harvested in the milk-dought stage on 17 May 2021 and on 10 May 2022. For statistical evaluations the crop was harvested manually with 3 repetitions on 0.3 m^2 (aboveground biomass) in the following way - cutting the crop 2 cm above ground and biomass was cut, weighed, dried and homogenised before the laboratory analyses.

Chemical analyses of the soil and plant biomass were conducted in a laboratory according to standard accredited procedures, as described below. The soil was extracted according to Mehlich III. The content of available phosphorus in the extract was determined colorimetrically, potassium by flame photometry and magnesium using the AAS method. Exchangeable soil reaction was determined by potentiometric measurement of the activity of hydrogen ions in the extract with 0.01 M $CaCl_2$. The wet method, the so-called modified Tyurin method, was used to determine the content of organic carbon (C_{ox}) (Valla *et al.*, 2002). The content of soil sulphur was determined in an ammonia acetate solution.

I: *Nutrient balances in 2021 and 2022*

Year	Nutrient	Inputs (kg/ha)	Outputs (kg/ha)	Balance (kg/ha)
2021	N	150	108.3	+ 41.7
	P	19	19.8	- 0.8
	K	171	151.4	+ 19.6
2022	N	150	78.6	+ 71.4
	P	19	22.5	- 3.5
	K	171	137.8	+ 33.2



1: *Average monthly temperatures (°C) and total precipitation (mm) in 2020–2022*

II: *Agrochemical soil analysis before digestate application in 2020–2021*

Year	Depth cm	pH ($CaCl_2$)	N_{min} mg/kg	Nutrient content mg/kg					Humus %
				P	K	Ca	Mg	S	
2020	0–30	5.94	21.2	87.5	390.0	2920	236.4	2.5	2.2
2021	0–30	6.54	20.3	52.5	263.0	2650	293.0	2.3	3.8

Kjeldahl's method was used to determine the total N content in the biomass samples. Crude protein (CP) denotes the content of nitrogen in the biomass multiplied by coefficient 6.25, the ash content was determined by dry oxidation. From the chemical point of view fibre can be determined or defined in various ways – our samples were determined as the difference between the combustible fraction and the leachate. Van Soest *et al.* (1991) considered fibre as cell wall composed of cellulose, hemicellulose and lignin, together creating fibre soluble in a neutral detergent (NDF). In addition to NDF also fibre soluble in an acid detergent, the so-called acido-detergent (ADF), was determined. The principle of the method is to separate ADF from the neutral matrix (NDF) based on acid hydrolysis of NDF and parallel denaturation of the matrix protein (Třináctý *et al.*, 2013).

The obtained results were statistically processed by one-factor and multi-factor analysis of variance (ANOVA) followed by testing using Fisher's least significant difference (LSD) at $p < 0.05$ in Statgraphics Plus 5.1.

RESULTS AND DISCUSSION

Rye Yields and Qualitative Parameters

The two-year pilot field experiments showed significant interannual differences among some monitored parameters (Tab. III) it being the so-called impact of the year. This is common and anticipated phenomenon based especially on the intensity and distribution of precipitation and air temperatures in the course of the year and is shown in Fig. 1. The total precipitation (September–April) in 2020/2021 was 423.8 mm, while in the following growing season 2021/2022 (also September–April) the total precipitation was 289.7 mm, representing 68.3% of the 2020/2021 period. The graph shows that the total precipitation in September and October 2020 (175.6 mm) was significantly higher than in 2021 (52.3 mm), and the precipitation total in 2021 represented 29.8% of the precipitation for the same period in 2020. The average monthly temperature in spring 2021 was 1.2 °C and in 2022 it was 2.8 °C, which, combined with the lower precipitation (January-April) in 2022, also contributed to the lower yield in 2022. In tandem with the selected hybrid and date of harvest this factor may have a significant impact on the yield and qualitative parameters (nutritive values) of rye silage.

The dry matter content of the aboveground biomass of winter rye ranged significantly from 15.6% (2021) to 16.6% (2022), Tab. III; Zeman *et al.* (2006) reported that the nutritive value of rye silage was high if the dry matter content was 17.1%, while Petrikovič *et al.* (2000) alleged that it was high if the dry matter content was 19.5%. However, according to other authors the optimal dry matter content at

III: *Yield and quality parameters of winter rye silage*

Years	Yield in FM (t/ha)	Yield in DM (t/ha)	DM (%)	N_{tot} (% in DM)	CP (% in DM)
Values from literature *	23.0–33.0	4.0–10.0	16.0–35.0	2.02	11.5–14.0
2021	31.07 a	4.9 a	15.6 a	2.21 b	13.8 b
2022	25.17 a	4.2 a	16.6 b	1.87 a	11.7 a
CR 2021/2022**	23.89/21.02	–	–	–	–
SR 2021/2022***	16.31/15.30	–	–	–	–

Different letters (a, b) indicate significant differences between years ($p < 0.05$)
FM – fresh matter, DM – dry matter, CR – Czech Republic, SR – Slovak Republic
* Kacerovský *et al.* (1990); Hrabě *et al.* (2004); Mikyska and Valenta (2007)
* Petrikovič *et al.* (2000); Gálik *et al.* (2018); Vavrišínová *et al.* (2021)
** Horáková (2021); Horáková (2022)
*** Rozborilová and Babincová (2021); Babincová and Rozborilová (2022)

harvest at the stage of milk-dought maturity was around 28–30%, and in terms of yields of dry matter and energy per area unit this is considered to be the optimal date for rye harvest. Třináctý *et al.* (2013) stated that if the plants do not achieve the required content of dry matter it is necessary to let them dry up to a minimal 35% content of dry matter.

Although the dry matter content (%) differed significantly between two years, year-to-year yields of the aboveground biomass in fresh matter (31.1 t/ha in 2021 versus 25.2 t/ha in 2022 in FM) and also in dry matter (4.9 t/ha in 2021 versus 4.2 t/ha in 2022 in DM) differed insignificantly. (Tab. III). A number of factors influences total yields and their quality; one of the most important is an adequate nutrition and fertilization. Digestates from biogas stations contain all the macro- and micro-nutrients and so they are suitable as organic fertlizers for winter rye, although their effect is more like the effect of combined mineral fertilizers. In contrast to farmyard manure digestates have a lower content of labile forms of organic matter. However, that is no obstacle when applied to haylage rye as rye has an extensive rooting system which substitutes (through its root hairs and secretion) labile primary organic substances which the digestates lack (Lošák *et al.*, 2014). From the agrochemical point of view the principle problem is that the digestate contains only a small amount of degradable organic matter (Kolář *et al.*, 2010). In recent years however we have seen that the effect of adequate precipitation during vegetation, or periods of drought, on yield performance has been increasing. (In)sufficiency of water affects both the effectiveness of nutrients from the applied fertilizers, in particular their solubility, uptake and transport in the plant, and microbial activity in the soil and thus the intensity of mineralization and intake of nutrients from organic fertlizers. In the present two-year experiments we were fortunate that the plants did not suffer long-term drought, although temperatures and precipitation did change.

The content of nitrogen in the biomass, or after recalculation the percentage of crude protein (% CP in DM), reflects the effect of the environment where fertilization plays an important role. Ammonium nitrogen (readily available and utilizable by plants) predominates in the digestate and also contains a proportion of organic nitrogen which must go through the process of mineralization if the plant is to utilize it and which is accomplished during pre-sowing application of digestate and mineralization in autumn. The contribution of digestate to the N availability in the soil presents an important argument for their application. Digestate is particularly rich in ammonium nitrogen (NH_4-N), a form of N that is readily available for uptake by plants (Jamison *et al.*, 2021). In our experiment the crude protein content (% CP in DM) in the aboveground biomass of rye (Tab. III) ranged between 13.8% (2021) and 11.7% (2022) and is in accord with Petrikovič *et al.* (2000) – 12.1% CP, and Třináctý *et al.* (2013) – 13.1% CP. Zeman *et al.* (2006) and Šimko *et al.* (2019) discovered that the nutritive value of silage rye was high when the CP content reached 13.3% in dry matter; this finding corresponds with our present results.

Ash, ADF and NDF in Silage Winter Rye

Interannual differences were discovered in the ash content and neutro-detergent fiber (NDF) only (Tab. IV). Some authors differ in their opinion of qualitative parameters in the rye biomass caused by the effect of several factors (growth stage and stage

IV: *Ash, ADF and NDF contents of winter rye silage*

Years	Ash % in DM	ADF % in DM	NDF % in DM
Values from literature *	6–10	23–44	35–65
2021	6.46 a	37.00 a	63.80 b
2022	7.60 b	35.20 a	57.80 a

Different letters (a, b) indicate significant differences between years ($p < 0,05$)

of development at harvest, hybrid, soil conditions, effect of the year,…), however our results are in accordance with available references.

The content of ash should not exceed 10% because higher values are usually caused by undesirable soil contamination of the green matter during harvest (Doležal, 2022). Třináctý *et al.* (2013) reported that the average values of ADF and NDF in the dry matter of the biomass of harvested cereals were 41.0% and 62.3%, respectively. According to Jatkauskas *et al.* (2022) average ADF and NDF values in the dry matter of silage rye harvested on three localities in the first decade of May were 23.4% and 43.2%, respectively. Stute *et al.* (2017) reported yields of rye amounting to 2.4 t/ha in dry matter; ADF and NDF in dry matter was 27.6% and 52.2%, respectively.

CONCLUSION

Based on results of two-year field experiments, digestate applied to winter rye forage prior to sowing at an amount of 30 t/ha proved to be sufficient in terms of biomass yield and its quality. In view of this finding digestate is a suitable and efficient organic fertilizer with readily available nitrogen and other macro- and microelements. The use of digestate is a cost-effective substitution for expensive mineral fertilizers, namely nitrogen, which is a very current topic now. Considering that winter rye forage is harvested in spring, usually in May, a very important factor for achieving high yields is the course of the weather i.e. the total amount and distribution of precipitation and temperature during vegetation especially. Residual nutrients in the soil after the winter rye forage harvest will be utilized by the subsequently grown maize in the dual rye-maize system which is an important economic-environmental benefit.

Acknowledgement

This publication could not have originated without the support of the Operational Programme Integrated Infrastructure for the project: Demand Oriented Research of Sustainable and Innovative Foodstuffs, Drive4SIFood 313011V336, jointly financed by the European Regional Development Fund.

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