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ORIGINAL PAPER

# The Effect of Oil-based Polymer Coated CAN Fertilizer on the Yield and Quality of *Triticum aestivum* L. and *Brassica napus* L.

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**Abstract**
The fertilization with nitrogen plays a crucial role in today's agriculture characteristic with a high demand for production. The utilization of coated fertilizers represents a possible option to lower the number of applications, lower the dose and limit the risk of environmental losses. The effect of conventional calcium ammonium nitrate (CAN) applied in a single application in blend (1:1 or 1:2) with oil-based polymer coated CAN in thicknesses of 4 ($cCAN_4$) or 6% ($cCAN_6$) by weight of the fertilizer on the yield and quality of winter wheat and oilseed rape was evaluate. The average yields of winter wheat were not significantly influenced by the examined fertilization in either the growing season (GS) or the experimental site. On the contrary, the qualitative parameters on average resulted in lower values in comparison with the control (split N fertilization), possibly due to the single application of nitrogen in early spring. The examined treatments significantly influenced the seed yield of oilseed rape in both GS and both experimental sites. On average, the highest yield of seed (2.8 t/ha) was observed on treatment $cCAN_4$ in a 1:2 ratio. This represents a significant increase by 24.8% compared to the control (2.2 t/ha). Similarly, to winter wheat, the qualitative parameter of oilseed rape (oil content) was lower after the examined blends with coated CAN. The fertilization of oilseed rape with blends of uncoated and coated CAN applied in the single application is a validate alternative to commonly used split nitrogen doses applied repeatedly during vegetation.

**Keywords** Control release fertilizers · Coating · Calcium ammonium nitrate · Winter wheat · Oilseed rape

## 1 Introduction

The global population is growing exponentially. It was estimated that the population will reach nearly 9.5 billion in the year 2050 (Yuan et al. 2022). This scenario may lead to almost double of the food demands, the production of agricultural crops should increase by up to 70%, according to some authors (Hemathilake and Gunathilake 2022). However, this would require a heavy reliance of crop production on the synthesis of mineral nitrogen fertilizers (Coskun et al. 2017) and doubling the nitrogen doses applied globally (Subbarao et al. 2012), which could possibly lead to a significant annual loss of nitrogen. One of the key elements is the harmonic fertilization by macro and micronutrients and the utilization of organic fertilizers to maintain optimal soil fertility. However, the most dominant nutrient is still nitrogen (synthetic). The application of mineral N fertilizers in agriculture accounts for more than half of every other fertilizer combined (IFA 2023). The positive effect of nitrogen on yield and quality is well-known, on the other hand, large amounts of nitrogen are often applied to agricultural ecosystems to meet the growing global demand for food production (Wang et al. 2021). The high mobility of nitrogen in the environment represents a possible significant loss of up to 70% (Tian et al. 2020). Studies have shown that crops use only 50% of the applied N effectively, while the rest is lost through various pathways to the surrounding environment (Govindasamy et al. 2023; Zhang et al. 2015). The efficiency of nitrogen application can possibly be increased if the fertilization is performed in the correct period of vegetation and meets the time of increasing plant demands (Bindraban et al. 2015). The NUE could be further influenced by

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the term of application, fertilization method, form of nitrogen contained in fertilizers, incorporation of fertilizers into the soil, and especially by the course of weather (Santillano-Cázares et al. 2018). Low NUE is related to low profitability of crop production (Lawrencia et al. 2021), decrease in soil fertility and reduced potential yield of cultivated crops. It is also environmentally unsafe and represents a possible risk to human and animal health due to the leaching of $NO_3^-$ (He et al. 2018), volatilization of $NH_3$, and emission of other N-containing gases (especially $N_2O$ and $NO_x$) (Hakeem et al. 2016). Therefore, improving the nitrogen use efficiency from fertilization should be the focus for sustainability in agriculture. The nitrogen loss, combined with an increased economic incentive for farmers to increase NUE associated with rising costs of mineral fertilizers, has placed an increased emphasis and imperative to implement nutrient management strategies that reduce nitrogen loss (Duff et al. 2022).

A globally used method to improve NUE in crop production is the split application of nitrogen contained in commonly available mineral fertilizers. Thus, nitrogen is usually applied in lower doses several times during the vegetation (or even before sowing especially for spring crops) with the goal of increasing yield and limiting the N loss; however, the additional applications represent a disadvantage (another field crossing, fuel, time, etc. (Anas et al. 2020). One of the more sophisticated possibilities to improve NUE is represented by the application of mineral fertilizers, which can adjust the release date, release period or release amount of contained nutrients according to the crop growth and development, or soil-weather conditions. According to the principle of nutrient release, these fertilizers can be classified as (1) slow-release fertilizers (SRF) with part of the nutrient in slowly soluble form (pattern of nutrient release is nearly unpredictable and remains subject to changes in soil type and climatic conditions) or (2) fertilizers with inhibitors of urease or nitrification (or both). Modern research is also focusing on the application of hydrogels, especially with natural and biodegradable polymers in combination with nutrients as a possible alternative (Kriška et al. 2023; Skarpa et al. 2023). Another group (3) are controlled-release fertilizers (CRF), where the pattern, quantity, and time of release can be within the limits predicted (Rajan et al. 2021). CRF is purposely designed coated or encapsulated fertilizers by water-insoluble, semipermeable, or impermeable-with-pores materials. Therefore, CRF release active fertilizing nutrients in a controlled, delayed manner in synchrony with the sequential needs of plants for nutrients. Thus, they provide enhanced nutrient efficiency along with enhanced yield and quality of products (Gil-Ortiz et al. 2020a; Liu et al. 2021; Zhu et al. 2020). The coating material should be able to slow down nutrient release to such a pace that a single application of CRF fertilizer can meet nutrient requirements of cultivated crops (Lawrencia et al. 2021). Application of CRF also has the potential to lower the fertilizer application dosage by 20–30% of the recommended value to achieve the same yield (Gil-Ortiz et al. 2020a). Generally, the controlled release mechanism depends on numerous factors such as the origin of the coating material, the type of CRF, agronomic conditions (temperature, moisture, pH) or even microbial activity (Lawrencia et al. 2021). CRF can be possibly coated by inorganic (e.g., sulphur, bentonite, phosphogypsum) or organic (polyurethane, polyethylene, alkyd resin, etc.) substances, super-absorbent materials, and even nanocomposites. Currently, one of the most effective methods of preparing CRF is by coating the surface of fertilizer with polyurethane materials. However, these coating materials are commonly linked with higher prices and origins from non-renewable petrochemical productions (Suryawanshi et al. 2019). Furthermore, the residue of polyurethane shells in soils is difficult to degrade and may cause a potential environmental risk (Hofmann et al. 2023). Therefore, there is a necessity for cheap, completely biodegradable, and renewable biobased materials (Heinrich 2019; Tian et al. 2021) that can also reduce dependence on fossil fuels (Smith et al. 2016). Nowadays, the ideal CRF should be coated with a natural (e.g., vegetable oil, starch, chitosan, cellulose) or at least semi-natural, environmentally friendly material (Mikula et al. 2020). Especially vegetable oil is considered to be the most significant material for bio-based polymers, and polymeric material preparation to be an adequate substitution for polyurethanes (Sun et al. 2019). Several studies have shown that the utilization of oil-based polymers as coating materials results in gradual, uniform nutrient release and proved a high rate of biodegradability (Feng et al. 2019; Škarpa et al. 2021). The most widely used vegetable oils to produce bio-based polymers are castor, linseed, canola, sunflower, palm, tobacco, corn, soy, and oilseed rape (Abbasi et al. 2019).

Most applied nitrogen fertilizer in the EU is calcium ammonium nitrate (CAN), which is characteristic for its equal proportion of nitrate (13.5%) and ammonium (13.5%) nitrogen. The aim of this study was to verify the effect of oil-based polymer-coated CAN fertilizer in two different coat thicknesses (4 and 6% by weight of granules) and in two blends (uncoated and coated CAN in 1:1 and 1:2 ratio) on the yield and quality of winter wheat and oilseed rape. The blends of uncoated and coated CAN fertilizer were chosen for two reasons: (1) The combination of quickly available nitrogen in uncoated CAN provides the necessary amount of nitrogen in the early stages of vegetation, while the coated CAN represents a gradual supplement of nitrogen; (2) The combination of coated and uncoated fertilizers is going to be a more available option from an economic perspective (only part of the fertilizer is more expensive). The effect of the single application of these blends was compared to the commonly used nitrogen fertilization based on three split doses of nitrogen in fertilizers CAN and urea ammonium nitrate (UAN). The hypotheses were (1) that the single application of coated CAN fertilizer is going to increase the yield of winter wheat and oilseed rape and (2) that the qualitative parameters of model crops are going to be comparable to the control treatment despite the missing fertilization later during the vegetation due to the gradual release of nitrogen from coated CAN. The experiment over two growing seasons (2020–2021) was established in the field conditions at the two experimental sites to examine the suggested hypothesis.

## 2 Materials and Methods

### 2.1 Experimental Sites and Climate-soil Conditions

A small plot field experiment was conducted in a randomized block design with winter wheat (*Triticum aestivum* L.), variety Julie (Selgen, Prague, Czech Republic), and oilseed rape (*Brassica napus* L.), variety DK Exception (Monsanto Technology LLC, USA), which were sown as model crops in experimental growing seasons (2019–2020 and 2020–2021). The experiment took place simultaneously at two field experimental sites belonging to Mendel University in Brno. The first experimental area is located in Žabčice (49.0229836 N, 16.6175028E), the altitude is 180 m above sea level, and it is characterised mostly by warm and drought climate. In fact, it is one of the warmest sites in the Czech Republic with an average annual temperature of about 10 °C. The possible limiting factor for crop production is the relative deficiency, or rather, the uneven distribution of precipitation during the year together with frequent drying winds. According to the long-term normal, Žabčice is characteristic with a low precipitation of about 490 mm per year. The average monthly temperatures and precipitation sums during the experiment are shown in Fig. 1 together with the climate data from the long-term normal 1990–2020. The second experimental area is located near Vatín (49.5170872 N, 15.9725964E). The altitude is 560 m above sea level, and it is characteristic with lower average temperatures and more precipitation in comparison with Žabčice (lower risk of drought periods). The average monthly temperatures and precipitation sums during the experimental years for this site are shown in Fig. 2 together with the long-term normal 1990–2020.

Due to the permanent influence of groundwater, the soil type of experimental area Žabčice is the Gleyic Fluvisols with clay loam structure. The soil type at the site Vatín is

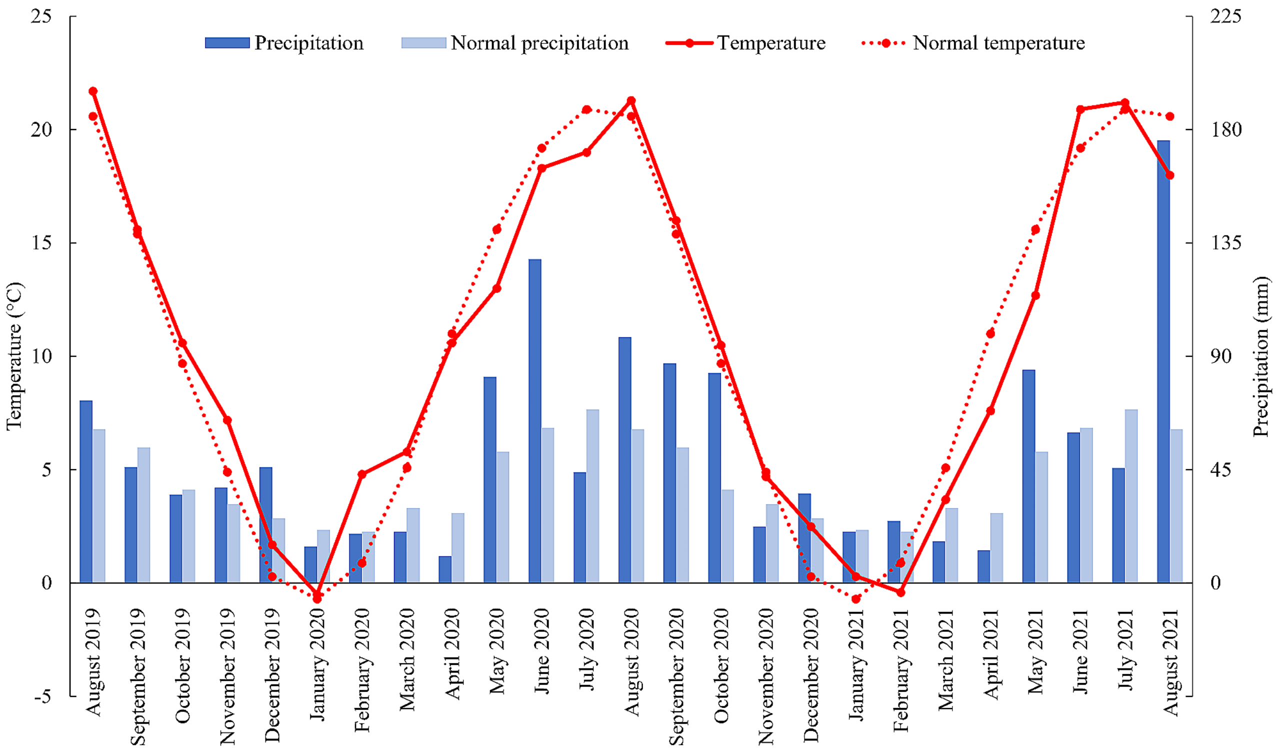

**Fig. 1** Characteristics of average monthly temperatures and precipitation sums with their comparison to the long-term normal during the experimental growing seasons in Žabčice

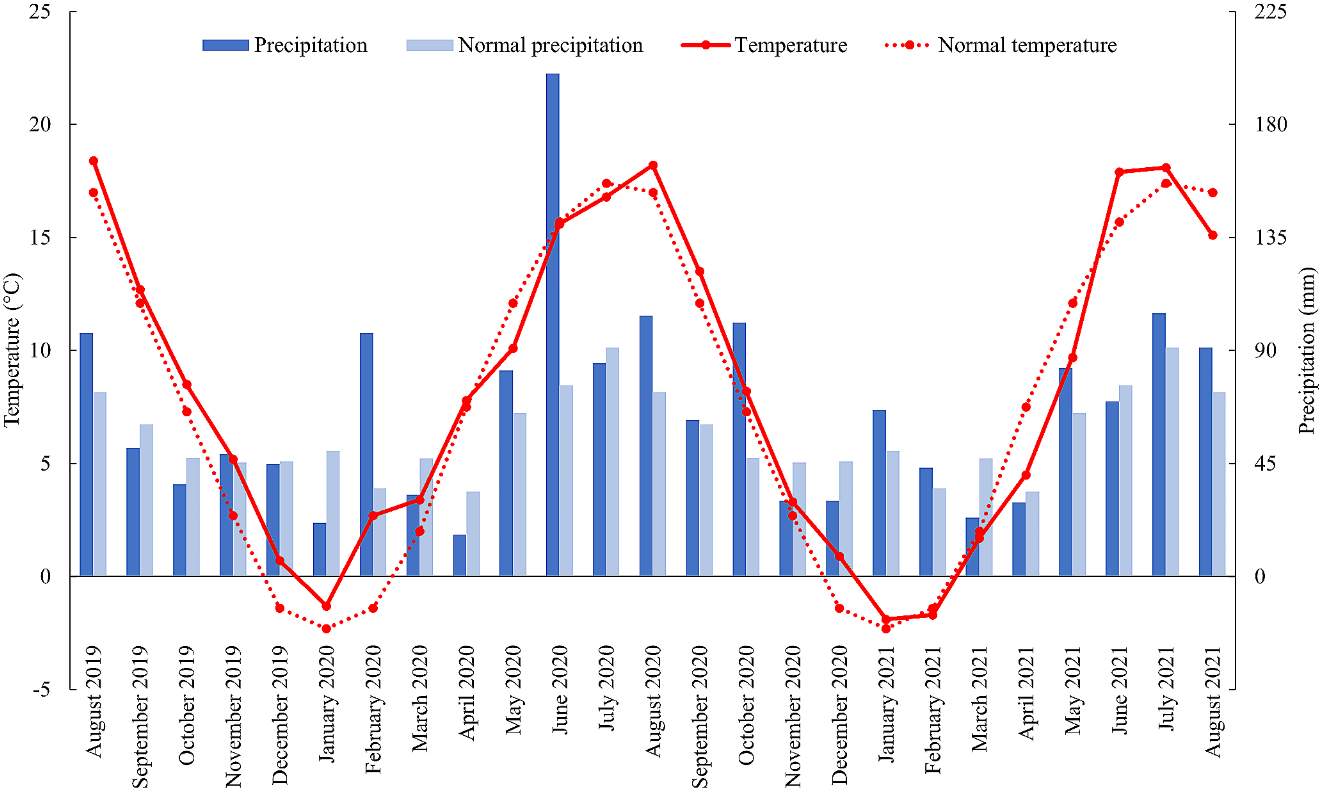

**Fig. 2** Characteristics of average monthly temperatures and precipitation sums with their comparison to the long-term normal during the experimental growing seasons in Vatín

**Table 1** The characteristic of soil at both experimental sites

| Site / Analysis | Žabčice 2020 | Žabčice 2021 | Vatín 2020 | Vatín 2021 |
|---|---|---|---|---|
| P (mg/kg) | 152 | 92 | 101 | 78 |
| K (mg/kg) | 283 | 184 | 312 | 294 |
| Ca (mg/kg) | 3641 | 3934 | 2433 | 2211 |
| Mg (mg/kg) | 411 | 355 | 164 | 173 |
| S (mg/kg) | 11 | 40 | 9 | 8 |
| pH ($CaCl_2$) | 6.4 | 5.9 | 6.0 | 5.7 |
| clay (< 2 µm) (%) | 27.3 | | 11.7 | |
| silt (50–2 µm) (%) | 26.0 | | 34.9 | |
| sand (2 000–50 µm) (%) | 11.5 | | 53.4 | |
| clay particles (< 0.01 mm) (%) | 31.0 | | 26.2 | |
| bulk density (kg $m^{-3}$) | 1 370 | | 1 197 | |
| total porosity (%) | 48.0 | | 54.4 | |
| maximum capillary water capacity (%) | 47.7 | | 39.9 | |
| minimal air capacity (%) | 11.5 | | 14.5 | |
| $C_{ox}$ (%) | 1.3 | | 1.8 | |

Cambisols, mostly with sandy soil structure. The average content of nutrients in the soil before sowing and exchangeable soil acidity was determined by certified methodology (Zbíral et al. 2022) in each growing season, the basic physical properties of the soils were determined before the experiment was first established. The basic characteristic of both experimental sites is given in Table 1. The content of nutrients in Vatín soils is mostly lower compared to Žabčice, the soil reaction is moderately acidic. In general, the experimental site Žabčice is considered more fertile in terms of soil type and soil characteristics, while the experimental site Vatín is characterized by more deficient and sandy soil.

## 2.2 Methodology of the Experiment and Field Treatments

The Randomized Complete Block Design was used during the experiment. The fertilizer calcium ammonium nitrate (CAN; 27% N; up to 13% N-$NH_4^+$ and 13% N-$NO_3^-$; Lovochemie a.s.; Lovosice, the Czech Republic) was coated by oil-based polymers using the LDP-3 fluidized bed granulating machine (Changzhou Jiafa Granulating Drying Equipment Co., Ltd., Changzhou, China). The coated CAN (cCAN, Fig. 3) fertilizer was prepared in two variants, coating up to 4 ($cCAN_4$) and 6 wt% ($cCAN_6$) (triglycerides of fatty acids, up to 75 wt% of which unsaturated were up to 45 wt%, polylactic acid up to 10 wt%; up to 25.9% N in 4 wt% coat and up to 25.4% N in 6 wt%; VUCHT a.s.; Bratislava; Slovakia) (Kučera et al. 2021). The nitrogen release dynamics of the coated CAN determined into deionised water is shown in Fig. 4 (EN 13266:2001).

The examined treatments were: the control treatment based on the application of commonly used fertilizers CAN and urea ammonium nitrate (UAN) in three split doses; the combination of uncoated CAN (4% or 6%) and coated CAN (c CAN) in a 1:1 ratio; and the combination of uncoated CAN (4% or 6%) and coated CAN in a 1:2 ratio. The blends of coated and uncoated CAN were applied in a single application in the tillering stage of winter wheat (BBCH 22–25) and at the start of the side shoot formation of oilseed rape (BBCH 20–25). Total doses of nitrogen at every treatment were identical for both model crops (160 kg/ha wheat; 195 kg/ha oilseed rape), as described in Table 2. Every treatment was established in four repetitions. The size of each experimental plot of wheat for the fertilization was 16.8 $m^2$ (10 rows with a length of 14 m and inter-row spacing of 0.12 m). The size of the experimental plots of oilseed rape was 18 $m^2$ (6 rows with a length of 12 m and inter-row spacing of 0.25 m). All the fertilizers were manually applied to each field plot separately.

The winter wheat and oilseed rape were cultivated identically in both growing seasons at both experimental sites. The blends of uncoated and coated CAN were applied in a single application at the end of February or at the beginning of March, depending on the course of weather and the crop vegetation. The first application of nitrogen (control treatment with split application) was performed simultaneously. The second fertilization of control treatment was then performed at the turn of March and April, depending on the BBCH stages of winter wheat and oilseed rape. The third application of nitrogen in control technology was performed at the turn of April and May. The winter wheat and oilseed rape were treated with permitted fungicides and insecticides as needed during the whole experiment. Upon the full ripening of model crops, plants were harvested from the harvested area of 10 $m^2$ within each fertilized plot.

## 2.3 Yield, Grain and Seed Quality Measurements

The weight of winter wheat grain and oilseed rape (kg) from the harvested area (10 $m^2$) was determined using the digital scale Kern ECE 20 K-2 N (KERN and Sohn GmbH, Balingen, Germany). The moisture content of harvested products was measured subsequently (portable moisture meter Wile 78 Crusher, Farmcomp Oy, Finland). The final wheat

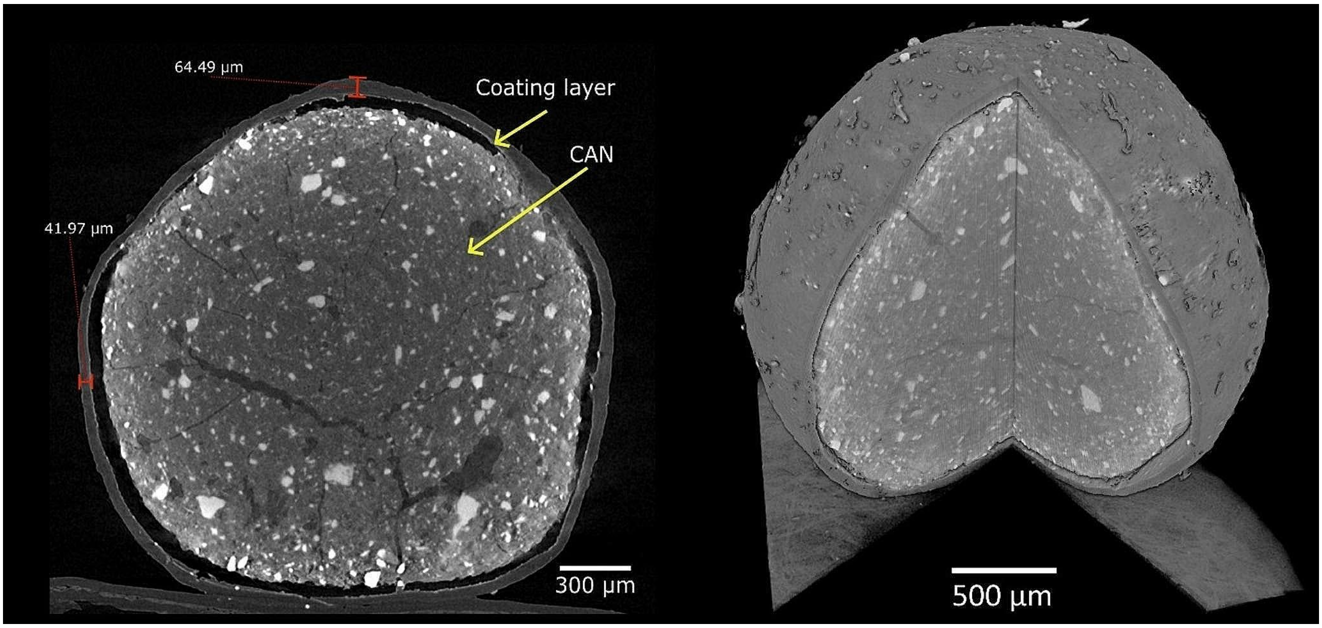

**Fig. 3** 2D and 3D rendering of the coated CAN ($cCAN_4$) at a clinical computed tomography (Rigaku Nano3DX)

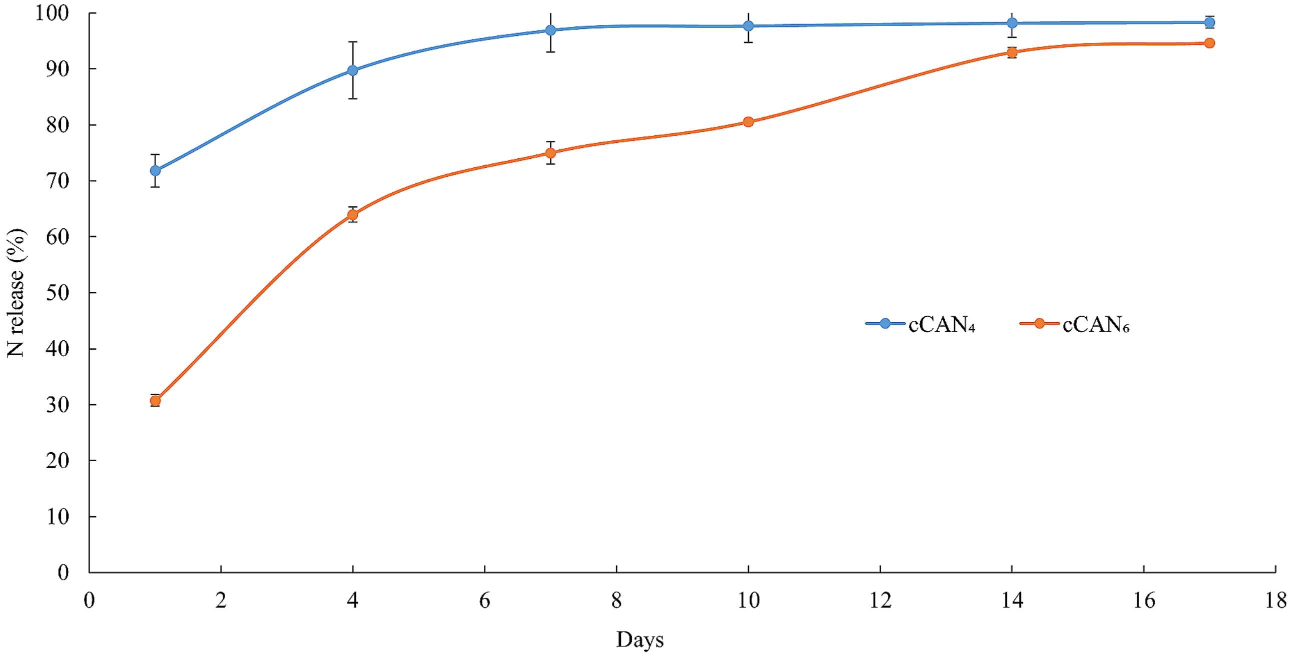

**Fig. 4** Fertilizer release profiles of nitrogen (% of N in fertilizer) in deionized water. Standard deviation is expressed by error bars

**Table 2** The experimental treatments (Žabčice and Vatín, 2019–2020 and 2020–2021)

| | | Winter wheat | | | | |
|---|---|---|---|---|---|---|
| Treatment | Tillering (BBCH 22–25) | | Stem elongation start (BBCH 30–32) | | Heading (BBCH 49–51) | |
| | N (kg/ha) | Fertilizer | N (kg/ha) | Fertilizer | N (kg/ha) | Fertilizer |
| CAN-CAN-UAN | 55 | CAN | 65 | CAN | 40 | UAN |
| CAN/cCAN$_4$ 1:1 | 160 | CAN + c CAN4 1:1 | - | - | - | - |
| CAN/cCAN$_6$ 1:1 | 160 | CAN + c CAN 6 1:1 | - | - | - | - |
| CAN/cCAN$_4$ 1:2 | 160 | CAN + c CAN 4 1:2 | - | - | - | - |
| CAN/cCAN$_6$ 1:2 | 160 | CAN + c CAN 6 1:2 | - | - | - | - |
| | | Oilseed rape | | | | |
| Treatment | Side shoot formation (BBCH 20–25) | | Stem elongation start (BBCH 30–32) | | Flower bud emergence (BBCH 50–55) | |
| | N (kg/ha) | Fertilizer | N (kg/ha) | Fertilizer | N (kg/ha) | Fertilizer |
| CAN-UAN-UAN | 105 | CAN | 45 | UAN | 45 | UAN |
| CAN/cCAN$_4$ 1:1 | 195 | CAN + c CAN 4 1:1 | - | - | - | - |
| CAN/cCAN$_6$ 1:1 | 195 | CAN + c CAN 6 1:1 | - | - | - | - |
| CAN/cCAN$_4$ 1:2 | 195 | CAN + c CAN 4 1:2 | - | - | - | - |
| CAN/cCAN$_6$ 1:2 | 195 | CAN + c CAN 6 1:2 | - | - | - | - |

grain yield was standardized at a 12.0% moisture content and expressed as tons per hectare (t/ha), the final yield of rape seed was standardized at 8% moisture content and also expressed as tons per hectare.

*Wheat Grain Quality* The test weight scale Wile 241 (Farmcomp OY, Tuusula, Finland) was used for the determination of the hectolitre weight of wheat grains. The content of protein in the grain was determined by the Kjeltec 2300 device (Foss, Hillerød, Denmark), followed by the multiplication by a 6.25 coefficient (the Kjeldahl method). The gluten content and the sedimentation index known as the Zeleny-test were estimated by the NIR (Near Infrared Spectroscopy) method on the Inframatic 9500 NIR grain analyzer (Perten Instruments, Hägersten, Sweden). The principle of the NIR method is the transmittance or reflectance measurement of radiation within the wavelength range of 800 to 2500 nm (12.500–4000 cm$^{-1}$), which is related to the different chemical groups contained in the sample (Azizian et al. 2007).

*Rape Seed Quality* The oil content was determined gravimetrically after the extraction of the samples with diethyl ether using the Soxhlet method based on the NMR extraction of rapeseeds in a continuous flow extractor Minispec mq series TD-NMR (Bruker Corporation, Ettlinger, Germany).

### 2.4 Economical Analysis

Economic analysis following a partial budget (CIMMYT Economics Program 1988) was performed for compared fertilization treatments. By its nature, this procedure considers only major differences between fertilization technologies and does not take all costs and benefits into account. Therefore, only the cost of applied fertilizers, the number of their applications and the price of commodities (winter wheat grain, oilseed rape seed) were considered. The cost of 1 tonne of used fertilizers was: CAN – 290 €; UAN – 315 €; $cCAN_4$ – 376 €; $cCAN_6$ – 428 €. The prices of coated fertilizers were calculated as the sum of the price of uncoated CAN and the price of the raw materials used for coating and the cost of coating according to the manufacturer (Lovochemie, a.s.; Lovosice; Czech Republic). The price of fertilizers for compared treatments has been recalculated according to the corresponding applied doses (Table 2). The cost of one application (fertilization in a selected BBCH stage) was 12 €/ha. The price of winter wheat was 230 €/t, the price of oilseed rape was 458 €/t. The prices were actual for the spring of 2024 (MATIF, Paris, France). However, the prices of input (fertilizers) and outputs (harvested commodities) usually fluctuate, making it difficult for economic analysis. Therefore, additional sensitivity analysis (Mohammed et al. 2022) was performed under three different scenarios to accommodate possible market dynamics and to see the effects of input and output price changes on the compared technologies of fertilization. These scenarios were: (1) an increase cost in N fertilizers by 10% but fixed commodity price, (2) an increase in commodity price by 10% with fixed N fertilizers cost, and (3) an increase in N fertilizers cost by 10% and a decrease in commodity price by 10% (the worst-case scenario from farmers' perspective). The average yield of winter wheat and oilseed rape from both experimental sites was used for the economic evaluation.

### 2.5 Statistical Analysis

The collected data (grain yield and qualitative parameters) were evaluated by the Statistica Software 14 CZ by multifactorial analysis of variance (ANOVA with factors: growing season, site, treatment) and subsequently by the Fisher's Least Significant Difference (LSD) test at the 5% level ($p \leq 0.05$) of significance. Normality and homogeneity of variances were checked using the Shapiro-Wilk test and Levene's test. The results were expressed as the arithmetical mean ± standard deviation (SD).

## 3 Results

### 3.1 Winter Wheat

The average grain yields of winter wheat observed in both growing seasons and both sites are described in Fig. 5. It is evident from these results that the application of coated fertilizers in blends did not result in a significant increase in yield at either site during two growing seasons. The overall average (from both experimental sites and both years) was also insignificant. The relatively highest overall grain yield was observed at the treatment $CAN/cCAN_4$ 1:1 (8.68 t/ha). Despite the statistically insignificant difference compared to the control treatment (8.57 t/ha), this relative increase in grain yield was reflected in higher revenues and most importantly, in positive net profit in every scenario described in economic evaluation (Table 3). The average qualitative parameters of winter wheat grain are described in Table 4. At experimental site Žabčice, the hectolitre weight (HW) was not statistically significant in either experimental growing season after the application of the examined blends in comparison with the control treatment. The statistical differences were observed at experimental site Vatín in both growing seasons. On average at Vatín, the highest values of HW were determined after the control treatment (72.3 kg/hl). On the contrary, the lowest HW was found after both ratios of $CAN/cCAN_4$ (70.8 kg/hl $CAN/cCAN_4$ 1:1; 70.7 kg/hl $CAN/cCAN_4$ 1:2). This represents a significant decrease of 2.1, respectively 2.2%, compared to the control treatment.

The statistical differences between protein contents in the wheat grain at the experimental site Žabčice were observed only in season 2019/2020. In this growing season, the protein content was the lowest after the control treatment, its content decreased by 2.5 up to 5.1 relative % in comparison with examined the treatments with coated CAN (Table 4). The results were the opposite in 2020/2021, every examined treatment provided a lower content of protein compared to the control, although not significantly. On average from both growing seasons at experimental site Žabčice, the differences in protein content were statistically insignificant. The statistical differences in protein content after the examined fertilization were found in both growing seasons and their average at the experimental site Vatín. On average from both growing seasons, the statistically lowest protein

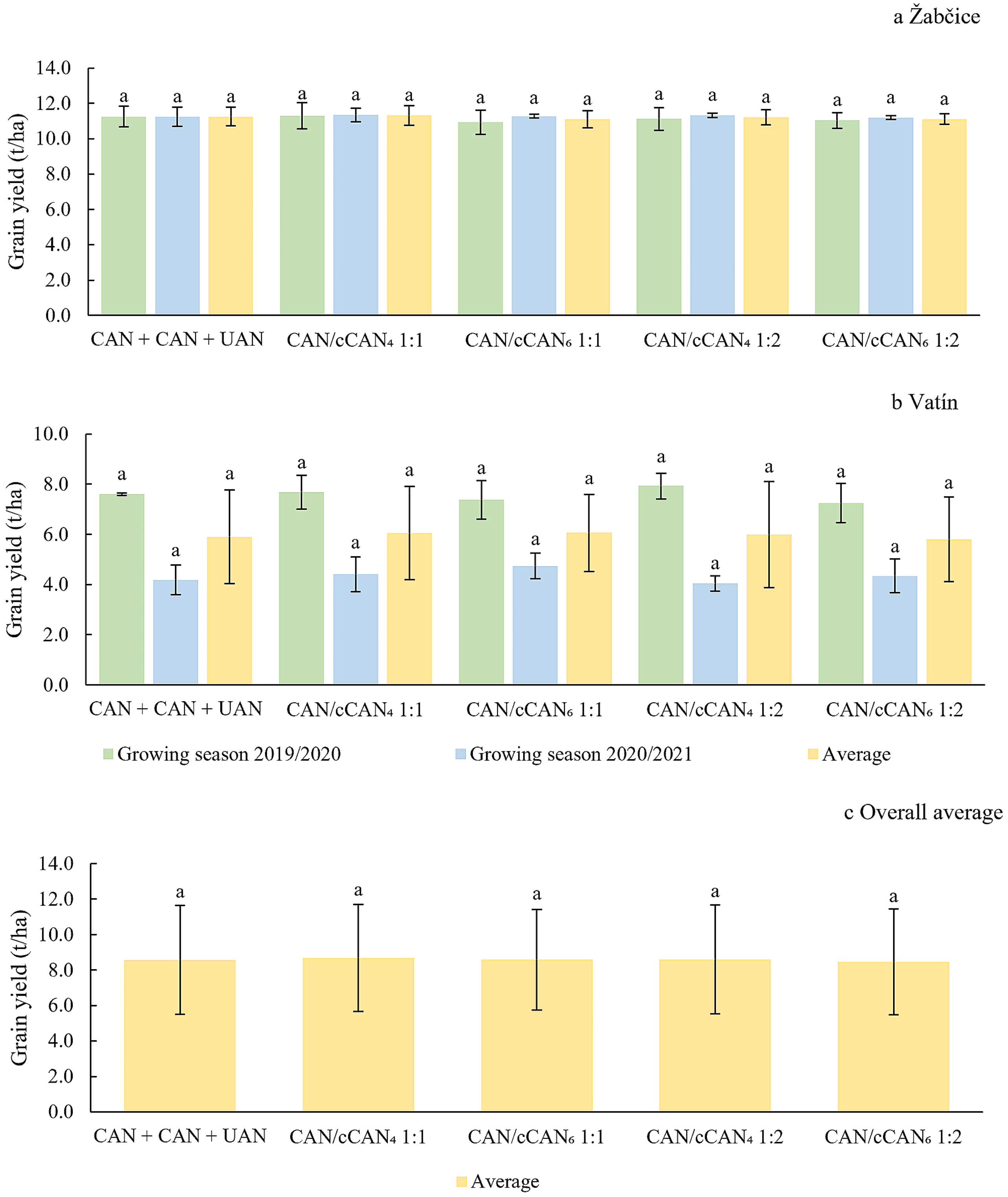

**Fig. 5** The average yield (t/ha) of winter wheat grain (Žabčice and Vatín). The same letters in the columns describe no statistically significant differences between treatments (LSD test). Standard deviation is expressed by error bars. Each growing season and its average were evaluated separately

**Table 3** Economic evaluation of average wheat yield according to the examined treatments (Žabčice and Vatín)

| Scenario | Treatment | Fertilizers cost | | | Increase in fertilizer cost* (€/ha) | Sales profit (wheat grain) | | | Revenue increase** (€/ha) | Net profit*** (€/ha) |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Fertilizer price (€/ha) | Application cost (€/ha) | Total costs (€/ha) | | Average yield (t/ha) | Purchase price (1 t of grain) | Total revenue (€/ha) | | |
| 2024 | CAN + CAN + UAN | 164 | 36 | 200 | 0 | 8.57 | 239 | 2 048 | 0 | - |
| | CAN/cCAN$_4$ 1:1 | 201 | 12 | 213 | 13 | 8.68 | 239 | 2 075 | 27 | 14 |
| | CAN/cCAN$_6$ 1:1 | 216 | 12 | 228 | 28 | 8.58 | 239 | 2 051 | 3 | -25 |
| | CAN/cCAN$_4$ 1:2 | 209 | 12 | 221 | 21 | 8.60 | 239 | 2 055 | 7 | -14 |
| | CAN/cCAN$_6$ 1:2 | 230 | 12 | 242 | 42 | 8.46 | 239 | 2 022 | -26 | -68 |
| 1 | CAN + CAN + UAN | 180 | 36 | 216 | 0 | 8.57 | 239 | 2 048 | 0 | 0 |
| | CAN/cCAN$_4$ 1:1 | 221 | 12 | 233 | 17 | 8.68 | 239 | 2 075 | 27 | 10 |
| | CAN/cCAN$_6$ 1:1 | 238 | 12 | 250 | 34 | 8.58 | 239 | 2 051 | 3 | -31 |
| | CAN/cCAN$_4$ 1:2 | 230 | 12 | 242 | 26 | 8.60 | 239 | 2 055 | 7 | -19 |
| | CAN/cCAN$_6$ 1:2 | 253 | 12 | 265 | 49 | 8.46 | 239 | 2 022 | -26 | -75 |
| 2 | CAN + CAN + UAN | 164 | 36 | 200 | 0 | 8.57 | 263 | 2 254 | 0 | 0 |
| | CAN/cCAN$_4$ 1:1 | 201 | 12 | 213 | 13 | 8.68 | 263 | 2 283 | 29 | 16 |
| | CAN/cCAN$_6$ 1:1 | 216 | 12 | 228 | 28 | 8.58 | 263 | 2 257 | 3 | -25 |
| | CAN/cCAN$_4$ 1:2 | 209 | 12 | 221 | 21 | 8.60 | 263 | 2 262 | 8 | -13 |
| | CAN/cCAN$_6$ 1:2 | 230 | 12 | 242 | 42 | 8.46 | 263 | 2 225 | -29 | -71 |
| 3 | CAN + CAN + UAN | 180 | 36 | 216 | 0 | 8.57 | 215 | 1 843 | 0 | 0 |
| | CAN/cCAN$_4$ 1:1 | 221 | 12 | 233 | 17 | 8.68 | 215 | 1 866 | 23 | 6 |
| | CAN/cCAN$_6$ 1:1 | 238 | 12 | 250 | 34 | 8.58 | 215 | 1 845 | 2 | -32 |
| | CAN/cCAN$_4$ 1:2 | 230 | 12 | 242 | 26 | 8.60 | 215 | 1 849 | 6 | -20 |
| | CAN/cCAN$_6$ 1:2 | 253 | 12 | 265 | 49 | 8.46 | 215 | 1 819 | -24 | -73 |

Scenario: 2024 – actual prices in spring 2024; 1 – an increase cost in N fertilizers by 10% but fixed commodity price; 2 – an increase in commodity price by 10% with fixed N fertilizers cost; 3 – an increase in N fertilizers cost by 10% and a decrease in commodity price by 10%. * Increase in fertilizer costs (€/ha) = Total fertilizer cost of examined blends (€/ha) – Total fertilizer cost of control treatment (€/ha). ** Revenue increase (€/ha) = Total revenue of examined blends (€/ha) – Total revenue of control treatment (€/ha). *** Net profit (€/ha) = Revenue increase (€/ha) – Increase in fertilizer costs (€/ha)

**Table 4** The average values of qualitative parameters of winter wheat grain (Žabčice and Vatín)

| Treatment | Žabčice | | | Vatín | | | Overall Average |
|---|---|---|---|---|---|---|---|
| | 2019/2020 | 2020/2021 | Average | 2019/2020 | 2020/2021 | Average | |
| | | | **Hectolitre weight (kg/hl)** | | | | |
| CAN + CAN + UAN | 76.7a ± 0.1 | 80.5a ± 0.2 | 78.6a ± 2.0 | 73.9a ± 0.5 | 70.6a ± 0.24 | 72.3a ± 1.77 | 78.5a ± 3.4 |
| CAN/cCAN$_4$ 1:1 | 76.2a ± 1.0 | 80.8a ± 0.2 | 78.5a ± 2.6 | 72.7ab ± 0.9 | 68.8b ± 0.42 | 70.8c ± 2.2 | 74.6b ± 4.6 |
| CAN/cCAN$_6$ 1:1 | 76.2a ± 0.7 | 80.3a ± 0.7 | 78.3a ± 2.3 | 73.8ab ± 1.4 | 69.6ab ± 1.22 | 71.7ab ± 2.5 | 75.0ab ± 4.1 |
| CAN/cCAN$_4$ 1:2 | 76.4a ± 0.8 | 80.8a ± 0.1 | 78.6a ± 2.4 | 72.5b ± 0.4 | 68.8b ± 0.95 | 70.7c ± 2.1 | 74.6b ± 4.6 |
| CAN/cCAN$_6$ 1:2 | 76.2a ± 1.0 | 80.8a ± 0.1 | 78.5a ± 2.5 | 73.2ab ± 1.0. | 69.0b ± 0.41 | 71.1bc ± 2.4 | 74.8b ± 4.5 |
| | | | **Protein content (%)** | | | | |
| CAN + CAN + UAN | 13.2b ± 0.5 | 13.4a ± 0.6 | 13.3a ± 0.5 | 12.9ab ± 0.1 | 13.0a ± 0.1 | 12.9a ± 0.1 | 13.1a ± 0.4 |
| CAN/cCAN$_4$ 1:1 | 13.7ab ± 0.5 | 13.3a ± 0.5 | 13.5a ± 0.5 | 12.8ab ± 0.1 | 11.5c ± 0.8 | 12.2b ± 0.9 | 12.8a ± 1.0 |
| CAN/cCAN$_6$ 1:1 | 13.5ab ± 0.2 | 12.6a ± 0.8 | 13.1a ± 0.7 | 13.1a ± 0.2 | 12.5ab ± 0.6 | 12.8a ± 0.5 | 12.9a ± 0.6 |
| CAN/cCAN$_4$ 1:2 | 13.6ab ± 0.4 | 13.1a ± 0.6 | 13.4a ± 0.5 | 12.5ab ± 0.8 | 12.0bc ± 0.4 | 12.3b ± 0.6 | 12.8a ± 0.8 |
| CAN/cCAN$_6$ 1:2 | 13.9a ± 0.4 | 13.2a ± 0.5 | 13.5a ± 0.5 | 12.3b ± 0.3 | 12.2b ± 0.3 | 12.3b ± 0.3 | 12.9a ± 0.8 |
| | | | **Gluten content (%)** | | | | |
| CAN + CAN + UAN | 29.5b ± 1.2 | 29.6a ± 1.8 | 29.5a ± 1.4 | 28.8ab ± 0.2 | 30.0a ± 0.5 | 29.4a ± 0.7 | 29.5a ± 1.1 |
| CAN/cCAN$_4$ 1:1 | 30.9ab ± 1.3 | 29.3a ± 1.5 | 30.1a ± 1.6 | 28.9ab ± 0.5 | 25.8b ± 2.5 | 27.3c ± 2.3 | 28.7a ± 2.4 |
| CAN/cCAN$_6$ 1:1 | 31.2a ± 0.5 | 27.3a ± 2.3 | 29.3a ± 2.6 | 29.7a ± 0.5 | 28.2a ± 1.8 | 29.0ab ± 1.4 | 29.1a ± 2.0 |
| CAN/cCAN$_4$ 1:2 | 30.7ab ± 1.1 | 29.0a ± 1.6 | 29.9a ± 1.5 | 28.0b ± 2.1 | 28.1ab ± 1.7 | 28.1abc ± 1.8 | 29.0a ± 1.9 |
| CAN/cCAN$_6$ 1:2 | 31.5a ± 0.8 | 29.1a ± 1.5 | 30.3a ± 1.7 | 27.6b ± 0.8 | 28.4a ± 0.6 | 28.0bc ± 0.8 | 29.1a ± 1.8 |
| | | | **Index of sedimentation (ml)** | | | | |
| CAN + CAN + UAN | 36b ± 3 | 50a ± 10 | 43a ± 10 | 31ab ± 1 | 49a ± 2 | 40a ± 10 | 42.a ± 10 |
| CAN/cCAN$_4$ 1:1 | 40ab ± 4 | 45ab ± 4 | 43a ± 5 | 31ab ± 1 | 35b ± 11 | 33c ± 7 | 38b ± 8 |
| CAN/cCAN$_6$ 1:1 | 41a ± 2 | 40b ± 6 | 40a ± 4 | 33a ± 2 | 44ab ± 6 | 38ab ± 7 | 40ab ± 6 |
| CAN/cCAN$_4$ 1:2 | 40ab ± 3 | 45ab ± 4 | 42a ± 4 | 29ab ± 5 | 44ab ± 5 | 36abc ± 10 | 40ab ± 8 |
| CAN/cCAN$_6$ 1:2 | 43a ± 2 | 42b ± 5 | 42a ± 4 | 27b ± 2 | 41ab ± 6 | 34bc ± 8 | 38b ± 7 |

Results are expressed as the mean ± standard deviation. The mean values with different letters are significantly different ($p < 0.05$) according to the LSD test. Each growing season and its average were evaluated separately

content was determined after both ratios of CAN/cCAN$_4$ (12.2% CAN/cCAN$_4$ 1:1; 12.3% CAN/cCAN$_4$ 1:2). This represents a significant decrease of 5.7, respectively 4.9%, compared to the control treatment. However, the result of multifactorial ANOVA (both growing seasons, both experimental sites) shows insignificant differences between examined treatments.

The gluten content in wheat grain was similar to the result of protein content. At Žabčice, the gluten content was statistically higher on almost every treatment in the first growing season 2020 within the range of 4.2-7.0 relative %. In correlation with protein content, the gluten content after the application of the coated blends decreased in 2021 compared to the control, although not significantly. On average from both growing seasons at Žabčice, the results were statistically insignificant, which corresponds with the two-year average of protein content in grain. The statistical differences in gluten content after the examined fertilization were found in both growing seasons at the experimental site Vatín. In both growing seasons, the gluten content after the application of blends was lower in comparison with the control treatment (28.8% in 2020; 30.0% in 2021), except for the treatment CAN/cCAN$_6$ 1:1 in growing season 2020 (29.7%). Both treatments (ratios) based on the single application of uncoated and cCAN$_4$ (27.3% CAN/cCAN$_4$ 1:1; 28.1% CAN/cCAN$_4$ 1:2) have provided lower content of gluten compared to the control treatment with split fertilization (29.4%). A strong correlation between gluten and protein contents in wheat grain was found (Fig. 6) as the overall average gluten content determined from both growing seasons and experimental localities were also insignificant.

The important parameter of wheat grain quality, which represents the viscoelastic characteristics of gluten protein and determines baking quality, is the index of sedimentation estimated as the Zeleny-test. The statistical differences between the examined treatments were found each season at both sites (Table 4). At Žabčice, every treatment with cCAN resulted in increased values (within the 40–43 ml range) in comparison with the control (36 ml) in 2019/2020. However, the results in 2020/2021 were the opposite, as every treatment with coated CAN resulted in decreased values (within the range of 40–45 ml) of the Zeleny-test compared to the control (50 ml). The average of both growing seasons from Žabčice shows that the values of the sedimentation index were comparable (statistically insignificant) between every treatment, most notably the control treatment (43 ml)

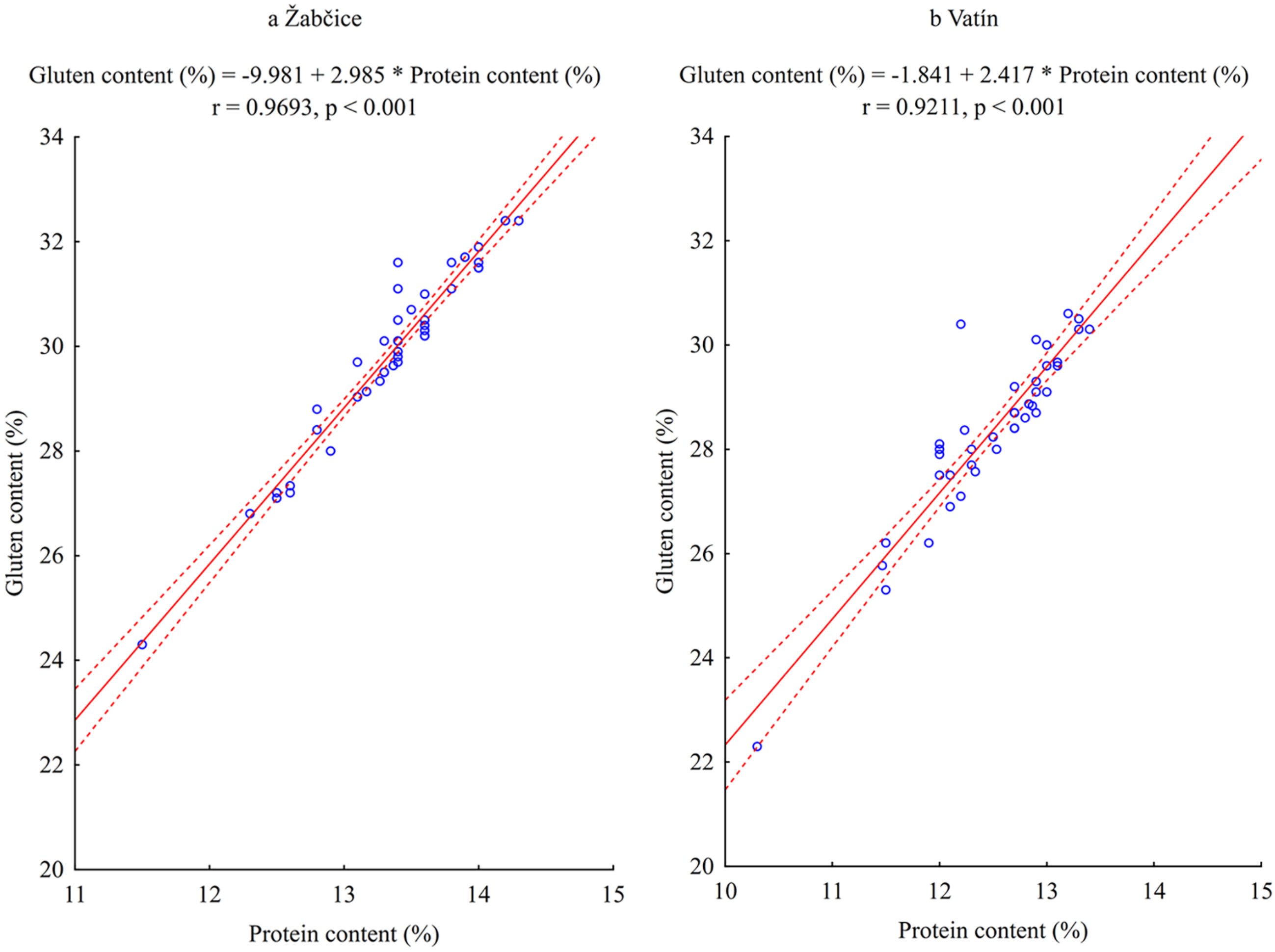

**Fig. 6** The corelation between gluten content (%) and protein content (%) in winter wheat grain (Žabčice and Vatín)

and CAN/cCAN$_4$ 1:1 (43 ml). On the contrary, every treatment with cCAN resulted in an average lower sedimentation index at the experimental site Vatín.

## 3.2 Oilseed rape

The average seed yields of oilseed rape obtained after two experimental seasons from both sites are described in Fig. 7, same as the overall average. It is evident from the presented results, that the effect of the examined blends of cCAN is different in comparison with the winter wheat response, as the statistical differences were found out each growing season at both sites depending on fertilization. The average yields of seed were higher after the application of cCAN compared to control (CAN-UAN-UAN) in both experimental seasons at Žabčice. At this experimental site, the single fertilization by CAN/cCAN$_4$ 1:1 resulted in a significantly increased yield by 16.6% (2.8 t/ha) compared to CAN-UAN-UAN (2.4 t/ha). The statistically highest yield was observed after the same treatment (cCAN$_4$) with a higher ratio 1:2 (3.8 t/ha). The application of 6% wt. cCAN also resulted in higher average yields, 2.8 t/ha after the fertilization with a blend in 1:1 and 2.7 t/ha after the same treatment with a higher ratio 1:2. The seed yields observed at Vatín were also higher for almost every examined treatment in both growing seasons. On average, the highest yield of oilseed rape was provided by the single fertilization with a blend of CAN/cCAN$_4$ in a 1:2 ratio (2.5 t/ha). This represents an increase of 0.4 t/ha in comparison with the control treatment (2.1 t/ha). Every other treatment with cCAN also resulted in a relative increase in yield (from 2.3 to 2.4 t/ha) similarly to the Žabčice. On average from both growing seasons and both sites, the highest yield of seed (2.8 t/ha) was observed on treatment cCAN$_4$ in the 1:2 ratio. This represents a significant increase by 24.8% compared to the control (2.2 t/ha). This significant increase in seed yield have positively influenced the economic evaluation (Table 5), as this treatment resulted in the highest revenues and net profit. On average, every examined treatment with coated fertilizers have provided higher overall seed yields compared

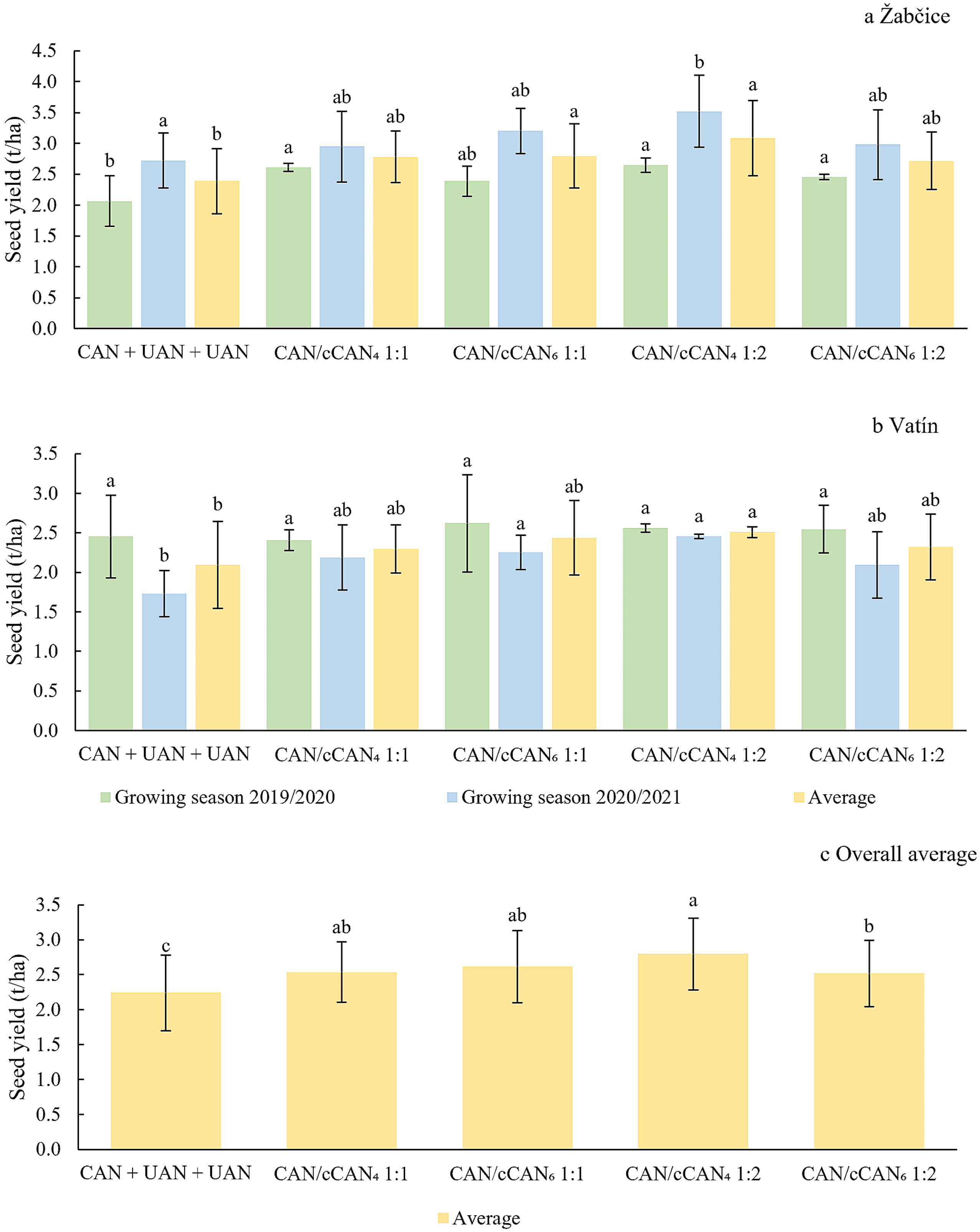

**Fig. 7** The average yield (t/ha) of oilseed rape seed (Žabčice and Vatín). The same letters in the columns describe no statistically significant differences between treatments (LSD test). Standard deviation is expressed by error bars. Each growing season and its average were evaluated separately

**Table 5** Economic evaluation of average seed yield according to the examined treatments (Žabčice and Vatín)

| Scenario | Treatment | Fertilizers cost | | | Increase in fertilizer cost* (€/ha) | Sales profit (wheat grain) | | | Revenue increase** (€/ha) | Net profit*** (€/ha) |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Fertilizer price (€/ha) | Application cost (€/ha) | Total costs (€/ha) | | Average yield (t/ha) | Purchase price (1 t of seed) | Total revenue (€/ha) | | |
| 2024 | CAN + UAN + UAN | 188 | 36 | 224 | 0 | 2.24 | 466 | 1 044 | 0 | - |
| | CAN/cCAN$_4$ 1:1 | 244 | 12 | 256 | 32 | 2.54 | 466 | 1 184 | 140 | 108 |
| | CAN/cCAN$_6$ 1:1 | 263 | 12 | 275 | 51 | 2.62 | 466 | 1 221 | 177 | 126 |
| | CAN/cCAN$_4$ 1:2 | 255 | 12 | 267 | 43 | 2.80 | 466 | 1 305 | 261 | 218 |
| | CAN/cCAN$_6$ 1:2 | 280 | 12 | 292 | 68 | 2.52 | 466 | 1 174 | 130 | 62 |
| 1 | CAN + UAN + UAN | 207 | 36 | 243 | 0 | 2.24 | 466 | 1 044 | 0 | 0 |
| | CAN/cCAN$_4$ 1:1 | 269 | 12 | 281 | 38 | 2.54 | 466 | 1 184 | 140 | 102 |
| | CAN/cCAN$_6$ 1:1 | 290 | 12 | 302 | 59 | 2.62 | 466 | 1 221 | 177 | 118 |
| | CAN/cCAN$_4$ 1:2 | 281 | 12 | 293 | 50 | 2.80 | 466 | 1 305 | 261 | 211 |
| | CAN/cCAN$_6$ 1:2 | 308 | 12 | 320 | 77 | 2.52 | 466 | 1 174 | 130 | 53 |
| 2 | CAN + UAN + UAN | 188 | 36 | 224 | 0 | 2.24 | 513 | 1 149 | 0 | 0 |
| | CAN/cCAN$_4$ 1:1 | 244 | 12 | 256 | 32 | 2.54 | 513 | 1 303 | 154 | 122 |
| | CAN/cCAN$_6$ 1:1 | 263 | 12 | 275 | 51 | 2.62 | 513 | 1 344 | 195 | 144 |
| | CAN/cCAN$_4$ 1:2 | 255 | 12 | 267 | 43 | 2.80 | 513 | 1 436 | 287 | 244 |
| | CAN/cCAN$_6$ 1:2 | 280 | 12 | 292 | 68 | 2.52 | 513 | 1 293 | 144 | 76 |
| 3 | CAN + UAN + UAN | 207 | 36 | 243 | 0 | 2.24 | 419 | 939 | 0 | 0 |
| | CAN/cCAN$_4$ 1:1 | 269 | 12 | 281 | 38 | 2.54 | 419 | 1 064 | 125 | 87 |
| | CAN/cCAN$_6$ 1:1 | 290 | 12 | 302 | 59 | 2.62 | 419 | 1 098 | 159 | 100 |
| | CAN/cCAN$_4$ 1:2 | 281 | 12 | 293 | 50 | 2.80 | 419 | 1 173 | 234 | 184 |
| | CAN/cCAN$_6$ 1:2 | 308 | 12 | 320 | 77 | 2.52 | 419 | 1 056 | 117 | 40 |

Scenario: 2024 – actual prices in spring 2024; 1 – an increase cost in N fertilizers by 10% but fixed commodity price; 2 – an increase in commodity price by 10% with fixed N fertilizers cost; 3 – an increase in N fertilizers cost by 10% and a decrease in commodity price by 10%. * Increase in fertilizer costs (€/ha) = Total fertilizer cost of examined blends (€/ha) – Total fertilizer cost of control treatment (€/ha). ** Revenue increase (€/ha) = Total revenue of examined blends (€/ha) – Total revenue of control treatment (€/ha). *** Net profit (€/ha) = Revenue increase (€/ha) – Increase in fertilizer costs (€/ha to the control treatment on the contrary to wheat (insignificant differences), which resulted in higher revenues and net profit for every coated blend in every scenario,

The average oil content (%) and oil production (t/ha) of oilseed rape is described in Table 6. It is evident that the average oil content in seeds after the single fertilization with uncoated and coated blends (CAN/cCAN) decreased in both experimental seasons at both sites compared to the control treatment with three split nitrogen doses. The CAN-UAN-UAN provided an overall average oil content of 43.1%, the decrease after the application of examined coated blends was within the range of 1.4-2.0 of relative %. The average oil production was expressed from average seed yield and oil content. It is evident that the application of the examined treatments with cCAN resulted in a total higher production of oil despite the lower oil content due to the higher yields of seed. While the correlation between oil production and oil yield was insignificant ($r$ = -0.076, $p = 0.501$), seed yield had a significant impact on oil production ($r$ = -0.985, $p < 0.001$). At Žabčice, the blends with CAN/cCAN$_4$ resulted in 1.3 t/ha (1:2 ratio) and 1.2 t/ha (1:1), which is an increase of 30.0%, respectively 20.0% compared to the control treatment (1.0 t/ha). Blends with cCAN$_6$ produced 1.2 (1:1 ratio), respectively 1.1 t/ha of oil (1:2 ratio). The highest oil production at Vatín was also observed after the application of CAN/cCAN$_4$ in a 1:2 ratio (1.1 t/ha). This represents a significant increase of 22.2% compared to the control (0.9 t/ha).

## 4 Discussion

The most important indicator of agricultural production is crop yield. The higher the yield, the higher the potential profit. Another important factor related to the higher yield is a potential food security or optimal food production (Mansouri et al. 2023). Although it is evident from the presented results that the single application of the CAN/cCAN blend did not result in a significant increase in winter wheat grain at either experimental site, it is necessary to point out that the obtained yields were almost identical to the control treatment based on three split nitrogen applications. Therefore, similar yields with no statistical differences can be considered as a positive result for coated fertilizer blends, as they were applied only in a single dose in early spring in comparison with commonly used technology with three split doses of nitrogen applied during the critical stages of vegetation. Logically, the nutrient availability from single applied coated fertilizers is declining over time (later in vegetation), as the mechanism of release can be characterized as a three-stage sigmoidal and non-linear curve (Lawrencia et al. 2021; Mansouri et al. 2023). Due to this mechanism, the CRF is able to provide nutrients more gradually and for longer period, however, the split fertilization by nitrogen can possibly provide a more nutrients after each fertilization (with a higher risk of environmental loss). For example, El Gharrak et al. (2022) are also referring to the extended-release duration of 100% of nutrients from oil-based coated NPK fertilizer in the soil (laboratory conditions) with maximal longevity of up to 70 days in comparison with the uncoated NPK. Thus, our result obtained from field conditions at two sites and two growing seasons confirms that the coated fertilizers with controlled nitrogen release can indeed positively influence the grain yield due to the slower release of nitrogen corresponding with the nutrient demands of crops (Wesołowska et al. 2021) while lowering the number of applications, therefore requiring less field crossing (fuel, soil compaction, etc.). On average (both growing seasons, both sites), the relatively highest yield of grain (8.7 t/ha) was determined after the single fertilization with blend

**Table 6** The average values of oil content and oil production (Žabčice and Vatín)

| Treatment | Žabčice | | | Vatín | | | Overall Average |
|---|---|---|---|---|---|---|---|
| | 2019/2020 | 2020/2021 | Average | 2019/2020 | 2020/2021 | Average | |
| | | | **Oil content (%)** | | | | |
| CAN + UAN + UAN | 40.8a ± 0.2 | 42.3a ± 0.7 | 41.6a ± 0.9 | 44.9a ± 0.3 | 44.5a ± 0.3 | 44.7a ± 0.4 | 43.1a ± 1.8 |
| CAN/cCAN$_4$ 1:1 | 40.5ab ± 0.2 | 42.5a ± 0.7 | 41.5a ± 1.2 | 43.0b ± 0.2 | 44.1a ± 0.7 | 43.6b ± 0.8 | 42.5b ± 1.4 |
| CAN/cCAN$_6$ 1:1 | 40.3b ± 0.3 | 41.6a ± 0.7 | 41.0b ± 0.8 | 43.3b ± 0.9 | 43.8a ± 0.5 | 43.6b ± 0.7 | 42.3b ± 1.6 |
| CAN/cCAN$_4$ 1:2 | 40.7ab ± 0.3 | 41.6a ± 0.3 | 41.1ab ± 0.6 | 43.3b ± 0.6 | 44.4a ± 0.5 | 43.8b ± 0.8 | 42.5b ± 1.5 |
| CAN/cCAN$_6$ 1:2 | 40.7ab ± 0.4 | 41.6a ± 0.5 | 41.2ab ± 0.6 | 43.6b ± 0.9 | 44.2a ± 0.8 | 43.9b ± 0.9 | 42.5b ± 1.6 |
| | | | **Oil production (t/ha)** | | | | |
| CAN + UAN + UAN | 0.8b ± 0.2 | 1.2a ± 0.2 | 1.0b ± 0.2 | 1.1a ± 0.2 | 0.8b ± 0.1 | 0.9a ± 0.3 | 1.0b ± 0.2 |
| CAN/cCAN4 1:1 | 1.1a ± 0.0 | 1.3a ± 0.3 | 1.2ab ± 0.2 | 1.0a ± 0.1 | 1.0ab ± 0.2 | 1.0ab ± 0.1 | 1.1ab ± 0.2 |
| CAN/cCAN6 1:1 | 1.0ab ± 0.1 | 1.3a ± 0.2 | 1.2ab ± 0.2 | 1.1a ± 0.3 | 1.0ab ± 0.1 | 1.1a ± 0.2 | 1.1ab ± 0.2 |
| CAN/cCAN4 1:2 | 1.1a ± 0.1 | 1.5a ± 0.3 | 1.3a ± 0.3 | 1.1a ± 0.0 | 1.1a ± 0.0 | 1.1a ± 0.0 | 1.2a ± 0.2 |
| CAN/cCAN6 1:2 | 1.0a ± 0.0 | 1.2a ± 0.3 | 1.1a ± 0.2 | 1.1a ± 0.1 | 0.9ab ± 0.2 | 1.0ab ± 0.2 | 1.1ab ± 0.2 |

Results are expressed as the mean ± standard deviation. The mean values with different letters are significantly different ($p < 0.05$) according to the LSD test. Each growing season and its average were evaluated separately

CAN/c$CAN_4$ 1:1. This represents an increase of 0.1 t/ha compared to the control (8.6 t/ha), although it was statistically evaluated as insignificant. This relative increase in grain yield together with lower application cost resulted in higher revenues and most importantly, the treatment CAN/c$CAN_4$ 1:1 was profitable in every examined scenario with winter wheat (increase from 6 to 16 €/ha) compared to the control treatment. On the contrary, the relatively lowest (statistically insignificant) average yield (8.5 t/ha) was determined after the application of a thicker coat (c$CAN_6$) in a 1:2 ratio. The relatively lower yield of wheat grain together with higher price of c$CAN_6$ turned to be unprofitable in every scenario in comparison with control treatment (CAN + CAN + UAN), despite the lower cost of application. One of the important factors of nutrient release from CRF is therefore coat thickness (dos Santos et al. 2021; Ganetri et al. 2021; Mikula et al. 2020) and a price of coating. The coating thickness has an inverse relationship with the release rate of nutrients from fertilizers (Ahmad et al. 2015). It is evident from presented result that the blend with 6% wt. coat in combination with a higher proportion of cCAN at the expense of quickly available N from uncoated CAN resulted in the slower availability of nitrogen early in vegetation, therefore in relatively lower yields. Additionally, the soil moisture was described as the most important factor in N release characteristics from CRF (Verburg et al. 2021), despite the coating material and thickness. Similar findings are also hinted by Fan et al. (2022). The positive effect of coated fertilizer and an increase in the yield of wheat are also described by several authors (Fan et al. 2022; Gil-Ortiz et al. 2020b; Shivay et al. 2016, 2017), although most of these publications focus on coated urea. The financial benefit is the major factor for farmers when selecting a fertilization strategy. The fertilization with CRF can present a possible optimalization of total profit, as it is described by Zhang et al. (2021). They demonstrated that a single application of blending urea (coated controlled-release urea and uncoated common urea) saved half of the labour expenses, which balanced the higher fertilizer N prices. Thus, the farmer's financial earnings were not affected by the implementation of CRF and could potentially been in fact improved. This partially corelated with presented results, where the total average grain yields after the single fertilization with coated blends were statistically equivalent to the split fertilization by nitrogen, which resulted in profitable treatment with thinner coated fertilizer in balanced ratio with uncoated fertilizer (CAN/c$CAN_4$ 1:1). On the contrary, the highest dose of coated urea, similar to the application nitrogen dose in our research (188 kg/ha), did not result in a significantly increased yield of grain over a 5-year experiment, as described by (Yan et al. 2022). A similar experiment to ours, although also with urea, was described by (Zheng et al. 2017). They examined the effect of uncoated and coated blends of urea, which also resulted in a positive effect on the grain yield. The different ratios of coated and uncoated urea were also examined by Farmaha and Sims (2013). They reported that the increased proportion of coated fertilizer resulted in comparable or even decreased grain yields. Overall, however, the application of coated fertilizer (mostly urea, sometimes MAP, NPK) is in the literature described as a positive, even for other types of crops (Qu et al. 2020; Shao et al. 2013; Shivay et al. 2019; Tian et al. 2017; Xu et al. 2015). Our results also showed a positive response of oilseed rape to every examined blend of uncoated and coated CAN in terms of average seed yield. Similar results were reported by Tian et al. (2016) or Lu et al. (2015). A single application of sulphur-coated urea significantly increased oilseed rape yield by 6.3–15.5% compared to the split application of conventional urea applied at three development stages of the oilseed rape (Geng et al. 2015). The biochar-coated urea increased nitrogen use efficiency by up to 20% compared to urea fertilizer in the oilseed rape experiment (Jia et al. 2021). Based on the results of their research, Liu et al. (2019) report that the application of urea coated with plant oil material generally increased seed yield relative to convention urea, and such effects were more pronounced at higher N rates (180 and 240 kg/ha) because of the sufficiency of the N supply over the whole growing season. The highest, statistically significant, average seed yield (both growing seasons, both sites) was observed after the fertilization with CAN/c$CAN_4$ 1:2 (2.8 t/ha) closely followed by both treatments with the 1:1 ratio (2.6 t/ha after CAN/c$CAN_6$ 1:1; 2.5 t/ha after CAN/c$CAN_4$ 1:1). The application of fertilizers blend containing the higher ratio (1:2) of cCAN with a thicker coat resulted in the lowest yield (2.5 t/ha), although it was still significantly higher compared to the control treatment (2.2 t/ha). Therefore, the economic evaluation of oilseed rape production resulted in higher revenues for every treatment with blend application, also due to the higher purchase price of seed in comparison with wheat grain. Most importantly, the examined treatments with coated fertilizers were profitable in every scenario with oilseed rape after the subtraction of increase in fertilizer price of coated CAN. The lowest net profit was observed after the treatment CAN/c$CAN_6$ 1:2. These results in combination with economic evaluation of winter wheat production support the idea that the use of CAN with the thicker coat (c$CAN_6$), the ratio of which in the fertilizer blend is 2/3 of the total applied nitrogen, will result in less suitable release and supply of nitrogen in comparison with the thinner coat (c$CAN_4$) and even ratio in blends, where the portion of quickly available and coated nitrogen are the same (1:1). In addition to the increase crop yield, another positive of coated fertilizers is the reduction of nitrogen loss, as it was described by many authors (Mansouri et al. 2023; Zheng et al. 2017) and even by our previous work with coated CAN fertilizers (Škarpa et al. 2021). Thus, based on the results obtained and the literature cited, it can be concluded that a single application of coated fertilizer blend is at least as effective in terms of crop yield as fertilization with nitrogen in conventional fertilizers several times during the growing season, if not more efficient. The economic evaluation of coated fertilizers is heavily dependent on the fluctuated market prices of commodities, but it can be profitable.

The qualitative parameters of cultivated crop are also an important indicator of optimal fertilization strategy. It is necessary to at least meet the minimal criteria (at best exceed it) of quality for good monetization, especially for winter wheat grain. In terms of quality, the HW, protein content, gluten content and index of sedimentation were evaluated in winter wheat grain; the oil content and oil production were evaluated in oilseed rape seed. The average result from two growing seasons at Žabčice showed, that the application of coated fertilizer in blends did not statistically influence any of the examined parameters of wheat grain, which is similar to (McKenzie et al. 2007). Again, such a result can be considered as a positive, as the slower nitrogen in CRF applied in a single dose still managed to support the quality of winter wheat to the equivalent levels compared to the control fertilization treatment with three split nitrogen applications. The relatively highest quality (although statistically insignificant), especially protein and gluten content, was observed after the fertilization with a blend of thinner coated $CAN_4$ in an even ratio of 1:1 with uncoated CAN. Similar findings is described by (Farmaha and Sims 2013). On the contrary, the qualitative parameters of winter wheat grain observed at experimental site Vatín showed statistical differences between the examined treatments. Most notably, the mentioned treatment $CAN/cCAN_4$ 1:1 provided significantly lower values of every parameter in comparison with the control treatment. It is necessary to mention that the average grain yield after this treatment was relatively higher by 3.3% in comparison with the control, which may provide an explanation of lower qualitative parameters at this less suitable site for crop growing. It was also proved, that it is not unusual for the qualitative parameters to decrease, as the grain yield increases (Bloom and Plant 2021). The single application of nitrogen in an evenly blend of CAN/cCAN with a thinner coat possibly results in its quicker utilization during the vegetation to promote biomass and yield formation. This is supported by general consensus, that N applied early in the growing season contributes mostly to the grain yield, while N supplied later in the vegetation contributes mostly to the grain quality, especially protein content (Woolfolk et al. 2002). Thus, the nitrogen was in deficit in the later stage of vegetation. This hypothesis is also supported by the obtained result of the examined blend CAN/$CAN_6$ 1:1. This treatment with the same ratio of coated and uncoated CAN, however with a thicker coat resulted in comparable (statistically insignificant) values of qualitative parameters in comparison with the control treatment. This may indicate that the release of nitrogen was slower due to the thicker coat, therefore, the nitrogen supply to the plants during the later vegetation stages was more suitable. The content of oil is an important parameter in oilseed rape production and monetization. The relationship between the optimal nitrogen supply and its impact on the yield and oil content of rapeseed has been described in several studies (Gu et al. 2017; Remya et al. 2021). It is evident from the presented results that the oil content was lower at every examined treatment in both growing seasons and at both experimental sites compared to the control. This could possibly be explained by the “dilution effect” (Olff et al. 2002). The younger the plants, the higher the nutrient concentrations. The more the plants grow, the lower the concentration of nutrients. It is evident from our result that the nitrogen in applied fertilizers was positively utilized for yield formation, thus, the higher seed yield (on average by 19% higher at Žabčice and by 14% higher at Vatín) resulted in a lower content of oil in seeds. It is necessary to mention again that the control treatment was based on three split nitrogen fertilization, while the examined treatments with coated CAN were applied only in a single application in early spring. On the contrary, the production of oil (t/ha) expressed from the average yield of seed and oil content again in favour of the examined treatments with the application of coated fertilizers, as the average production of oil was by 18% higher than control at Žabčice and by 12% higher at Vatín. The results are consistent with a previous study (Škarpa et al. 2021) where a single application of CAN coated with oil-based polyurethane polymer and oil-based polymer significantly increased the oil production of oilseed rape. Therefore, oilseed rape fertilized with a blend of uncoated and coated CAN produces more oil compared to conventional technology, mainly due to higher yields of seeds. Thus, in terms of quality, the obtained results indicate that a single application of nitrogen in coated fertilizers blend is comparable to the split nitrogen fertilization in conventionally used fertilizers. This commonly used technology resulted in higher values of examined parameters, probably because of the nitrogen application at later vegetation stages.

## 5 Conclusion

The use of a unique CRF, calcium ammonium nitrate coated by oil-based polymers (cCAN) in examined blends and ratios with uncoated CAN appears to be a very promising strategy for fertilizing winter wheat and oilseed rape. Application of these blends represents a cost saving in crop fertilization and a reduction in environmental burden while increasing the yield of harvested products and maintaining the parameters of quality. The potential of cCAN coated with a 4 wt% coat applied with CAN at 1:1 and 1:2 ratios was found out in the field experiment with winter wheat, while their use significantly increased seed production in the experiment with oilseed rape.

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## Declarations

**Competing Interests** The authors declare no competing interests.

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