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REVIEW PAPER

Enhancing productivity and technological quality of wheat and oilseed rape through diverse fertilization practices – an overview*

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Abstract

Through literature review, the study compares the effects of diverse fertilization types (mineral, organic, and mineral-organic) on wheat grain and rape seed quality parameters. It was emphasized that balanced fertilization of plants is essential for maximizing yield while maintaining its high technological quality, and that the technological value of wheat grain and rape seeds depends primarily on the genetic characteristics of their cultivars. In addition to genetic traits, the qualitative characteristics of the generative yield are significantly influenced by agrotechnical treatments, including fertilization. The amount and type of fertilizer applied directly translates into the volume and quality of the crop, determining its subsequent use (e.g. for consumption, fodder or energy purposes). It was noted that particular attention is paid in the scientific literature to nitrogen fertilization and its impact on the yield and technological value of the feedstock. Much less emphasis is placed on the impact of fertilization with other mineral nutrients. This study reviews the literature to compare the effects of different types of fertilization (mineral, organic, and mineral-organic) on the qualitative parameters of wheat grains and rape seeds. The most important quality parameters of wheat and oilseed rape were presented in this paper. They were yield, protein content, gluten content and quality, starch content, and sedimentation index for wheat, and yield, erucic acid content, oiliness, and glucosinolate content for oilseed rape. This review proves that there is a need for greater focus on the use of combinations of organic and mineral fertilizers. Reducing fertilizer use while maintaining or even improving seed yield and quality is an ongoing environmental and economic challenge. This can make sustainable production and agriculture more environmentally friendly, especially in the face of climate change. Moreover, constant increase of wheat and rapeseed production is crucial for satisfying diverse needs of a growing global population, e.g. to ensure food security, support industries, and promote sustainable agriculture.

Keywords: yield qualitative parameters, fertilizers, soil, wheat grain, oilseed rape

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INTRODUCTION

In today's agriculture, and especially in crop production, the use of innovative technologies is of great importance, mainly the application of hardware and software technologies, including positioning and imaging satellites, deployment of sensor networks that monitor the condition of crops, e.g. soil moisture content, soil nutrient abundance or plant nutritional status (Bacco et al. 2019). Modern agricultural production requires the development of these technologies so that they can be safely used in all elements of the ecosystem, especially in agricultural crops (Apaeva et al. 2020). The growing worldwide demand for plant biomass due to increasing food and energy needs has led to a rise in the production of cereals (wheat, rice, and corn) and protein and oilseed crops (soybeans, rapeseed). Between 1998 and 2017, grain production increased by 2% annually, while the production of oilseed crops grew at a much higher rate of 5-6% per year (Sokólski et al. 2020). Globally, wheat production in 2021 reached 771 million tons, while in Poland its production is almost 12 million tons. As regards oilseed rape, the latest data from 2020 show that global production was 25 million tonnes, and 1 million tonnes in Poland.

The world is striving to constantly increase the production of wheat and rapeseed for several reasons. Wheat is one of the most important staple foods globally, thus increasing its production helps to ensure food security and meet the growing demand for food as the world's population increases. Increasing wheat and rapeseed production helps keep up with the food demand that is growing with the ever-increasing global population (Chmielewska et al. 2021). Besides, wheat and rapeseed are valuable sources of nutrients, including proteins, fats, vitamins, and minerals. Adequate production helps to meet the nutritional needs of people and animals. Rapeseed is used to produce high-quality oil for human consumption, but its by-product (rapeseed meal) is used as animal feed. Meeting the demand for livestock feed is essential for the growth of livestock industry. Apart from food, wheat and rapeseed have various industrial applications. Wheat is used in the production of flour, starch, biofuels, and other products, while rapeseed is processed for edible oil, biodiesel, and industrial uses. Wheat and rapeseed are major commodities in international trade, contributing significantly to the economies of many countries. Increased production can enhance export opportunities and boost economic growth. Including wheat and rapeseed in crop rotations helps improve soil health, prevent pest and disease buildup, and promote sustainable agricultural practices. Rapeseed is an essential feedstock for biodiesel production. As the world seeks to reduce reliance on fossil fuels and transition to cleaner energy sources, increasing rapeseed production becomes vital for biofuel production. Overall, the constant increase in wheat and rapeseed production is crucial for meeting diverse needs of a growing global population, ensuring food security, supporting industries, and promoting sustainable agriculture (Sharma et al. 2015, Chmielewska et al. 2021).

The technological value of quality wheat grain and rape seeds depends primarily on the genetic characteristics of their cultivars. In addition to genetic traits, the qualitative characteristics of the generative yield are significantly influenced by agrotechnical treatments, including fertilization. The basic principle in modern plant fertilization (including that of wheat and oilseed rape) is to fertilize strictly according to the nutritional needs of the plants, which corresponds to the amount of a nutrient that plants need to take up during their ontogenetic development to produce good quality yield (Bacco et al. 2019). Depending on the abundance of the soil and its fertility, nutritional needs of plants in rational fertilization are covered in part (and in the case of micronutrients, sometimes even entirely) by nutrients from the natural resources of the soil, and only secondarily from natural or mineral fertilizers (Kocoń 2005). Wheat grain and rape seeds intended for consumption should have a high technological value. In the scientific literature, particular attention is paid to nitrogen fertilization and its impact on the yield and technological value of the feedstock. Much less emphasis is placed on the impact of fertilization with other mineral nutrients.

Both deficiency and excess of nutrients can lead to deterioration of the productive function of the soil. The use of fertilizers aimed at supporting crop production is intended to supplement the nutrients in the soil as well. This supports plant growth and development, which translates into the quantity and quality of yield. On the other hand, excessive use of fertilizers can lead, *inter alia*, to groundwater and surface water pollution as well as nutrient losses through leaching into the soil profile. Therefore, fertilizers should be applied at optimal doses to ensure sustainable agricultural production in line with the principles of environmental protection (Zeng et al. 2018, Kumar et al. 2019).

Economic aspects (fertilizer and fuel prices) as well soil and climatic conditions are among the biggest constraints to the intensification of crop production. In the case of the latter, a special role is played by soil's organic matter (OM) content and pH, as they have fundamental influence on the bioavailability of nutrients supplied with fertilizers. These parameters indirectly contribute to meeting plant needs by shaping the rate of nutrient release and the level of nutrient bioavailability to plants, and consequently affect the general-use characteristics of yield. For both studied crops, the basis for rational fertilization is a regulated soil pH. The lower limit of optimum soil pH is 6.0 for winter wheat and 5.5 for spring wheat on light soils as well as 6.5 and 6.0, respectively, on heavy soils (Kocoń 2005). For oilseed rape, the pH needs to be regulated to a range of 6.0-7.0 (Podleśna 2014). It should be noted that both crops are very sensitive to low soil pH and react strongly to soil acidification with a decrease in yield.

Wheat is the primary agricultural plant in the crop structure worldwide (3^{rd} place in world production, after maize and rice), while oilseed rape is the most important industrial crop in some countries, like Poland and Germany (Russo et al. 2021). The yield of both plants as well as the quality of the yield produced, in addition to the aforementioned soil and climatic conditions, depend on the position in crop rotation, the species and cultivar, the method of plant protection and fertilization, and the soil cultivation technology. Given the fact that human influence on soil and climatic factors is negligible, optimization of agrotechnical factors, including balanced fertilization, becomes a priority. Macronutrient requirements of individual plant groups depend on the production of different amounts of biomass of stems, leaves, roots, and the size of generative parts (Table 1).

Table 1

Nutrient requirements of selected crops (Podleśna 2014, Jarecki, Czernicka 2022)

Plant	Component (kg t^{-1} seed including straw)					
	N	P	K	Ca	Mg	S
Cereals	25	4	20	5	2	4
Oilseed rape	55	13	52	40	6	16

Quantities of nutrients are ascertained via meticulous soil testing and the consideration of nutrient depletion ensuing from the harvest of grains and straw. A winter wheat crop yielding 6.7 tonnes of grain per hectare engages approximately 200 kg of nitrogen (N), 55 kg of phosphorus (P_2O_5), and 252 kg of potassium (K_2O) per hectare. Within subtropical Indian contexts, a crop producing 4.6 tonnes of grains and 6.9 tonnes of straw absorbs 128 kg of nitrogen, 46 kg of phosphorus, 219 kg of potassium, 27 kg of calcium (Ca), 19 kg of magnesium (Mg), 22 kg of sulfur (S), 1.8 kg of iron (Fe), 0.5 kg of zinc (Zn), 0.5 kg of manganese (Mn), and 0.15 kg of copper (Cu). Approximately 70% of the absorbed nitrogen and phosphorus, as well as 20-25% of the absorbed potassium culminate in grain development. The nutritional requirement is minimal pre-winter, surging during robust spring growth, with ear emergence accounting for 80% of nutrient uptake. These nutrient needs exhibit variations contingent upon soil quality, climatic conditions, cultivar attributes, and anticipated yield (Roy et al. 2006).

Oilseed rape necessitates a substantial and well-timed nutrient supply to ensure robust growth and elevated seed yield. A crop yielding 4.5 tonnes of seed per hectare absorbs a total amount of nutrients in the order of (in kilograms): nitrogen (N) 300-350, phosphorus (P_2O_5) 120-140, potassium (K_2O) 300-400, magnesium (Mg) 30-50, and sulfur (S) 80-100. The seeds predominantly house the nutrient reservoir, with the exception of potassium (K), which mainly resides in the straw. Notably, around 20% of the overall nutrient uptake occurs pre-winter, while approximately 50% transpires during the spring phase preceding flowering (Roy et al. 2006).

The amount and type of fertilizer applied directly translates into the size and quality of the crop, determining its subsequent use (e.g. for consumption, fodder or energy purposes) (Litke et al. 2018). The use of wheat and rape for consumption or fodder purposes is determined by different parameter values. The parameters determining the technological value of wheat grains for consumption purposes in the European Union, according to their intended use, include (Sagan et al. 2019, Leslie et al. 2021, So, Raboanatahiry et al. 2021, Guzmán et al. 2022, Prieto-Vázquez del Mercado et al. 2022, Klikocka, Szczepaniak 2023):

A) maximum humidity – 14.5%;

B) maximum content of impurities – 6%;

C) minimum grain density in bulk state – should be at least 72 kg hl^{-1}, although it is best if it exceeds 76 kg hl^{-1};

D) falling number – for wheat, the falling number should be no less than 220 seconds;

E) Zeleny's sedimentation index – grain intended as a raw material for flour should have a value of this index above 25 ml. Meanwhile, an index below 20 ml indicates the use of grain for fodder purposes;

F) protein content – should not be lower than 12.5%; however, grain intended for use as an improver in milling mixtures with grains of low or medium baking value should have a minimum of 14% protein;

G) gluten content – 26%.

On the other hand, in the case of oilseed rape, these are: seed yield, erucic acid content in fat, oiliness, seed protein and starch contents (Sharma, Chetani 2017, Cesarano et al. 2017). Rapeseed seeds in the European Union should meet the following quality parameters (Regulation (EC) of the European Parliament and of the Council No 183/2005):

A) moisture: max. 9%,

B) total impurities: max. 2%,

C) inert impurities: max. 1%,

D) oil content: min. 40%,

E) erucic acid content: max. 2%,

F) glucosinolate content: max. 25 μmol g^{-1} of defatted dry matter,

G) polyunsaturated fatty acid content: max. 2%,

H) germinated seed content: max. 1%,

I) rapeseed free from live pests, healthy, of commercial quality, with a distinctive aroma.

Seeds and grains that do not meet these consumption requirements are used for fodder or for industrial purposes. In the case of wheat, parameters such as grain size, weight, and color are key determinants of grain edibility. A higher content of nutrients and desirable baking properties of wheat are useful for making bread and bakery products. Wheat gluten content and quality play a significant role in determining its suitability for bread and other bakery products. Gluten provides the elasticity and structure needed in dough for baking. For rapeseed, the oil content is critical. High-quality rapeseed for consumption purposes should be characterized by a high oil content, as it is mainly used for making cooking oil. However, the composition of fatty acids in rapeseeds influences the quality of the oil produced, especially with regard to its taste, stability, and health benefits. All wheat and rapeseed must be up to strict quality standards to be free of toxins and other sources of harmful substances that may would make them unfit for human consumption. In addition to the quality standards provided for nutrients, the nutritional profile, including such as nutrients vitamins, minerals and amino acids, is essential to assess their suitability for the human diet (Sagan et al. 2019, Leslie et al. 2021, So, Duncan 2021, Guzmán et al. 2022, Prieto-Vázquez del Mercado et al. 2022).

In turn, as regards fodder purposes, the protein content becomes important, which determines the nutritional value of feed for livestock. Higher protein content is desirable to support animal growth and health. In addition, the feed needs to have the right fiber content to aid digestion in livestock. In addition to the important quality parameters of wheat and rape seeds, their availability and cost on the local market affect their use as fodder. In general, the decision to use wheat and rapeseed for consumption or feed purposes depends on their specific quality characteristics and how well they meet the nutritional requirements of humans or livestock, respectively (Raboanatahiry et al. 2021, Klikocka, Szczepaniak 2023).

Nowadays, innovative solutions are constantly being sought in fertilizer production technology that would take into account not only the problems of modern agriculture (including drought, steadily decreasing organic matter content of soils, acidification), but also efforts to achieve climate neutrality in Europe. Increasing attention is focused on the production of mineral-organic fertilizers that will provide plants with nutrients, and on the other hand, rebuild soil organic matter reserves when applied systematically. The European Commission is also constantly looking for solutions for sustainable agricultural production by implementing successive strategic plans that aim, among other things, to increase biodiversity and decarbonize the agricultural sector.

This study aims at reviewing the current state of knowledge and evaluating the effects of different types of fertilization on the quality parameters of wheat grains and rape seeds.

FERTILIZER TYPES – SHORT CHARACTERISTIC

The legal basis for fertilization in Poland is set out in the Act of 26 April 2007 on fertilizers and fertilization (Act on fertilizers and fertilization, Journal of Laws 2021, item 89, as amended). This law regulates the production, marketing, and use of fertilizers, as well as the principles of control and supervision of fertilization in Poland. According to this act, fertilizers are "products intended to provide plants with nutrients or increase soil fertility or increase the fertility of fish ponds, which are mineral fertilizers, natural fertilizers, organic fertilizers and organic-mineral fertilizers." The legal act divides fertilizing products into: mineral fertilizers, natural fertilizers, organic fertilizers, organic-mineral fertilizers, soil conditioners, growth promoters, plant boosters, and microbial fertilizer products. In modern agriculture, the efficiency of fertilization should be measured by the increase in crop yield and ecological effects. That principle can be met with the use of balanced fertilization, covering the needs of plants for nutrients brought into the soil, e.g. with organic and mineral fertilizers (Roberts, Mattoo 2018).

Mineral fertilization

Mineral fertilization is one of the most common types of fertilization. According to the accepted definition, mineral fertilizers are "non-EU inorganic fertilizing products produced by chemical or physical transformation or processing of mineral raw materials, including fertilizer lime, e.g. fertilizer lime containing magnesium, as well as some fertilizers of organic origin" (Act on fertilizers and fertilization, Journal of Laws 2021, item 89, as amended). These fertilizers are quickly absorbed by plants and can effectively make up for nutrient deficiencies in the soil. The advantage of mineral fertilization is that individual nutrients can be precisely dosed and tailored to specific plant needs (Kumar et al. 2019). Mineral fertilizers are an important element allowing stable and high yields of good quality grain (Panfilova et al. 2020).

Organic fertilization

The main advantages of organic fertilization are increased organic matter content of the soil and improved soil structure, including water and nutrient retention (Kumar et al. 2019). According to Polish legislation, organic fertilizers are "non-EU fertilizing products produced from organic matter or mixtures of organic matter, including composts, as well as composts produced using earthworms" (Act on fertilizers and fertilization, Journal of Laws 2021, item 89, as amended). In agriculture, these fertilizers are mainly made from organic plant or animal residues (e.g. compost, vermicompost, manure, slurry).

Mineral-organic fertilization

Mineral-organic fertilizers combine the advantages of both mineral and organic fertilizers. On the one hand, their use plays an important role in optimizing the pool of nutrients by supplying them to plants in readily available mineral forms. On the other hand, they support the process of restoring soil organic matter reserves. As reported by Zhang et al. (2016), the application of mineral-organic fertilizers can have a beneficial effect on crop growth and quality, as mineral fertilizers are quickly absorbed by plants and can effectively replenish nutrient deficiencies, while organic additives improve the structure of soil and its ability to store nutrients. The fertilizing effect of mineral-organic fertilizers is spread out over time due to the introduction of nutrients bound to organic matter which are released in the process of soil mineralization.

EFFECT OF FERTILIZATION ON SELECTED QUALITATIVE PARAMETERS OF WHEAT GRAIN AND RAPE SEEDS

Results of quality parameters of wheat grain

Fertilization, especially with nitrogen, is a factor that strongly shapes yield and its quality. It also has a major impact on plant health. Wheat (*Triticum aestivum* L.) is one of the world's most important crops and it plays a key role in maintaining global food security. Previous studies showed that the increased level of nitrogen fertilization is accompanied by an increase in wheat yield, and usually an improvement in the technological quality of grain (Kocoń 2005, Cacak-Pietrzak, Sułek 2007). When the optimum nitrogen dose is exceeded, grain yield may decrease and grain quality may deteriorate. According to Ralcewicz, Knapowski (2004), nitrogen administered in the initial period of growth and development affects mainly the yield, while when administered at later stages of wheat development, it has a particularly beneficial effect on yield quality, i.e. technological characteristics of grain (Hlisnikovský et al. 2020). Numerous studies on fertilization of quality wheat with nitrogen clearly showed that as nitrogen rates increase in the substrate (from 160 to 180 kg N ha^{-1}), grain yield as well as protein and gluten contents in grain also increase. The distinguishing features of wheat as a valuable cereal are its high productivity and multiple application options (Yue et al. 2019, Hlisnikovský et al. 2020, Panfilova et al. 2020). The main priority for wheat remains the continuous improvement of grain yield and quality to meet the growing market demand, which is a consequence of the ever-increasing global population. The quality of wheat grain depends on its species, soil and climatic conditions, and good management practices in crop production (e.g. fertilization, use of crop protection products), irrigation regime, sowing date and density, use of catch crops or crop rotation. Among these strategies, the nitrogen fertilizer application method is generally the most effective way to increase grain yield and grain protein content in wheat production (Wu et al. 2019, Hlisnikovský et al. 2020). Below is a brief description of selected wheat quality parameters.

Grain yield

To address the challenge of the rising population growth and shrinking arable land, enhancing grain yield is crucial for satisfying food demands. Grain yield relies on factors like spike density, kernels per spike, and kernel weight. These components can be improved through advanced cultivars and nutrient management. Effective fertilizer use is vital for sustainable yields, increased nutrient efficiency, and conservation of resources. Both macro- and micronutrients significantly influence crop nutrition, fostering higher yields and robust plant growth (Mikos-Szymańska et al. 2018, Sabbahi et al. 2023). Fordoński et al. (2015) determined that the weather conditions during the winter oilseed rape growing season were conducive to the species' growth, winter survival, and yield.

Grain density in bulk state

It is one of the basic parameters determining grain quality. The density of wheat grain indicates the suitability of grain for milling. Ideal grain for milling reaches the density of 76 kg hl^{-1}, but a result oscillating around 72 kg hl^{-1} allows the grain to be classified as quality grain (Mikos-Szymańska et al. 2018).

Protein content in grain

Grain protein content is a crucial trait that influences the nutritional quality of wheat grain and the quality of end products made from wheat flour. It holds significant importance in wheat breeding programs focused on enhancing quality traits. The primary factor determining the usefulness of its grains and thus flour for bread baking is the appropriate content of total protein, which is influenced by genetic traits (Ktenioudaki et al. 2011). The minimum protein content in wheat for consumption processed by the milling industry should be 12.5% so that the end product of milling, i.e. flour, is characterized by good parameters (Tao et al. 2018). Other fundamental quality parameters of winter wheat grains are Farinograph Falling Number (FZM), bulk density, wet gluten content, or sedimentation index. These technological characteristics determine the quality of bread, which has been a well-known source of nutrition for humans since ancient times. By 2050, cereal production needs to increase by approximately 40% to ensure global food security. Regardless of this challenge, enhancing the production of nutritious wheat grains with improved quality remains a significant goal in wheat breeding programs. Consuming grains or grain products that lack sufficient protein can negatively impact human health, leading to protein malnutrition, 'hidden hunger' (micronutrient malnutrition), and various diseases (Balyan et al. 2013). The optimal range for achieving higher protein content in wheat production lies within the nitrogen application doses of approximately 80 kg N ha^{-1} to 120 kg N ha^{-1} (Klikocka et al. 2016). Furthermore, incorporating appropriate NPK and sulfur fertilization practices can significantly enhance protein content in wheat grain (Tao et al. 2018).

Gluten content

A commonly used indicator determining the quality of the wheat grain protein complex is the determination quality and quantity (flowability) of wet gluten. The better the quality of gluten (i.e. lower spreadability) and the higher its amount, the better the grain is for the production of flour for baking bread. Gluten consists of storage proteins: gliadin and glutenin. Gluten content and its properties, i.e. ductility, elasticity and resistance to spreading determine the properties of wheat dough. The higher quantity and quality of gluten, the better raw material characteristics of the grain for the production of flour. The minimum gluten value required in mills is 26% because a lower gluten content means that the flour will be of poor quality (Uthayakumaran et al. 2017).

Thousand grain weight

The 1000-grain weight (TGW) exhibits a discernible reliance on the botanical genotype (variety), with weather conditions and the cultivation system having no influence on this attribute. TGW constitutes one of the metrics underpinning the assessment of wheat grain's aptitude for milling. A higher value attributed to this metric corresponds to amplified outputs of lightly extracted flour. This augmentation finds its roots in the augmented share of the endosperm within the grain. Although no obligatory stipulations govern the minimal threshold of this metric, it remains verifiable that an elevated TGW augments the potential milling properties of the grain (Mitura et al. 2023). The optimal approach to attain a higher thousand grain weight in wheat production entails the utilization of increased NPK doses and tailored fertilizer formulations like micronized suspension and NPK liquid fertilizers. This strategy, supported by Debiase et al. (2016), highlights the potential of the MT treatment, offering a promising pathway to elevate seed weight up to 56.5 g.

Zeleny's sedimentation index

Grain intended for the production of flour for bakery purposes should have a sedimentation index of no less than 30 units. Sedimentation below 25 units suggests poor quality gluten proteins that determine the quality and volume of bread (Uthayakumaran et al. 2017). The sedimentation value according to Zeleny (Zeleny's value) describes the degree of sedimentation of flour suspended in a lactic acid solution during a standard time interval, and this is taken as a measure of the baking quality. Swelling of the gluten fraction of flour in lactic acid solution affects the rate of sedimentation of a flour suspension. Both a higher gluten content and a better gluten quality give rise to slower sedimentation and higher Zeleny's test values. The sedimentation value of flour depends on the wheat protein composition and is mostly correlated to the protein content, the wheat hardness, and the volume of pan and hearth loaves. A stronger correlation between loaf volume and Zeleny's sedimentation volume compared to SDS sedimentation volume could be due to the protein content influencing both the volume and Zeleny's value (Litke et al. 2018).

Falling number

The falling number determines the level of amylolytic enzymes contained in the grain. If the value is below 150 seconds, it may mean that the grain will be disqualified as potentially suitable for the production of flour for baking purposes (Klikocka et al. 2016). Such a value indicates an excessively high activity of amylolytic enzymes. Such wheat may also have a tendency to self-heating and moistening. Ideal grain should have a falling number of 250-350 seconds. Just as the density of wheat should be ideal and not exceed the set criteria, the falling number should not be higher than 400 seconds (Jarecki et al. 2017).

Humidity

Grain with high moisture undergoes unfavorable processes that reduce its quality. An increase in humidity and temperature creates favorable conditions for the development of microorganisms and pests. In grains contaminated with soil and dust and in fragments of plants, weeds and straw, favorable conditions for development of fungal spores may occur. During storage, carbohydrates are broken down and a loss in dry matter of grain, with its moisture content above 15%, appears alongside an increase in enzyme activity causing changes in the chemical composition and deterioration of quality parameters. Hence, it has been agreed among entities purchasing cereals that the moisture content of wheat grain should not exceed 14.5% (Hlisnikovský, Kunzová 2014, Tao et al. 2018).

Starch content

Starch, forming 80% of the wheat endosperm's carbohydrate composition, stands as a fundamental ingredient of wheat grain. It plays a pivotal role as a primary carbohydrate source in human diets, and is also used in the production of alcoholic beverages, fuel ethanol, and various other industrial products. Starch constitutes a substantial portion (60-70%) of wheat flour's mass, with soft wheat types generally containing more starch and less protein compared to their hard counterparts (Tao et al. 2018). Global nutritional guidelines consistently highlight the significance of carbohydrates, particularly from cereal grains. Starch granules within the endosperm of a size ranging from <1 mm to approximately 40 mm contain amylose, amylopectin as well as minute quantities of protein, lipid, and polysaccharides (Uthayakumaran et al. 2017). The optimal approach to attaining higher starch content in wheat production involves incorporating sulfur fertilization practices, particularly the S45 treatment. This signifies that integrating sulfur fertilization at the S45 treatment level can effectively enhance the starch content in wheat grain (Tao et al. 2018).

Wu et al. (2019) suggested that a nitrogen dose of 100 kg N ha^{-1} is optimal for the growth and development of spring wheat, and increasing N doses does not further increase yields. In turn, Béreš et al. (2019) obtained the highest amount of aerial wheat biomass at a fertilization dose of 80 kg N ha^{-1}. Hlisnikovský, Kunzová (2014) proved that winter wheat grain yield increased with increasing nitrogen doses (Table 2).

The study by Panfilova et al. (2020) revealed that the application of foliar fertilization to the Kolchuga cultivar wheat increased the crude gluten content from 7.0 to 11.5% compared to the control. On the other hand, in the case of the Zamozhnis cultivar, the gluten content of winter wheat grain in the same study increased from 7.2 to 12.4%. The authors also determined an increase in the protein yield content by 22% for cv. Kolchuga and by 20.5% for cv. Zamozhnist.

The analysis by Klikocka et al. (2016) revealed that N and S fertilizers had a significant positive impact on the grain yield and quality characteristics of spring wheat. The highest grain yield of 5.40 t ha^{-1} was obtained with the application of 80 kg N ha^{-1}, showing a 13.1% increase compared to the control. Both N and S content in the grain increased directly with the N application dose, reaching their highest levels at 120 kg N ha^{-1} (N – 28.59 g kg^{-1} DM and S – 1.39 g kg^{-1} DM) (Table 2). Effects of mineral, organic and mineral-organic fertilization on selected quality parameters of wheat grains are shown in Tables 2-4.

The study by Šimon et al. (2016) showed that fertilization with digestate also significantly increased wheat yield compared to the non-fertilized treatment. In contrast, Holik et al. (2018) conducted a 4-year experiment using mineral and manure fertilization. The authors noted the highest grain yield in the first year of the experiment, and the lowest yields in the following two years. The highest grain yield was obtained in the treatment containing manure and NPK fertilization with the highest nitrogen dose, i.e. 120 kg ha^{-1}. A similar relationship was observed for the gluten content, i.e. the lowest average gluten content was recorded in the second year of the experiment, while the highest one was in the first year. Their results confirm that the application of organic and mineral fertilizers has a favourable effect on the yield of winter wheat.

Results of quality parameters of rape seeds

Oilseed rape (*Brassica napus* L.) is widely grown around the world as an edible oilseed and forage crop. At the same time, it is considered one of the

Table 2

Qualitative parameters determined after applying mineral fertilization for different cultivars of wheat

Qualitative parameters	Applied fertilizer dose	Plant	Soil type	Effect	Literature
Yield (kg ha^{-1})	In the first year of the experiment, nitrogen treatments included five combinations of application rates and timing, while two additional treatments were added in the second year of the experiment. The applied dose was between 0 and 200 kg N ha^{-1}.	Spring wheat, Carberry and AAC Scotia cultivars	-	In both years, the grain yield increased significantly (p<0.05) with increasing N dose, both after pre-sowing and split-N applications. The highest grain yield of 3.41 t ha^{-1} was obtained in the N50+100 treatment for the AAC Scotia cultivar in 2016, while the N50+50 treatment yielded a record 4.95 t ha^{-1} for the same cultivar. In both years, grain yields were not significantly different between split-N application and the equivalent N-only pre-sowing application.	Wu et al. (2019)
	Fertilized with different levels of N and S, which gave 8 combinations: 0N-0S; 40N-0S; 80N-0S; 120N-0S; 0N-50S; 40N-50S; 80N-50S and 120N-50S.	Spring wheat, Tybalt cultivar	light silty sand	Grain yield was the highest after the application of 80 kg N ha^{-1} (5.40 t ha^{-1}), increasing by 1.30 t ha^{-1} (13.1%) compared to the control, and also 120 kg N ha^{-1}.	Klikocka et al. (2016)
	NPK fertilization levels: 80-30-60 kg ha^{-1} (level I) and 120-45-90 kg ha^{-1} (level II).	Spring wheat, Arabella cultivar	gleic fluvisol	The application of the higher NPK dose significantly increased the grain yield by 0.79 t ha^{-1} compared to the lower dose.	Jarecki et al. (2017)
	Treatments: 1. No fertilization (control) 2. NPK + S1 (ammonium sulfate) 3. NPK + S1 (mixture of ammonium nitrate and ammonium sulfate) 4. NPK + S1 (elemental sulfur)	Winter wheat, Wydma cultivar	silt loam	The applied fertilization significantly affected the grain yield of wheat. Fertilized plants yielded significantly higher than control (unfertilized) plants. Fertilization with a double dose of a mixture of nitrate and ammonium sulfates was the most beneficial	Filipek-Mazur et al. (2019)

cont. Table 2

	5. NPK + S2 (ammonium sulfate) 6. NPK + S2 (mixture of ammonium nitrate and ammonium sulfate) 7. NPK + S2 (elemental sulfur) N at the doses of 80 kg ha^{-1} and 120 kg ha^{-1} (in the second term), P at the dose of 26.2 kg ha^{-1}, K at the dose of 116.2 kg ha^{-1}, S1 at the dose of 12.5 kg ha^{-1}, and S2 at the dose of 25 kg ha^{-1}.			(wheat grain yield higher by 31%).	
	Fertilized with urea, superphosphate, and potassium chloride at respective concentrations of 90 mg N, 90 mg P, and 80 mg K kg^{-1} soil before sowing. Two sulfur fertilization levels were used: 0 (S0) and 45 (S45) kg ha^{-1}.	Winter wheat, Gaoyou 2018 and Zhongm aand 8 cultivars	silt loam	Sulfur fertilization significantly increased the grain yield of both cultivars (p<0.05). Grain yield and weight were higher in the S45 treatment than in the S0 treatment. On average, the yield in GY2018 sulfur treatments in both years increased by 34.7% and 30.2% (S45) compared to the control (S0). In ZM8, in both years, the average yield increases were about 11.2% and 14.2% higher under S45 than under S0.	Tao et al. (2018)
	Nitrogen fertilization for spring wheat consisted of 30 kg N ha^{-1} applied before sowing and 60 kg N ha^{-1} added at the stage of stem extension. Superphosphate (17.4% P) was supplied in the following doses: 26.16 kg P ha^{-1} under field bean, seed pea, and spring wheat; 34.88 kg of P ha^{-1} under blue lupine. Potassium fertilizers (in the form of potassium salt 49.8% K) were	Spring wheat, Trappe cultivar	haplic luvisol	Very high grain yields were obtained in all years of the experiment. The average grain yield of spring wheat was about 6.5 t ha^{-1}.	Fordoński et al. (2015)

cont. Table 2

	applied in the following quantities: 83 kg K ha^{-1} under field bean, seed pea, and spring wheat; 116.2 kg K ha^{-1} under blue lupine.				
	Treatments were as follows: 1. T1 – control – standard NPK fertilization: 50 kg N ha^{-1} as 34% ammonium nitrate (AN), 80 kg P_2O_5 ha^{-1} as granular triple superphosphate, 100 kg K_2O ha^{-1} as potassium salt before sowing, and 40 kg N ha^{-1} as 34% ammonium nitrate at the stem elongation phase; 2. T2 – standard NPK fertilization plus liquid NPK (10-11-11) fertilizer at doses of 10 L ha^{-1} at the tillering and 5 L ha^{-1} at the stem elongation phase (foliar application); 3. T3 – standard NPK fertilization plus liquid NPK (10-11-11) fertilizer with microelements (0.01% B, 0.03% Fe-EDTA, 0.01% Mn-EDTA, 0.001% Mo, 0.004% Zn-EDTA, 0.004% Cu-EDTA) at one dose of 5 L ha^{-1} at the tillering phase (foliar application); 4. T4 – standard NPK fertilization plus calcium micronized suspension fertilizer (19.5% Ca) in two doses of 5 kg Ca ha^{-1} (26 kg Ca ha, respectively) at the tillering and at the stem elongation phases (foliar application);	Spring wheat, Harenda cultivar	-	There was a trend for grain yield to increase after the application of liquid NPK and liquid micronutrient-enriched NPK fertilizers compared to the control (by 15.7 and 11.7%, respectively)	Mikos--Szymańska et al. (2018)

cont. Table 2

	5. T5 – standard NPK fertilization plus Cu, Mn, Zn, Ca micronized suspension fertilizers (33% Cu, 23% Mn, 51% Zn, 19.5% Ca) in two doses of 100 g Cu ha^{-1}, 300 g Mn ha^{-1}, 400 g Zn ha^{-1}, and 5 kg Ca ha^{-1} (a mixture of 0.303 kg of Cu suspension + 1.305 kg of Mn suspension + 0.785 kg of Zn suspension + 26 kg of Ca suspension ha^{-1}, respectively) at the tillering and at the stem elongation phases (foliar application)				
	a) 103 N + 52 P_2O_5+ 52 K_2O (200 kg ha^{-1} NPK 8:26:26 ploughed in autumn + 100 kg ha^{-1} urea 46% N applied before sowing + top-dressing with 150 kg ha^{-1} calcium ammonium nitrate or CAN 27% N); b) 133 N + 182 P_2O_5+ 182 K_2O (F-1 + 500 kg ha^{-1} NPK before sowing); c) 183 N + 312 P_2O_5 + 312 K_2O (F-1 + 1000 kg ha^{-1} NPK before sowing).	Winter wheat, Renata cultivar	-	The highest grain yield of 5.17 t ha^{-1} was obtained with the application of 175 N + 150 P_2O_5 + 125 K_2O (kg ha^{-1}) and was 52% higher compared to the unfertilized plot (2.50 t ha^{-1}).	Kovačević et al. (2013)
Protein content in grain (%)	In the first year of the experiment, nitrogen treatments included five combinations of application doses and timing, while two additional treatments were added in the second year of the experiment. The applied dose was between 0 and 200 kg N ha^{-1}.	Spring wheat, Carberry and AAC Scotia cultivars	-	In both years, the protein content in grain (%) increased significantly ($p<0.05$) with increasing N dose, both for pre-sowing and split application, with the lowest yield for the unfertilized treatment (N0).	Wu et al. (2019)
	Fertilized with different levels of N and S, which gave 8 combinations: 0N-0S; 40N-0S; 80N-0S; 120N-0S; 0N-50S;	Spring wheat, Tybalt cultivar	light silty sand	The highest total protein values were observed after applying 80 kg N ha^{-1} and	Klikocka et al. (2016)

cont. Table 2

	40N-50S; 80N-50S and 120N-50S.			120 kg N ha^{-1} (15.83% and 16.28%).	
	NPK fertilization levels: 80-30-60 kg ha^{-1} (level I) and 120-45-90 kg ha^{-1} (level II).	Spring wheat, Arabella cultivar	gleic fluvisol	The application of a higher NPK dose significantly increased the total protein content in grain.	Jarecki et al. (2017)
	Pot soil was fertilized with urea, superphos-phate, and potassium chloride at respective concentrations of 90 mg N, 90 mg P, and 80 mg K kg soil before sowing. Two sulfur fertilization levels were used: 0 (S0) and 45 (S45) kg ha^{-1}.	Winter wheat, Gaoyou 2018 and Zhongm aand 8 cultivars	silt loam	Sulfur fertilization significantly increased the protein content in grain in both wheat cultivars (p<0.05). The protein content of the S45 treatment was 16.6% higher in GY2018 in both years compared to the S0 treatment. The protein content of the S45 treatment was 6.2% higher in ZM8 in both years compared to the S0 treatment.	Tao et al. (2018)
	Nitrogen fertilization for spring wheat consis-ted of 30 kg N ha^{-1} applied before sowing and 60 kg N ha^{-1} added at the stage of stem extension. Superphosphate (17.4% P) was supplied in the following doses: 26.16 kg P ha^{-1} under field bean, seed pea, and spring wheat; 34.88 kg of P ha^{-1} under blue lupine. Potassium fertilizers (in the form of potassium salt 49.8% K) were applied in the following quantities: 83 kg K ha^{-1} under field bean, seed pea and spring wheat; 116.2 kg K ha^{-1} under blue lupine.	Spring wheat, Trappe cultivar	haplic luvisol	A low total protein content of 731.7 t ha^{-1} in spring wheat grain was obtained.	Fordoński et al. (2015)
Glutent content (%)	Fertilized with different levels of N and S, which gave 8 combinations: 0N-0S; 40N-0S; 80N-0S;	Spring wheat, Tybalt cultivar	light silty sand	The gluten content was highest for the dose of 120 kg N ha^{-1} (34.15%) and increased in direct	Klikocka et al. (2016)

cont. Table 2

	120N-0S; 0N-50S; 40N-50S; 80N-50S and 120N-50S.			proportion to the increase in nitrogen dose.	
	Treatments: 1. No fertilization (control); 2. NPK + S1 (ammonium sulfate); 3. NPK + S1 (mixture of ammonium nitrate and ammonium sulfate); 4. NPK + S1 (elemental sulfur); 5. NPK + S2 (ammonium sulfate); 6. NPK + S2 (mixture of ammonium nitrate and ammonium sulfate); 7. NPK + S2 (elemental sulfur) N at the doses of 80 kg ha^{-1} and 120 kg ha^{-1} (in the second term), P at the dose of 26.2 kg ha^{-1}, K at the dose of 116.2 kg ha^{-1}, S1 at the dose of 12.5 kg ha^{-1}, and S2 at the dose of 25 kg ha^{-1}.	Winter wheat, Wydma cultivar	silt loam	Grains of plants fertilized with sulfur contained significantly more gluten than grains of unfertilized wheat and wheat supplemented with mineral fertilizers without sulfur (the highest gluten content was found in grains of wheat fertilized once with ammonium sulfate).	Filipek-Mazur et al. (2019)
Starch content (g kg^{-1})	Treatments: 1. No fertilization (control); 2. NPK + S1 (ammonium sulfate); 3. NPK + S1 (mixture of ammonium nitrate and ammonium sulfate); 4. NPK + S1 (elemental sulfur); 5. NPK + S2 (ammonium sulfate); 6. NPK + S2 (mixture of ammonium nitrate and ammonium sulfate); 7. NPK + S2 (elemental sulfur) N at the doses of 80 kg ha^{-1} and 120 kg ha^{-1} (in the second term), P at the dose of 26.2 kg ha^{-1}, K at	Winter wheat, Wydma cultivar	silt loam	The starch content of the control plant reached 635 g kg^{-1} and was slightly higher than that of the fertilized plants.	Filipek-Mazur et al. (2019)

cont. Table 2

	the dose of 116.2 kg ha^{-1}, S1 at the dose of 12.5 kg ha^{-1}, and S2 at the dose of 25 kg ha^{-1}.				
	Pot soil was fertilized with urea, superphosphate, and potassium chloride at respective concentrations of 90 mg N, 90 mg P, and 80 mg K kg^{-1} soil before sowing. Two sulfur fertilization levels were used: 0 (S0) and 45 (S45) kg ha^{-1}.	Winter wheat, Gaoyou 2018 and Zhongm a and 8 cultivars	silt loam	Sulfur fertilization significantly increased the total starch content in grains of both cultivars (p<0.05). The total starch content was consistently higher in the S45 treatment than in the S0 treatment. On average, the total starch content in the GY2018 sulfur treatments from both years increased by 14.2% (S45) compared to the control (S0). In ZM8, in both years, the average increases in the total starch content were about 12.3% (S45) higher than in S0.	Tao et al. (2018)
Thousan d grain weight (g)	Fertilized with different levels of N and S, which gave 8 combinations: 0N-0S; 40N-0S; 80N-0S; 120N-0S; 0N-50S; 40N-50S; 80N-50S and 120N-50S.	Spring wheat, Tybalt cultivar	light silty sand	No effect was observed for the thousand grain weight.	Klikocka et al. (2016)
	NPK fertilization levels: 80-30-60 kg ha^{-1} (level I) and 120-45-90 kg ha^{-1} (level II).	Spring wheat cultivar Arabella	gleic fluvisol	The higher NPK dose significantly increased the thousand grain weight compared to the lower dose. The average difference was 2.7 g.	Jarecki et al. (2017)
	Treatments were as follows: 1. T1 – Control – standard NPK fertilization: 50 kg N ha^{-1} as 34% ammonium nitrate (AN), 80 kg P_2O_5 ha^{-1} as granular triple superphosphate, 100 kg K_2O ha^{-1} as potassium salt before sowing, and 40 kg N ha^{-1} as 34%	Spring wheat, Harenda cultivar	-	The applied fertilizers significantly affected the thousand grain weight (TGW). The highest TGW was observed for micronized suspension fertilizer (T4, T5), followed by NPK liquid fertilizer (T2) and NPK with microelement liquid fertilizer (T3), and the lowest TGW was	Mikos--Szymańska et al. (2018)

cont. Table 2

	ammonium nitrate at the stem elongation phase; 2. T2 – standard NPK fertilization plus liquid NPK (10-11-11) fertilizer at doses of 10 L ha^{-1} at the tillering and 5 L ha^{-1} at the stem elongation phase (foliar application); 3. T3 – standard NPK fertilization plus liquid NPK (10-11-11) fertilizer with microelements (0.01% B, 0.03% Fe-EDTA, 0.01% Mn-EDTA, 0.001% Mo, 0.004% Zn-EDTA, 0.004% Cu-EDTA) at one dose of 5 L ha^{-1} at the tillering phase (foliar application); 4. T4 – standard NPK fertilization plus calcium micronized suspension fertilizer (19.5% Ca) in two doses of 5 kg Ca ha^{-1} (26 kg of Ca suspension ha^{-1}, respectively) at the tillering and at the stem elongation phases (foliar application); 5. T5 – standard NPK fertilization plus Cu, Mn, Zn, Ca micronized suspension fertilizers (33% Cu, 23% Mn, 51%Zn, 19.5% Ca) in two doses of 100 g Cu ha^{-1}, 300 g Mn ha^{-1}, 400 g Zn ha^{-1}, and 5 kg Ca ha^{-1} (a mixture of 0.303 kg of Cu suspension + 1.305 kg of Mn suspension + 0.785 kg of Zn suspension + 26 kg of Ca suspension ha^{-1}, respectively) at the tillering and at the stem elongation phases (foliar application)			determined for standard NPK fertilizer (T1).	

cont. Table 2

Leaf area index (LAI m^2 m^{-2})	NPK fertilization levels: 80-30-60 kg ha^{-1} (level I) and 120-45-90 kg ha^{-1} (level II).	Spring wheat cultivar Arabella	gleic fluvisol	The higher level of NPK increased the LAI compared to its lower level. The significant difference was 0.29 m^2 m^{-2}.	Jarecki et al. (2017)
Micro- and macroele ment content in grain (g kg^{-1} d.m.)	NPK fertilization levels: 80-30-60 kg ha^{-1} (level I) and 120-45-90 kg ha^{-1} (level II).	Spring wheat cultivar Arabella	gleic fluvisol	The content of microelements was generally medium.	Jarecki et al. (2017)
	Nitrogen fertilization for spring wheat consisted of 30 kg N ha^{-1} applied before sowing and 60 kg N ha^{-1} added at the stage of stem extension. Superphosphate (17.4% P) was supplied in the following doses: 26.16 kg P ha^{-1} under field bean, seed pea, and spring wheat; 34.88 kg of P ha^{-1} under blue lupine. Potassium fertilizers (in the form of potassium salt 49.8% K) were applied in the following quantities: 83 kg K ha^{-1} under field bean, seed pea and spring wheat; 116.2 kg K ha^{-1} under blue lupine	Spring wheat, Trappe cultivar	haplic luvisol	The content of macro- and micronutrients in spring wheat grain differed significantly from the similarity degree of the grain chemical composition by 82.1%.	Fordoński et al. (2015)

most demanding crops, and its fertilization should be adapted to the growth rate and nutrient uptake dynamics. Results by Ren et al. (2013) indicated that increased doses of mineral fertilizers significantly improved oilseed rape yield, quality, and nutrient use efficiency (Table 3). In turn, the study by Gaj (2010) showed that Ca, K, and N are elements that significantly limit oilseed rape yield. Elements that do not limit oilseed rape yield are: P, Cu, Mn, Zn, Fe, and Mg.

Oilseed rape is a versatile crop, with every part – flowers, seeds, leaves, stem, and root – finding use in manufacture of food, remedies, cosmetics, or other industrial applications. The seeds are particularly useful as they serve as oil and protein sources. Oilseed rape oil and protein contents vary across cultivars, and the seeds also contain components like glucosinolates, phenols, phytic acid, cellulose, and sugars. Rapeseed is renowned for its high-quality vegetable oil production, making it a competitive crop in the

Table 3

Qualitative parameters determined after applying organic fertilization for different cultivars of wheat

Qualitative parameters	Applied fertilizer dose	Plant	Soil type	Effect	Literature
Yield (kg ha^{-1})	Five fertilization treatments were applied in the experiment: 1. Control – without organic or mineral fertilization; 2. Dig – digestate; 3. Dig + St – digestate + straw; 4. NPK – mineral fertilization; 5. CSl – cattle slurry.	Winter wheat, Mulan cultivar	orthic luvisol, clay loam	All fertilized treatments significantly increased grain yield compared to the unfertilized control. The increase in grain yield ranged from 39.6-47.4%, and the order was as follows: digestate > NPK > cattle slurry > digestate + straw.	Šimon et al. (2016)
	The following treatments were used: unfertilized treatment (control); digestate (Dig); digestate + straw (Dig + St); cattle slurry (Csl); and mineral NPK fertilizer (NPK).	Winter wheat	orthic luvisol	A strong correlation was observed between cadmium content in wheat grain and wheat yield.	Barłóg et al. (2019)
	Granulated organic fertilizer was used in a dose of 300 kg ha^{-1}.	Spring wheat	-	Organic fertilizers significantly increased spring wheat yield by 44% compared to the control.	Apaeva et al. (2021)
	1. BM_{80} blood meal at sowing; 2. BM_{40}/BM_{40} 50% at tillering as blood meal and 50% at wheat shooting as blood meal; 3. RL_{80} roasted leather at sowing; 4. RL_{40}/BM_{40} 50% at tillering as roasted leather and 50% at wheat shooting as blood meal; 5. $N0_{NS}$ unfertilized control; 6. $N80_{NS}$ 50% at tillering and 50% at wheat shooting as urea;	Winter wheat, Aubusson cultivar	clay loam vertisol	Wheat yield was affected by treatments in all 3 years. Among organic fertilizers, BM showed a better effect on yield compared to RL. Split organic fertilization had a positive effect on yield in only one year, and the most pronounced effect was observed in BM treatments that generally showed a slightly higher yield compared to RL in all 3 years. TIC yield	Tosti et al. (2016)

cont. Table3

	7. N160$_{NS}$ 50% at tillering and 50% at wheat shooting as urea; 8. TIC N assimilated by faba bean, the legume was incorporated into the soil at wheat shooting; 9. N0$_{WS}$ unfertilized control; 10. N80$_{WS}$ 50% at tillering and 50% at wheat shooting as urea; 11. N160$_{WS}$ 50% at tillering and 50% at wheat shooting as urea.			was similar to BM$_{80}$ (+31% compared to N0$_{WS}$).	
	The main plot was characterized by two different tillage systems: conventional tillage (CT) and minimum tillage (MT). The CT treatment included moldboard plowing (40-45 cm deep) and both disk harrowing and vibrating tine cultivator two-three times while the MT treatment consisted of two disk harrowing at least 7 days between then and one vibrating (10-15 cm deep). Treatment: (i) mineral N (N_{min}) as urea, with 100 kg N ha^{-1}; (ii) OMSW compost application (N_{comp}), with 100 kg N ha^{-1} of total N (3.82 Mg ha^{-1}); (iii) compost and mineral application (N_{mix}), with 50 kg N ha^{-1} of organic N ($OMSW_{compost}$) and 50 kg N ha^{-1}	Winter wheat, Simeto cultivar	silty-clay	The compared fertilizer treatments showed, on average, 32% more of wheat yield compared to the unfertilized control.	Debiase et al. (2016)

cont. Table 3

	of mineral N; (iv) Sewage sludge application (N_{ss}), with 100 kg N ha^{-1} of total N (1.81 Mg ha^{-1}). These treatments were compared with an unfertilized control (N_0).				
Protein content in grain (%)	1. BM_{80} blood meal at sowing; 2. BM_{40}/BM_{40} 50% at tillering as blood meal and 50% at wheat shooting as blood meal; 3. RL_{80} roasted leather at sowing; 4. RL_{40}/BM_{40} 50% at tillering as roasted leather and 50% at wheat shooting as blood meal; 5. $N0_{NS}$ unfertilized control; 6. $N80_{NS}$ 50% at tillering and 50% at wheat shooting as urea; 7. $N160_{NS}$ 50% at tillering and 50% at wheat shooting as urea; 8. TIC N assimilated by faba bean, the legume was incorporated into the soil at wheat shooting; 9. $N0_{WS}$ unfertilized control; 10. $N80_{WS}$ 50% at tillering and 50% at wheat shooting as urea; 11. $N160_{WS}$ 50% at tillering and 50% at wheat shooting as urea.	Winter wheat, Aubusson cultivar	clay loam vertisol	The protein content in grain was affected by treatments in all 3 years. Split nitrogen rate had a minor effect on the protein content in grain. BM_{80} generally had a slightly higher protein content in grain than RL_{80} (especially in 2011 and 2012). TIC fertilization significantly improved the protein content in wheat grain in all 3 years.	Tosti et al. (2016)

cont. Table 3

	The main plot was characterized by two different tillage systems: conventional tillage (CT) and minimum tillage (MT). The CT treatment included moldboard plowing (40-45 cm deep) and both disk harrowing and vibrating tine cultivator two-three times while the MT treatment consisted of two disk harrowing at least 7 days between then and one vibrating (10-15 cm deep). Treatment: (i) mineral N (N_{min}) as urea, with 100 kg N ha^{-1}; (ii) OMSW compost application (N_{comp}), with 100 kg N ha^{-1} of total N (3.82 Mg ha^{-1}); (iii) compost and mineral application (N_{mix}), with 50 kg N ha^{-1} of organic N ($OMSW_{compost}$) and 50 kg N ha^{-1} of mineral N; (iv) Sewage sludge application (N_{ss}), with 100 kg N ha^{-1} of total N (1.81 Mg ha^{-1}). These treatments were compared with an unfertilized control (N_0).	Winter wheat, Simeto cultivar	silty-clay	The protein content was higher in the CT treatment than MT treatment.	Debiase et al. (2016)
Thousand grain weight (g)	The main plot was characterized by two different tillage systems: conventional tillage (CT) and minimum tillage (MT). The CT treatment included moldboard plowing (40-45 cm deep) and both disk harrowing	Winter wheat, Simeto cultivar	silty-clay	The MT treatment showed a significant increase in the weight of 1000 seeds than CT treatment. The 1000 seeds weight ranged between 56.5 g and 48.7 g for N_0 and	Debiase et al. (2016)

cont. Table 3

	and vibrating tine cultivator two-three times while the MT treatment consisted of two disk harrowing at least 7 days between then and one vibrating (10-15 cm deep). Treatment: (i) mineral N (N_{min}) as urea, with 100 kg N ha^{-1}; (ii) OMSW compost application (N_{comp}), with 100 kg N ha^{-1} of total N (3.82 Mg ha^{-1}); (iii) compost and mineral application (N_{mix}), with 50 kg N ha^{-1} of organic N ($OMSW_{compost}$) and 50 kg N ha^{-1} of mineral N; (iv) Sewage sludge application (N_{ss}), with 100 kg N ha^{-1} of total N (1.81 Mg ha^{-1}). These treatments were compared with an unfertilized control (N_0).			N_{min} treatments, respectively.	

agricultural industry (Raboanatahiry et al. 2021). Below is a brief description of selected wheat quality parameters.

Grain yield

Oilseed rape yield is the product of the number of seeds per unit area and their weight. The number of seeds per unit area depends on the number of plants, the number of branches on the plant, the number of pods on the main shoot and side shoots, and the number of seeds in pods on the main shoot and side shoots. In practice, a rapeseed cultivation technology should be focused on building an optimal yield structure by the plant, i.e. at a certain cast to produce such a quantity of the above-mentioned elements of the structure that will ensure a high yield with good quality parameters (Raboanatahiry et al. 2021). The seed yield is a very complex feature that consists of direct and indirect yield-related traits. The number of siliques per plant, number of seeds per silique, and thousand-seed weight

Table 4

Qualitative parameters determined after applying mineral-organic fertilization for different cultivars of wheat

Qualitative parameters	Applied fertilizer dose	Plant	Soil type	Effect	Literature
Yield (kg ha^{-1})	1. Control without fertilization (C); 2. Farmyard manure at the rate of 40 t ha^{-1}; 3. FYM + P; 4. FYM + K; 5. FYM + PK; 6. FYM + N_1; 7. FYM + N_2; 8. FYM + N_1PK; 9. FYM + N_2PK; 10. FYM + N_3P; in a P dose of 60 kg ha^{-1} (superphosphate); K – 60 kg ha^{-1} (potassium chloride); N_1 – 40 kg ha^{-1}; N_2 – 80 kg ha^{-1} and N_3: 120 kg ha^{-1} (calcium-ammonium nitrate).	Winter wheat, Mulan cultivar	greyic phaeozem	In the first year of the experiment, grain yield was highest in the FYM + N_3PK (10.77 t ha^{-1}) and FYM + P (10.18 t ha^{-1}) fertilizer treatments. In contrast, the lowest grain yields were obtained in the control (6.39 t ha^{-1}), FYM (7.01 t ha^{-1}), and FYM + PK (7.03 t ha^{-1}) treatments. There was a general decrease in yields in the second year, with average yields ranging from 6.19 t ha^{-1} (FYM + K) to 6.79 t ha^{-1} (FYM + P). Lower total yields were also recorded in the third year of the experiment. When comparing the average grain yields from each year, it was noted that the highest grain yields were obtained in the fourth year of the experiment (9.05 t ha^{-1}), and the lowest in the second year (6.39 t ha^{-1}).	Holik et al. (2018)
	The experiment included 5 doses of nitrogen fertilization:	Winter wheat, Jinmai - 47 cultivar	calcic cambisols	Another application of manure increased grain yield by an average	Zhang et al. (2016)

cont. Table 4

	1. 0 kg N ha^{-1}; 2. 75 kg N ha^{-1}; 3. 150 kg N ha^{-1}; 4. 225 kg N ha^{-1} and 300 kg N ha^{-1}. Each dose was considered in a variant with and without manure.			of 8% compared to a single application of inorganic fertilizer during three experimental years.	
	The experiment included the following treatments: 1. Control (non-fertilized from 1954); 2. Np (20 kg N ha^{-1} applied to straw); 3. NPK, NPK+farmyard manure (NPK+FYM); 4. NPK+cattle slurry (NPK+CS); 5. NPK+cattle slurry+straw (NPK+CS+straw); 6. PK+Np, NPK+pig slurry (NPK+PS); 7. NPK+pig slurry+straw (NPK+PS+straw).	Winter wheat	illimerized luvisol	In the first year of the experiment, the lowest grain yield (4.8 t ha^{-1}) was discovered in the control treatment, while the highest (9.38 t ha^{-1}) in the NPK+CS+straw treatment. Wheat grain yield increased with increasing nitrogen dose. In the second year of the experiment, grain yield ranged from 5.29 t ha^{-1} (control) to 9.52 t ha^{-1} (NPK+PS).	Hlisnikovský, Kunzová (2014)
	There were three levels of mineral N fertilizer (120, 160, and 200 kg ha^{-1}), two levels of organic N fertilizer (160 and 200 kg ha^{-1}), two levels of S fertilizer applied to the soil (0 and 70 kg ha^{-1}), and two levels of foliar S applied at flag leaf stage (0 and 5 kg ha^{-1}).	Durum wheat, Dylan, Iride, and Saragolla cultivars	clay	The Dylan cultivar had a grain yield significantly higher than the other Iride and Saragolla cultivars, both in NO_{160} (+21% and +19%, respectively) and NO_{200} (+23% and +19%, respectively).	Rossini et al. (2018)
	For the purpose of the study, 6 fertilizing treatments were evaluated:	Winter wheat, Samanta and Alana cultivars	cambisol, sandy loam/ chernozem, silt loam	In the S_1 experiment, the lowest average yield of the control object was only 2.59 t ha^{-1}, while	Buráňová et al. (2015)

cont. Table 4

	1. No fertilization (control), 2. Sewage sludge (SS), 3. Farmyard manure (FYM), 4. N as mineral fertilizer (N), 5. NPK as mineral fertilizer (NPK), 6. N as mineral fertilizer + spring barley straw (N+ST).			the NPK treatment increased the average yield by 144%, reaching 6.31 t ha^{-1}.	
Protein content in grain (%)	The experiment included the following treatments: 1. Control (non-fertilized from 1954); 2. Np (20 kg N ha^{-1} applied to straw); 3. NPK, NPK+farmyard manure (NPK+FYM); 4. NPK+cattle slurry (NPK+CS); 5. NPK+cattle slurry+straw (NPK+CS+straw); 6. PK+Np, NPK+pig slurry (NPK+PS); 7. NPK+pig slurry+straw (NPK+PS+straw).	Winter wheat	illimerized	Crude protein content was significantly influenced by the method of fertilization in 2010, with the lowest protein content recorded in Np (10.28%) and the highest in NPK+CS+straw (13.86%). Significant differences were found between treatments without direct fertilizer (Control and Np) and with fertilizer, while there were no differences between mineral fertilizers (NPK) and mineral fertilizers enhanced with organic compounds.	Hlisnikovský, Kunzová (2014)
	There were three levels of mineral N fertilizer (120, 160, and 200 kg ha^{-1}), two levels of organic N fertilizer (160 and 200 kg ha^{-1}), two levels of S fertilizer applied	Durum wheat, Dylan, Iride, and Saragolla cultivars	clay	The protein content in grain was significantly higher in 2012 than in 2011 for all cultivars and nitrogen fertilizers except for NO_{200}, where it remained	Rossini et al. (2018)

cont. Table 4

	to the soil (0 and 70 kg ha^{-1}), and two levels of foliar S applied at flag leaf stage (0 and 5 kg ha^{-1}).			essentially unchanged. The Dylan cultivar showed significantly higher protein content than Iride and Saragolla cultivars for each nitrogen fertilization treatment in 2011, except for NO_{200}.	
	The experimental design included the following variants: 1. Control (without fertilizers); 2. $N_{30}P_{30}$ for pre-sowing cultivation; 3. $N_{30}P_{30}$ and urea K1; 4. $N_{30}P_{30}$ and urea K2; 5. $N_{30}P_{30}$ and Escort-bio; 6. $N_{30}P_{30}$ and urea K1 and urea K2; 7. $N_{30}P_{30}$ and organic D2.	Winter wheat, Kolchuga and Zamozhnist cultivars	chernozem soils	With the introduction of mineral fertilizer doses under winter wheat, the protein yield of the Kolchuga cultivar increased by 22.0 compared to the unfertilized control, while the yield of the Zamozhnist cultivar increased by 20.5%. Foliar supplementation increased that parameter by 38.5 to 44.8% for the Kolchuga cultivar and by 39.7 to 47.0% for Zamozhnist cultivar.	Panfilova et al. (2020)
Glutent content (%)	10 treatments: 1. Control without fertilization (C); 2. Farmyard manure at the rate of 40 t ha^{-1}; 3. FYM + P; 4. FYM + K; 5. FYM + PK; 6. FYM + N_1; 7. FYM + N_2; 8. FYM + N_1PK; 9. FYM + N_2PK;	Winter wheat, Mulan cultivar	greyic phaeozem	The lowest average gluten index was recorded in the second year of the experiment (68.48), while the highest in the first year of the experiment (96.09). Comparing the fertilizers applied, the highest average gluten	Holik et al. (2018)

cont. Table 4

	10. FYM + N_3P; in a P dose of: 60 kg ha^{-1} (superphosphate); K: 60 kg ha^{-1} (potassium chloride); N_1: 40 kg ha^{-1}; N_2: 80 kg ha^{-1} and N_3: 120 kg ha^{-1} (calcium-ammonium nitrate).			index was obtained in the control (92.06), and the lowest in FYM + N_3PK (87.57).	
	The experimental design included the following variants: 1. Control (without fertilizers); 2. $N_{30}P_{30}$ for pre-sowing cultivation; 3. $N_{30}P_{30}$ and urea K1; 4. $N_{30}P_{30}$ and urea K2; 5. $N_{30}P_{30}$ and Escort-bio; 6. $N_{30}P_{30}$ and urea K1 and urea K2; 7. $N_{30}P_{30}$ and organic D2.	Winter wheat, Kolchuga and Zamozhnist cultivars	chernozem soils	For the Kolchuga cultivar, an increase in the crude gluten content of 7.0-11.5% was observed after foliar fertilization relative to the control. On the other hand, the gluten content in the winter wheat grain of the Zamozhnis cultivar increased by 7.2-12.4% compared to the control.	Panfilova et al. (2020)
Thousand grain weight (g)	10 treatments: 1. Control without fertilization (C); 2. Farmyard manure at the rate of 40 t ha^{-1}; 3. FYM + P; 4. FYM + K; 5. FYM + PK; 6. FYM + N_1; 7. FYM + N_2; 8. FYM + N_1PK; 9. FYM + N_2PK; 10. FYM + N_3P; in a P dose of: 60 kg ha^{-1} (superphosphate); K: 60 kg ha^{-1} (potassium chloride); N_1: 40 kg ha^{-1}; N_2: 80 kg ha^{-1} and N_3: 120 kg ha^{-1}	Winter wheat, Mulan cultivar	greyic phaeozem	Thousand grain weight (TGW) varied significantly between years and fertilizers applied. The lowest average TGW was recorded in 2012 (43.63 g), and the highest in 2013 (48.85 g). When comparing fertilizers, the highest TGW (48.37 g) was found in FYM + N3PK fertilizer, and the lowest (45.60 g) in the control fertilizer.	Holik et al. (2018)

cont. Table 4

	(calcium-ammonium nitrate).				
Zeleny sedimentation test (ml)	10 treatments: 1. Control without fertilization (C); 2. Farmyard manure at the rate of 40 t ha^{-1}; 3. FYM + P; 4. FYM + K; 5. FYM + PK; 6. FYM + N_1; 7. FYM + N_2; 8. FYM + N_1PK; 9. FYM + N_2PK; 10. FYM + N_3P; in a P dose of: 60 kg ha^{-1} (superphosphate); K: 60 kg ha^{-1} (potassium chloride); N_1: 40 kg ha^{-1}; N_2: 80 kg ha^{-1} and N_3: 120 kg ha^{-1} (calcium-ammonium nitrate).	Winter wheat, Mulan cultivar	greyic phaeozem	Zeleny sedimentation test varied greatly from year to year. The lowest average ZST (18.75 ml) was recorded in 2011, while the highest (38.08 ml) in 2012. When assessing the fertilization treatments, the lowest value (21.38 ml) was recorded in the control, while the highest (38.21 ml) in FYM + N_3PK.	Holik et al. (2018)

have the greatest impact on the size of the yield. The last two features are related to indirect yield traits such as the length and width of the siliques. The silique length is positively correlated with the number of seeds per silique (the longer the siliques, the more seeds) and the silique width, with the thousand-seed weight (the wider the siliques, the bigger the seeds) (Russo et al. 2021, Sabbahi et al. 2023).

Moisture

During storage, oilseed rape is much more susceptible to spoilage than cereal grains, and this is due to its content of fat, which is easily decomposed, especially in moist and damaged seeds. Oilseed rape seeds can contain 11% to 20% of fat, although in the event of unfavorable weather conditions such as heavy rainfall, the seed fat content can be higher. Meanwhile, the humidity that guarantees safe storage of rapeseed is at the level of 6-9% (Béreš et al. 2019).

Thousand grain weight

Oilseed rape, also known as canola, is primarily grown for its oil-rich seeds. The weight of the seeds can vary depending on factors such as the variety of rapeseed, growing conditions, and agricultural practices.

The weight of a thousand rapeseed seeds can typically range from around 2 to 6 grams, depending on these factors (Béreš et al. 2019).

Oil content

Oilseed rape typically has around 40-45% oil content, which means that for every 100 grams of rapeseed, you can expect to obtain approximately 40 to 45 grams of oil (Said-Al Ahl et al. 2016). The oil content in rapeseed represents a multifaceted quantitative trait intertwined with other storage and structural compounds within the seed. Oil crops are crucial in global agriculture and industries. In Brassica species, primary fatty acids are palmitic (C16:0), stearic (C18:0), oleic (C18:1), linoleic (C18:2), linolenic (C18:3), eicosanoic (C22:0), and erucic (C22:1) acids. Brassica oil displays rich genetic diversity in fatty acid composition, particularly high erucic acid unique to this genus. Although useful industrially, high erucic acid is not fit for consumption. Brassica breeding aims for creating erucic acid-free and high erucic acid varieties, elevating oleic and linoleic acids while reducing linolenic acid (Sharafi et al. 2015). Both Turinek et al. (2017) and Filipek-Mazur et al. (2019) suggest that achieving a favourable high fatty acids content range for seed production might involve prioritizing the enhancement of oleic acid levels in the range of 63.4% to 64.7%, while lowering the content of linoleic and linolenic acids.

Erucic acid content

Oilseed rape oils rich in erucic acid (high erucic acid rapeseed) are used for technical purposes. In contrast, only rapeseed oils with very low levels of erucic acid (low erucic acid rapeseed), which are considered toxicologically safe, are permitted for human consumption. In the first half of the 20th century, rapeseed oil was of little acceptance and importance as an edible oil because of its unfavorable sensory properties and the high concentration of erucic acid, a fatty acid regarded as nutritionally and toxicologically negative (Turinek et al. 2017, Sabbahi et al. 2023). Only with the breeding of rapeseed varieties with low levels of erucic acid and glucosinolates, referred to as “double low” or “double zero (00)” varieties (later often labeled as canola), and the advances in production and processing technology, the conditions for using rapeseed oil as an edible oil improved significantly (Russo et al. 2021). National, European Union and Canadian requirements for erucic acid allow its presence in rape seeds to a maximum of 2%.

Glucosinolate content

For the evaluation of rapeseed seeds, the presence of undesirable substances such as glucosinolates is also important. Currently, the maximum allowable content of these components in seeds is 25 micromoles/1 gram of defatted dry matter (Sharafi et al. 2015). Glucosinolates themselves are not harmful, but the products of their enzymatic hydrolysis are highly toxic (volatile compounds like thiocyanates, isothiocyanates, or cyanides). The presence of these anti-nutritional compounds reduces the nutritional value of the press cakes and post-extraction rapeseed meals, limiting their utilization in animal feeding (Sagan et al. 2019). Many research findings indicate that under conditions of waste deficiency, the glucosinolate content significantly increases.

Crude fat content plays an important role in shaping the quality of oilseed rape. This characteristic is affected by natural (weather) and agrotechnical (fertilization) factors (Sikorska et al. 2021).The cultivation of oilseed rape can be subject to some agrotechnical mistakes resulting in seeds with poorer oiliness, low thousand grain weight or insufficient fatty acid content (Sharafi et al. 2015). The second important characteristic of rape seeds is erucic acid content (22:1). The study by Varényiová et al. (2017) showed that sulfur at 40 kg ha^{-1} combined with nitrogen at 160 kg ha^{-1} was the most effective in terms of rape yield and oil content. However, the difference between the effect of 40 kg ha^{-1} and 15 kg ha^{-1} of sulfur is almost imperceptible. The effect of mineral, organic, and mineral-organic fertilization on selected quality parameters of wheat grains and rape seeds are shown in Tables 5-7.

In the case of organic fertilization, Turinek et al. (2017) showed that the application of cattle slurry had less effect on the fatty acid composition of rapeseed oil than mineral fertilizers. They found a decrease in oleic acid and an increase in linoleic acid compared to the control. For the most part, increased nitrogen fertilization was associated with a decrease in the share of oleic acid and, at the same time, an increase in the contents of linoleic, linolenic, and erucic acids. The results of Turinek et al. (2017) indicated that oil and protein contents of oilseed rape were significantly higher compared to the control. The authors noted that, under conditions of good soil moisture content, very high nitrogen fertilization positively affects the protein content of seeds, while negatively affecting the fat content. In turn, Filipek-Mazur et al. (2019) showed that among all fatty acids, rape seeds contained the highest amount of oleic acid, but there was no clear relationship between the applied sulfur-enriched mineral fertilization and the fatty acid profile. Similar conclusions were drawn by Jankowski et al. (2019), who stated that the applied fertilization had no significant effect on the fatty acid profile. The authors observed a slight increase in oleic acid content and a decrease in linoleic acid content. Similar observations as for wheat were also found for oilseed rape. Mojeremane et al. (2015) found that the application of organic fertilizers significantly improved the growth, development, and yield performance in terms of plant height, number of leaves, leaf area, and fresh weight. Koszel et al. (2020) discovered a significant effect of a digestate application dose on the fat and protein contents of winter oilseed rape. In addition to these parameters, the authors observed that the size of the digestate dose also had a positive effect on the yield and the thousand seed weight.

Table 5

Qualitative parameters determined after applying mineral fertilization to different cultivars of oilseed rape

Qualitative parameters	Applied fertilizer dose	Plant	Soil type	Effect	Literature
Yield (kg ha^{-1})	Autumn fertilization was divided into three variants: 1. Control without fertilization, 2. 40 kg N ha^{-1}, 3. 80 kg N ha^{-1}. Spring fertilization was uniform: it was applied in four doses of 180 kg N ha^{-1}, mainly with CAN.	Winter oilseed rape, DK Exstorm cultivar	haplic luvisol – clay loam	In all three years of the experiment, the highest seed yield was obtained after applying 40 kg N h^{-1}, with an average increase of 10.6% (seed yield of 5.7-6.5 t ha^{-1}). The fertilization dose of 80 kg N ha^{-1} only increased the yield by 7.4% on average (seed yield of 5.4-6.3 t ha^{-1}).	Béreš et al. (2019)
	Treatments: 1. No fertilization (control); 2. NPK + S1 (ammonium sulfate); 3. NPK + S1 (mixture of ammonium nitrate and ammonium sulfate); 4. NPK + S1 (elemental sulfur); 5. NPK + S2 (ammonium sulfate); 6. NPK + S2 (mixture of ammonium nitrate and ammonium sulfate); 7. NPK + S2 (elemental sulfur) N at the doses of 100 kg ha^{-1} and 140 kg ha^{-1} (in the second term), P at the dose of 32.7 kg ha^{-1}, K at the dose of 132.8 kg ha^{-1}, S1 at the dose of 25 kg ha^{-1}, and S2 at the dose of 50 kg ha^{-1}.	Spring oilseed rape, Markus cultivar	silt loam	The applied fertilization significantly affected the rape seed yield. Fertilized plants yielded significantly higher than control (unfertilized) plants. Fertilization with a double dose of a mixture of nitrate and ammonium sulfates was the most beneficial (rape seed yield higher by 40%).	Filipek-Mazur et al. (2019)
	1. No K fertilization (only N and P doses from 120 to 300 kg N ha^{-1}, and the P doses varying from 5 to 17 kg P ha^{-1});	Winter oilseed rape	-	The increase in seed yield averaged 18.5% and ranged from 9.4% to 26.8%, indicating that the seed yield potential	Ren et al. (2013)

cont. Table 5

	2. With NPK fertilization. The average K application dose was 89 kg K ha^{-1}, ranging from 57 to 117 kg K ha^{-1}, depending on site conditions. The N and P fertilizer application doses were the same as for the first treatment at each site.			of winter oilseed rape was higher with optimal K fertilization.	
	1. Control without foliar fertilization, 2. One application of foliar fertilizers. One fertilization treatment consisted of: 120 g ha^{-1} N, 125 g ha^{-1} K, 24 g ha^{-1} Mg, 28 g ha^{-1} S, 4.4 g ha^{-1} B, 7.3 g ha^{-1} Cu, 14.5 g ha^{-1} Fe, 21.8 g ha^{-1} Mn, 0.2 g ha^{-1} Mo, and 14.5 g ha^{-1} Zn (FoliQ Mikromax at 1 dm^3 ha^{-1}).	Winter oilseed rape	haplic luvisol	In the first and second seasons of the study, yield-forming effects were observed only after two foliar fertilizer applications.	Jankowski et al. (2019)
	Experiment A Two factors were studied in the experiment: I. factor: 4 multicomponent mineral fertilizers (NPK 6-20-30), i.e. two Belarusian (1 and 2), one Russian, and one Polish (Polifoska 6); II. factor: 4 doses of fertilization: 0 – control variant, minimum, optimum, maximum. The minimum dose was 50% lower than the optimal dose of 100 kg P_2O_5 ha^{-1}, and the maximum dose was 50% higher. Doses of multicomponent fertilizers were 250, 500, and 750 kg ha^{-1}, respectively. Polifoska 6	Winter oilseed rape, DK EXPLIC IT hybrid cultivar	loamy sand	In experiments A and B, the average seed yield of winter oilseed rape from two years ranged from 2.30 to 2.58 and from 2.55 to 2.64 t ha^{-1}, respectively.	Stankowski et al. (2019)

cont. Table 5

	is a complex granular NPK(S) 6-20-30(7). Experiment B The study compared two factors: I. factor: 3 multicomponent mineral fertilizers of Belarusian, Russian, and Polish production – Polifoska 8. The applied fertilizers were characterized by the following composition of NPK(S): Belarusian 8-24-24, Russian 9-25-25(4), and Polish 8-24-24(9); II. factor: 4 doses of fertilization: 0 – control variant, minimum, optimum, maximum, amounting to 200, 400, and 600 kg ha^{-1}, respectively.				
	The design of spring oilseed rape experiment included three N doses: 0, 90, and 150 kg N ha^{-1} (N0, N90, and N150, respectively) and three S doses: 0, 20, and 40 kg S ha^{-1} (S0, S20, and S40, respectively). To adjust equal amounts of K in all treatments, potassium chloride was applied.	Spring oilseed rape, Maskot cultivar	neutral light loam	The maximum use of N and S fertilizers for seed yield and seed quality components was obtained in the cultivation years 2004 and 2005 at a fertilizer dose of 90 kg N ha^{-1} combined with 20 kg S ha^{-1}.	Šiaudinis, Butkutė (2013)
	The experiments were two-factorial and were carried out in 4 replications. With increasing sulfur doses: a1 – 0 (control); a2 – 20 kg S ha; a3 – 40 kg S ha; a4 – 60 kg S ha, winter oilseed rape fertilization with optimal doses of boron and copper: b1 – 0	Winter oilseed rape	light soils (loamy sand)	Sulfur fertilization in a dose higher than 40 kg S ha^{-1} significantly increased the seed yield by 11-12% compared to control treatments, ranging from 0.35 to 0.61 t ha^{-1}. The application of a sulfur dose higher than 60 kg S ha^{-1} gave a similar yield-forming effect.	Sienkiewicz--Cholewa, Kieloch (2016)

cont. Table 5

	(control); b2 – 2 kg B ha^{-1}, and b3 – 5 kg Cu ha^{-1}; b4 – 2 kg B ha^{-1} + 5 kg Cu ha^{-1}. The examined fertilization was introduced into the soil before sowing; sulfur fertilization was in the form of granulated fertilizer WIGOR S (90% S), fertilization with microelements was in the form of copper sulfate $CuSO_4 \cdot 5 H_2O$ and boric acid H_3BO_3.				
	200 kg ha^{-1} NPK fertilizer 5:10:30 (before sowing)	Winter oilseed rape, Siska cultivar	gleysol on clay and sand	Mineral fertilization had no significant effect on oilseed rape yields in the two production seasons.	Turinek et al. (2017)
	Calcium super phosphate (P_2O_5, 15.5%) was applied before sowing at the rates of 0.0 (P0), 100 (P1), and 200 (P2) kg calcium superphosphate fed. Ammonium sulfate (20.5%, N) and potassium sulfate (48-50%, K_2O) were added in two equal doses of 100 kg ammonium sulfate fed^{-1} and 50 kg potassium sulfate fed^{-1} 21 and 45 days after sowing, respectively.	Winter oilseed rape	-	P fertilization significantly increased seed yield (kg fed^{-1}) compared to unfertilized treatments. The maximum values of these parameters were observed in plants fertilized with 200 kg fed^{-1}.	Said-Al Ahl et al. (2016)
	The first treatment was an unfertilized control. The other three treatments were fertilized with the same nitrogen dose of 160 kg ha^{-1} and increasing doses of sulfur. The second	Winter oilseed rape, Artoga cultivar	luvic chernozem	The highest average yield of 3.96 t ha^{-1} was obtained in the treatment where a medium dose of sulfur (40 kg ha^{-1}) was applied.	Varényiová et al. (2017)

cont. Table 5

	treatment was fertilized with 15 kg ha^{-1} S, the third with 40 kg ha^{-1} S, an a dose of 65 kg ha^{-1} S was applied to the fourth treatment.				
Thousand grain weight (g)	Autumn fertilization was divided into three variants: 1. Control without fertilization; 2. 40 kg N ha; 3. 80 kg N ha. Spring fertilization was uniform: it was applied in four doses of 180 kg Nha^{-1}, mainly with CAN.	Winter oilseed rape, DK Exstorm cultivar	haplic luvisol - clay loam	Only in 2013/14 there was an increase in thousand seed weight for a dose of 80 kg N ha^{-1}.	Béreš et al. (2019)
	Experiment A Two factors were studied in the experiment: I. factor: 4 multicomponent mineral fertilizers (NPK 6-20-30), i.e. two Belarusian (1 and 2), one Russian, and one Polish (Polifoska 6), II. factor: 4 doses of fertilization: 0 – control variant, minimum, optimum, maximum. The minimum dose was 50% lower than the optimal dose of 100 kg P_2O_5 ha^{-1}, and the maximum dose was 50% higher. Doses of multicomponent fertilizers were 250, 500, and 750 kg ha^{-1}, respectively. Polifoska 6 is a complex granular NPK(S) 6-20-30(7). Experiment B The study compared two factors: I factor: 3 multicomponent mineral fertilizers	Winter oilseed rape, DK explicit hybrid cultivar	loamy sand	The thousand seed weight of winter oilseed rape grown in both experiments was analogous to that obtained in the experiment of the Research Centre for Cultivar Testing in 2015 for the same oilseed rape cultivar.	Stankowski et al. (2019)

cont. Table 5

	of Belarusian, Russian, and Polish production – Polifoska 8. The applied fertilizers were characterized by the following composition of NPK(S): Belarusian 8-24-24, Russian 9-25-25(4), and Polish 8-24-24(9). II factor: 4 doses of fertilization: 0 – control variant, minimum, optimum, maximum, amounting to 200, 400, and 600 kg ha^{-1}, respectively.				
Oil content (%)	Autumn fertilization was divided into three variants: 1. Control without fertilization; 2. 40 kg N ha; 3. 80 kg N ha. Spring fertilization was uniform: it was applied in four doses of 180 kg N ha, mainly with CAN.	Winter oilseed rape, DK Exstorm cultivar	haplic luvisol - clay loam	The effect of fertilization on oil content was not statistically significant. The results indicated that, given the low mineral nitrogen content of the soil, the most appropriate nitrogen dose for autumn fertilization is 40 kg N ha^{-1}.	Béreš et al. (2019)
	Calcium super phosphate (P_2O_5, 15.5%) was applied before sowing at the rates of 0.0 (P0), 100 (P1), and 200 (P2) kg calcium superphosphate fed^{-1}. Ammonium sulfate (20.5%, N) and potassium sulfate (48-50%, K_2O) were added in two equal doses of 100 kg ammonium sulfate fed^{-1} and 50 kg potassium sulfate fed^{-1} 21 and 45 days after sowing, respectively.	Winter oilseed rape	-	The results showed that the seed oil yield was more influenced by soil moisture deficiency than the oil content was. This was caused by a much greater control of the oil content over genetic factors, and the oil yield was more affected by changes in the seed yield than the oil content.	Said-Al Ahl et al. (2016)

cont. Table 5

Leaf area index (LAI)	Experiment A Two factors were studied in the experiment: I. factor: 4 multicomponent mineral fertilizers (NPK 6-20-30), i.e. two Belarusian (1 and 2), one Russian, and one Polish (Polifoska 6); II factor: 4 doses of fertilization: 0 – control variant, minimum, optimum, maximum. The minimum dose was 50% lower than the optimal dose of 100 kg P_2O_5 ha^{-1}, and the maximum dose was 50% higher. Doses of multicomponent fertilizers were 250, 500, and 750 kg ha^{-1}, respectively. Polifoska 6 is a complex granular NPK(S) 6-20-30(7). Experiment B The study compared two factors: I factor: 3 multicomponent mineral fertilizers of Belarusian, Russian, and Polish production – Polifoska 8. The applied fertilizers were characterized by the following composition of NPK(S): Belarusian 8-24-24, Russian 9-25-25(4), and Polish 8-24-24(9). II factor: 4 doses of fertilization: 0 – control variant, minimum, optimum, maximum, amounting to 200, 400, and 600 kg ha^{-1}, respectively.	Winter oilseed rape, DK explicit hybrid cultivar	loamy sand	The LAI physiological index was significantly differentiated depending on the fertilizers used. The application of the Belarusian 1 fertilizer was the factor causing the oilseed rape plants growing on these treatments to have a lower greening index of 55.0 and an LAI index of 1.86. Fertilizers applied in Experiment B, Belarusian, Russian, and Polifoska 8 did not differentiate the LAI index.	Stankowski et al. (2019)
Micro- and macro-	Nitrogen dose: 1. 0 (control); 2. 60 kg N ha^{-1} (one application	Winter oilseed rape,	podsolic soil	The micronutrient content of winter oilseed rape increased	Fordoński et al. (2016)

cont. Table 5

element content in grain (g kg^{-1} d.m.)	in spring before plant growth); 3. 120 kg N ha^{-1} (split into two applications: 60 kg in spring before plant growth, and 60 kg – 2 weeks later); 4. 180 kg N ha^{-1} (split into three applications: 60 kg in spring before plant growth, 60 kg – 2 weeks later, and 60 kg – at the end of bud formation).	Californium cultivar		significantly in response to increased nitrogen fertilization.	
Fatty acids (%)	200 kg ha^{-1} NPK fertilizer 5:10:30 (before sowing)	Winter oilseed rape, Siska cultivar	gleysol on clay and sand	In both years, the most abundant fatty acid was oleic, followed by linoleic and linolenic acid in both years. Oleic acid levels ranged from 63.4% to 64.7% in 2009/2010 and 2011/2012, respectively.	Turinek et al. (2017)
	Treatments: 1. No fertilization (control); 2. NPK + S1 (ammonium sulfate); 3. NPK + S1 (mixture of ammonium nitrate and ammonium sulfate); 4. NPK + S1 (elemental sulfur); 5. NPK + S2 (ammonium sulfate); 6. NPK + S2 (mixture of ammonium nitrate and ammonium sulfate); 7. NPK + S2 (elemental sulfur) N at the rates of 100 kg ha^{-1} and 140 kg ha^{-1} (in the second term), P at the rate of 32.7 kg ha^{-1}, K at the rate of 132.8 kg ha^{-1}, S1 at the rate of 25 kg ha^{-1}, and S2 at the rate of 50 kg ha^{-1}.	Spring oilseed rape, Markus cultivar	silt loam	Rape seeds contained the most oleic acid (63.5-6.2%), then linoleic acid (21.0-21.6%), and the least stearic acid (1.76-1.84%). There was no clear relationship between the applied fertilization and the fatty acid profile.	Filipek-Mazur et al. (2019)

cont. Table 5

	1. Control – without foliar fertilization, one application of foliar fertilizers; 2. One fertilization treatment consisted of (g ha^{-1}): 120 N, 125 K, 24 Mg, 28 S, 4.4 B, 7.3 Cu, 14.5 Fe, 21.8 Mn, 0.2 Mo, and 14.5 Zn (FoliQ Mikromax at 1 dm^3 ha^{-1}).	Winter oilseed rape	haplic luvisol	Autumn foliar fertilization caused a significant modification of the fatty acid profile – higher oleic acid content, lower linoleic acid content.	Jankowski et al. (2019)
	Calcium super phosphate (P_2O_5, 15.5%) was applied before sowing at the rates of 0.0 (P0), 100 (P1), and 200 (P2) kg calcium super phosphate fed^{-1}. Ammonium sulfate (20.5%, N) and potassium sulfate (48-50%, K_2O) were added in two equal doses of 100 kg ammonium sulfate fed^{-1} and 50 kg potassium sulfate fed^{-1} 21 and 45 days after sowing, respectively.	Winter oilseed rape	-	The treatments had no effect on the fatty acid composition of rape seeds.	Said-Al Ahl et al. (2016)

In turn, the study by Tosti et al. (2016) proved that mineral fertilization with nitrogen gives better results compared to organic fertilization, both in terms of yield and protein content of the crop. Their study showed that winter wheat fertilized organically had yields on average up to 19% lower than winter wheat fertilized with mineral nitrogen (Table 3). Compared to the study by Rossini et al. (2018), taking into account the same dose of N, fertilization with mineral nitrogen resulted in a significantly higher grain yield than organic fertilization did at the doses of 160 and 200 kg ha^{-1}, in the range of 21-23%. Similarly, protein content after mineral fertilization was higher than after organic fertilization, and increased with an increasing nitrogen dose. The results of Tosti et al. (2016) revealed that 160 kg ha^{-1} N in either mineral or organic fertilization is the optimal dose for high yields with good technological value.

The chemical composition of grains and seeds can vary depending on the plant species. In order to determine the suitability of a crop for consumption, fodder or energy purposes, the quality of grains/seeds should be assessed.

Table 6

Qualitative parameters determined after applying organic fertilization for different cultivars of oilseed rape

Qualitative parameters	Applied fertilizer dose	Plant	Soil type	Effect	Literature
Yield (kg ha^{-1})	The experiment was laid out in a complete randomized block design (RCBD) with four different application doses of organic fertilizer: 0, 5, 7.5, and 10 kg m^{-2}, each replicated three times.	Winter oilseed rape	sandy loams	Soils enriched with 10 kg m^{-2} of organic fertilizer gave a relatively higher marketable yield of oilseed rape, and decreased as the dose of organic fertilizer applied in each harvest round decreased.	Mojeremane et al. (2015)
	Factorial combination of two sowing dates (October 17 and 27, respectively, as the optimal and late sowing dates) and two doses of vermicompost (0 and 20 t ha^{-1}).	Winter oilseed rape	-	The FJL290 and BAL102 enotypes produced the highest values of grain yield (5.853 and 5.763 kg ha^{-1}, respectively).	Joughi et al. (2018)
	The pot experiment included 5 treatments: 1. Soil without N fertilizer and biochar (CK); 2. Soil amended with 3.31 g of biochar (equivalent ~ 1 t ha^{-1}) and without N (B); 3. Soil amended with 3.31 g of biochar and 1.34 g of urea (B + U); 4. Soil amended with 1.34 g of urea and without biochar (urea); 5. Soil amended with 4.65 g of BCRNF (Biochar-based controlled release nitrogen fertilizer) as N fertilizer (BCRNF).	Winter oilseed rape, Xiangyou15 cultivar	-	Under the BCRNF treatment, plant grain yield notably exceeded other treatments. However, the B + U treatment's yield closely resembled Urea treatment, while BCRNF yielded around 16.6% more grain than urea.	Liao et al. (2020)
	Seven biochar application rates (0, 2.5, 5, 10, 20, 30, and 40 t ha^{-1}) were	Winter oilseed rape	red soil	Rapeseed yield fluctuated across five years, peaking in 2012 and hitting	Jin et al. (2019)

cont. Table 6

	labeled as control (CK), C1, C2, C3, C4, C5 and C6, respectively.			its lowest point in 2016. The C6 treatment's 2016 rapeseed yield was 1.11 t ha^{-1}, even lower than the control yield in 2012.	
Oil content (%)	Factorial combination of two sowing dates (October 17 and 27, respectively, as the optimal and late sowing dates) and two doses of vermicompost (0 and 20 t ha^{-1}).	Winter oilseed rape	-	Oil yield and content can be increased by 10 t ha^{-1} vermicompost.	Joughi et al. (2018)
Fatty acids (%)	Factorial combination of two sowing dates (October 17 and 27, respectively, as the optimal and late sowing dates) and two doses of vermicompost (0 and 20 t ha^{-1}).	Winter oilseed rape	-	Application of vermicompost reduced harmful fatty acid (erucic acid) and increase useful fatty acids such as oleic, linoleic and linolenic acids.	Joughi et al. (2018)

In turn, the quality of the yield depends on its chemical composition. The chemical composition of the yield can be shaped by the genotype of the cultivar, environmental conditions and agrotechnical treatments (Wójtowicz, Jajor 2006).

Fertilization of plants has a significant impact on the chemical composition of grains and seeds, including protein and fat contents as well as mineral composition. For example, nitrogen fertilization can increase the protein content of grains and seeds. Nitrogen affects protein synthesis, which can lead to increased amino acid and protein contents. Phosphorus has important and irreplaceable functions in plant life processes, such as respiration, photosynthesis, fat metabolism, and nitrogen metabolism. The addition of phosphorus can also affect the quality of seeds by increasing their oil composition. With a deficiency of phosphorus and potassium in the soil and intensive nitrogen fertilization, the chemical composition of the grain changes, and the protein and gluten contents decrease. Potassium, on the other hand, plays an important role in regulating plant water management, enzyme activation, and nutrient transport. Potassium fertilization can affect potassium accumulation in grains and seeds, which can influence their nutrient content, quality, and storage capacity. In addition, micronutrients such as iron, copper, zinc, manganese, and molybdenum are essential for proper plant development. Appropriate fertilization with micronutrients can affect

Table 7

Qualitative parameters determined after applying mineral-organic fertilization for different cultivars of oilseed rape

Qualitative parameters	Applied fertilizer dose	Plant	Soil type	Effect	Literature
Yield (kg ha^{-1})	Polifoska 6 mineral fertilizer (with 6% nitrogen (N) content as ammonium, 20% phosphorus (P_2O_5), 30% potassium (K_2O) was applied before sowing. The following doses of Polifoska 6 were used: 2017 – 350 kg ha^{-1}; 2018 – 350 kg ha^{-1}; and 2019 – 350 kg ha^{-1}. The scope of the field tests covered 4 variants of the experiment on which digestate was sprayed (using a slurry tanker with an adapter with hoses on the soil surface): variant I – the total digestate dose of 25,000 L ha^{-1} (I dose – 12,500 L ha^{-1}, II dose – 12,500 L ha^{-1}); variant II – the total digestate dose of 37,500 L ha^{-1} (I dose – 18,750 L ha^{-1}, II dose – 18,750 L ha^{-1}); variant III – the total digestate dose of 50,000 L ha^{-1} (I dose – 25,000 L ha^{-1}, II dose – 25,000 L ha^{-1}); variant IV – a control treatment sown with seeds that were not fertilized with digestate.	Winter oilseed rape, Artoga cultivar	medium soil of sandy dust granulation	Analysis of the study results revealed a discrepancy in yields in the first growing season of 2016/2017 from 3.32 to 3.45 t ha^{-1}. In the second growing season of 2017/2018, the values were similar and ranged from 3.35 to 3.47 t ha^{-1}.	Koszel et al. (2020)

cont. Table 7

Protein content (%)	Polifoska 6 mineral fertilizer (with 6% nitrogen (N) content as ammonium, 20% phosphorus (P_2O_5), 30% potassium (K_2O) was applied before sowing. The following doses of Polifoska 6 were used: 2017 – 350 kg ha^{-1}; 2018 – 350 kg ha^{-1}; and 2019 – 350 kg ha^{-1}. The scope of the field tests covered 4 variants of the experiment on which digestate has been spilled (using a slurry tanker with an adapter with hoses on the soil surface): variant I – the total digestate dose of 25,000 L ha^{-1} (I dose – 12,500 L ha^{-1}, II dose – 12,500 L ha^{-1}); variant II – the total digestate dose of 37,500 L ha^{-1} (I dose – 18,750 L ha^{-1}, II dose – 18,750 L ha^{-1}); variant III – the total digestate dose of 50,000 L ha^{-1} (I dose – 25,000 L ha^{-1}, II dose – 25,000 L ha^{-1}); variant IV – a control treatment sown with seeds that were not fertilized with digestate.	Winter rape seeds, Artoga cultivar	medium soil of sandy dust granu-lation	The average protein content of winter rape seeds harvested from the control plot was 22.39% from three years of the study. In the other experiment variants, the average protein content increased with the increase of the post-fermentation rate and ranged from 22.65% to 22.95%.	Koszel et al. (2020)
Thousand seed weight (g)	Polifoska 6 mineral fertilizer (with 6% nitrogen (N) content as ammonium, 20% phosphorus (P_2O_5), 30% potassium (K_2O)	Winter oilseed rape, Artoga cultivar	The field experiment was established on medium soil of sandy dust	The thousand seed weight was from 5.20 to 5.34 g on average for three years.	Koszel et al. (2020)

cont. Table 7

	was applied before sowing. The following doses of Polifoska 6 were used: 2017 – 350 kg ha^{-1}; 2018 – 350 kg ha^{-1}; and 2019 – 350 kg ha^{-1}. The scope of the field tests covered 4 variants of the experiment in which digestate was sprayed (using a slurry tanker with an adapter with hoses on the soil surface): variant I – the total digestate dose of 25,000 L ha^{-1} (I dose – 12,500 L ha^{-1}, II dose – 12,500 L ha^{-1}); variant II – the total digestate dose of 37,500 L ha^{-1} (I dose – 18,750 L ha^{-1}, II dose – 18,750 L ha^{-1}); variant III – the total digestate dose of 50,000 L ha^{-1} (I dose – 25,000 L ha^{-1}, II dose – 25,000 L ha^{-1}); variant IV – a control treatment sown with seeds that were not fertilized with digestate.		granu-lation		

their content in grains and seeds, as well as the quality of food (Poisson et al. 2019, Grzebisz et al. 2020).

However, it is worth noting that the effect of fertilization on the chemical composition of grains and seeds can be complex and depends on many factors, such as the type of fertilizer, doses, time and method of application, soil and climatic conditions, and plant cultivar.

Technical grains

Technical grains are a group of crops that are grown for the purpose of producing various types of industrial products rather than for human or animal consumption. Examples of technical cereal crops include flax, hemp, cotton, jute, canola, soybeans, sunflowers, sugar cane, spelt, waxy maize, and many others. Technical grains have a wide range of industrial applications and are essential raw materials in the production of various products, such as fabrics, paper, oils, biofuels, insulation materials, and animal feed. For instance, wheat as a technical grain can be used in the production of glues and starches, beer, ethanol, chipboard and plywood, as well as staves. Parameters of technical grains may vary depending on the species and the intended industrial application. One of the most significant characteristics of technical grains is their moisture content, as it affects their durability, quality, and susceptibility to spoilage. Depending on the species and intended industrial application, the moisture content of technical grains can range from a few percent to several dozen percent. The protein content, on the other hand, is an important component of technical grains used in food and fodder production, and it varies depending on the type of grain and its variety. High oil content is important for plants such as rapeseed or sunflower, which are cultivated for their use in oil production. The parameter that determines the dietary fiber content in technical grains is crucial for their use in paper production, insulation, and other products. Moreover, grain size, shape, and color play a critical role in their industrial applications. All these quality parameters are determined to assess the suitability of technical grains for the production of various industrial products (Gírio et al. 2017).

SUMMARY

Numerous study results indicate that both the dose and the method of application of mineral, organic or mineral-organic fertilizers have a significant impact on the yield and its technological parameters. Nitrogen fertilization plays a special role here, as it has a decisive effect on the grain yield and baking value characteristics: protein content, gluten content, sedimentation index, dough rheological characteristics, but it negatively affects the gluten index. Increased nitrogen rate generally increases the crop protein content. Wheat is used to make hundreds of different products around the world, each with specific grain quality requirements. Yield quality should be an integral part of the cultivation process considered in cultivar development. On the other hand, rapeseed yields valuable oil for human consumption and its by-product (rapeseed meal) serves as animal feed, vital for the livestock industry. Rapeseed also plays a pivotal role in biodiesel production, essential for transitioning to cleaner energy sources. This increasing production of both wheat and rapeseed is vital to meet global needs, ensure food security, support industries, and promote sustainable agriculture. Study results to date prove that there is a need for greater focus on the use of combinations of organic and mineral fertilizers. Reducing fertilizer use while

maintaining or even improving seed yield and quality is an ongoing environmental and economic challenge. This can make sustainable production and agriculture more environmentally friendly, especially in the face of climate change.

Fertilizer innovations have been continuously evolving to improve nutrient efficiency, reduce environmental impacts, and enhance crop productivity. Some notable examples of fertilizer innovations used in agriculture nowadays include e.g. hybrid fertilizers, fertilizers containing functionalized materials or nanofertilizers. By providing a more balanced nutrient supply, hybrid fertilizers aim to improve macronutrients and microelmenets uptake and yield while minimizing wastage. Meanwhile, functionalized materials in fertilizers are used to improve nutrient absorption, reduce leaching, and enhance nutrient availability in the soil. Furthermore, nanofertilizers can enhance nutrient uptake and distribution within plant tissues, leading to improved growth and yield. They have the potential to reduce fertilizer usage, minimize nutrient losses, and increase crop resilience to abiotic stresses. These innovations contribute to sustainable and efficient agriculture (Calabi-Floody et al. 2018, Jakhar et al. 2022, Jarosz et al. 2022).

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Author contributions

L.M-M. – writing – original draft preparation, methodology, data curation, visualization, writing – review & editing; M.M-H. – writing – original draft preparation, methodology, writing – review & editing; data curation, supervision, funding acquisition.

Conflicts of interest

The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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