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REVIEW

# Analysis of yield and plant traits of oilseed rape (*Brassica napus* L.) cultivated in temperate region in light of the possibilities of sowing in arid areas

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## Abstract

This work is a review of selected literature on the species of *Brassica* with the greatest economic significance. Oilseed rape (*Brassica napus* ssp. *oleifera*) currently ranks third worldwide among oilseed crops used for oil production and is the most important in the temperate zone. The manifold uses of rape include not only human consumption of oil, but also the use of post-extraction meal to feed livestock as well as industrial applications as a source of bioenergy or cellulose. The improvement in the economic position of rape among crop plants is also due to the doubling of its yield between 1970 and 2009; the average annual increase in seed yield worldwide was 27 kg $ha^{-1}$ $yr^{-1}$. The yield level in Europe exceeds the average yields achieved in the world, particularly in Asia. Recently, the cultivation of oilseed rape was started on a relatively large acreage in Iran where the yield amounted 2.1 t $ha^{-1}$, exceeding the yields of China and India. In Poland, the acreage of oilseed rape cultivation between 1965 and 2013 increased 3–4 times, and during this period the annual increase in seed yield was 29 kg $ha^{-1}$ $yr^{-1}$. Under the field conditions of the temperate climate zone, winter oilseed rape yield is mainly determined by agro-climatic conditions during the growing period, the level of nitrogen fertilization, and the production potential of varieties, which is currently highest in hybrids. There is a noticeable tendency of hybrids towards formation of more siliques by individual oilseed plants. Different production categories of plants appear in a rape crop. Semi-dwarf varieties of winter rapeseed are distinguished by greater silique density, particularly on the main shoot. Moreover, these hybrids are characterized by faster growth of the root system, which enables them to take up nitrogen from the soil more efficiently.

## Keywords

cultivars; seed yield components; aboveground and belowground biomass

## Introduction

Four species of the genus *Brassica* are commonly grown as oilseed crops: *Brassica napus* (Swede rape), *B. rapa* (turnip rape), *B. juncea* (Indian mustard), and *B. carinata* (Ethiopian mustard) [1]. *Brassica rapa* is the most widespread *Brassica* species and has the longest history of domestication in the Old World (Europe, Western Asia, and Northern Africa) [2]. *Brassica juncea* is grown mainly in India and in some regions of China. The primary range and area of cultivation of *Brassica carinata* are limited to Northeast Africa, mainly Ethiopia.

*Brassica napus* (oilseed rape) has a long tradition of cultivation in European countries, Canada as well as in Asia. The winter form of oilseed rape is grown in the temperate climate zone of Europe, while only the spring form (canola), known for its high oil quality, is cultivated in the western (prairie and semiarid) provinces of Canada – currently mainly GM varieties [3]. In Europe, winter form, which is more productive than the spring form, dominates for biological and legal reasons [4–6]. The breeding of heterotic varieties is a step that radically increases the production potential of the species. It is agreed that the biological yield of rape is conditioned by the rate of growth and the length of the growing period, so varieties meeting these two criteria are sought after. Emphasis is currently placed on the many uses of the seed yield, both for human consumption (vegetable fat) or livestock feed (post-extraction meal) and as a source of bioenergy in industry [7]. Oilseed rape yield must be competitive with that of other winter crops in order to become an attractive alternative for farmers [8]. Mousavi et al. [9] emphasize that in countries with an arid or semi-arid climate, including Iran (its unforested region), farmers are taking up cultivation of spring rape which, apart from seeds, also supplies stalks used as a source of cellulose for paper production. The economic significance of this taxon appears to be greater there than in the temperate climate zone, where only the seed yield is useful as a source of oil.

## Oilseed rape productivity

Tab. 1 and Tab. 2 present the increasing acreage of oilseed rape worldwide and in certain countries as well as its systematically growing yield. The mean global yield of oilseed rape doubled from 1970 to 2009, increasing from about 800 to 1900 kg $ha^{-1}$ at a rate of about 27 kg $ha^{-1}$ yr−1 during this period [10]. In Central Europe, the seed yield of winter oilseed rape (WOR) increased by 29 kg $ha^{-1}$ $yr^{-1}$, which was similar to the global trend and, at the same time, much higher than the trend of 9 kg $ha^{-1}$ $yr^{-1}$ estimated for Australia and India where the spring form is cultivated [10]. In Finland, the major *Brassica* crop is turnip rape (*B. rapa* L. var. *oleifera* subvar. *annua*), which is grown on over 93% of the area where oilseed crops are cultivated, whereas oilseed rape (*B. napus* L. var. *oleifera* subvar. *annua*), which matures later, is grown only in the most favorable southern and southwestern parts of the country [11]. Waalen et al. [12] emphasize that Norway has also seen interest in cultivation of winter forms of *B. napus* and *B. rapa* and in increasing their resistance so that they can be grown in northern Scandinavia. In Poland, the productivity of the winter form of oilseed rape is significantly higher than that of white mustard, an alternative species [13].

The increase in the acreage of oilseed species is oriented at diversifying the structure of agricultural crops, primarily by reducing monoculture of cereal crops. This solution may offer numerous benefits, both agronomical and environmental [12]. In the cooler part of the temperate climate zone, the winter hardiness of oilseed rape plays an important role, as emphasized by Rapacz and Markowski [14]. Oilseed rape is gaining an advantage in yield in Central and Northern European countries, while turnip rape is perceived as a less productive oilseed crop, although the Central Statistical Office of Poland (GUS) still reports combined seed yields for rapeseed and turnip rape. This trend is also noted in Finland, though with some delay, as from 1976 to 2006 the increase in seed yield of oilseed rape (41%) was much higher than in the case of turnip rape (19%), and moreover, was not associated with a longer seed-filling phase and later ripening, as in fact the reverse was observed [11].

The global oilseed rape yield during the last 40 years has increased by 3.4% $yr^{-1}$, while that of wheat and soybean increased by 2.6% and 1.7% $yr^{-1}$, respectively [10]. Direct comparison of these data shows that oilseed rape yield is increasing at twice the rate of soybean yield. Oilseed rape (species of the genus *Brassica*) is one of the most commonly cultivated oil crops worldwide. Global rapeseed production in 2011 amounted to about 62.7 million tons [15]. Unal et al. [16] report that Canada is the largest producer of oilseed rape in the world, accounting for almost a quarter of global production, followed by China, India, France, and Germany. In China, about 87% of rapeseed is currently cultivated along the Yangtze River, accounting for 89% of the total national oilseed rape yield [17]. According to Weymann et al. [18], about 40%

**Tab. 1** Changes in acreage of rapeseed (1000 ha) in regions of the world and selected countries over a period of 48 years.

| Country | 1965 | 1980 | 1990 | 1995 | 2000 | 2005 | 2010 | 2013 |
|---|---|---|---|---|---|---|---|---|
| World | 7065 | 10992 | 17611 | 23816 | 25844 | 27690 | 32231 | 36499 |
| Asia | 5526 | 7102 | 11123 | 13656 | 14189 | 15403 | 13952 | 14880 |
| Europe | 837 | 1665 | 3615 | 4267 | 4620 | 5460 | 8945 | 9307 |
| European Union | 764 | 1504 | 2972 | 3865 | 4153 | 4887 | 7087 | 6724 |
| Canada | 581 | 2080 | 2529 | 5273 | 4859 | 5175 | 6848 | 8007 |
| China | 1842 | 2843 | 5504 | 6907 | 7494 | 7279 | 7370 | 7519 |
| India | 2910 | 3471 | 4967 | 6060 | 6027 | 7316 | 5580 | 6340 |
| Germany | 165 | 262 | 722 | 974 | 1078 | 1344 | 1461 | 1466 |
| France | 173 | 390 | 680 | 864 | 1186 | 1232 | 1464 | 1438 |
| Poland | 274 | 320 | 500 | 606 | 437 | 550 | 946 | 921 |
| United Kingdom | 1 | 92 | 390 | 439 | 402 | 593 | 642 | 715 |
| Czech Republic | - | - | - | 253 | 324 | 267 | 369 | 419 |
| Iran | - | - | - | - | - | 161 | 160 | 170 |
| Turkey | 8 | 10 | 2 | - | - | 1 | 31 | 31 |

Data source: FAOSTAT [52].

**Tab. 2** Increasing yield of rapeseed (t ha$^{-1}$) worldwide and in rapeseed growing countries.

| Country | 1965 | 1980 | 1990 | 1995 | 2000 | 2005 | 2010 | 2013 |
|---|---|---|---|---|---|---|---|---|
| World | 0.7 | 1.0 | 1.4 | 1.4 | 1.5 | 1.8 | 1.9 | 2.0 |
| Asia | 0.5 | 0.6 | 1.0 | 1.2 | 1.2 | 1.4 | 1.5 | 1.6 |
| Europe | 1.9 | 2.3 | 2.6 | 2.5 | 2.5 | 3.0 | 2.6 | 2.7 |
| European Union | 1.9 | 2.3 | 2.8 | 2.7 | 2.7 | 3.2 | 2.9 | 3.1 |
| Canada | 0.9 | 1.2 | 1.3 | 1.2 | 1.5 | 1.8 | 1.9 | 2.2 |
| China | 0.6 | 0.8 | 1.3 | 1.4 | 1.5 | 1.8 | 1.8 | 1.9 |
| India | 0.5 | 0.4 | 0.8 | 1.0 | 1.0 | 1.0 | 1.2 | 1.2 |
| Germany | 1.9 | 2.6 | 2.9 | 3.2 | 3.3 | 3.8 | 3.9 | 3.9 |
| France | 1.9 | 2.8 | 2.9 | 3.2 | 2.9 | 3.7 | 3.3 | 3.0 |
| Poland | 1.8 | 1.8 | 2.4 | 2.3 | 2.2 | 2.6 | 2.4 | 2.9 |
| United Kingdom | 2.5 | 3.3 | 3.2 | 2.8 | 2.9 | 3.2 | 3.5 | 3.0 |
| Czech Republic | - | - | - | 2.6 | 2.6 | 2.9 | 2.8 | 3.4 |
| Iran | - | - | - | - | - | 2.0 | 2.1 | 2.1 |
| Turkey | 0.9 | 1.2 | 1.0 | 1.3 | 2.3 | 1.7 | 3.4 | 3.3 |

Data source: FAOSTAT [52].

of the variation in seed yield in Germany can be explained by weather conditions during the individual stages of growth, of which the most important were the start of silique and seed formation (BBCH 50–65) and seed development (BBCH 71–79). Intensive research is currently being conducted on expanding oilseed rape cultivation in Turkey [16,19,20] and Iran [21–25]. Cultivation of sesame (*Sesamum* L.) and olive (*Olea europea* L.) was once dominant in these conditions, but more productive varieties of oilseed rape have become the main source of oil in the semiarid region. In these agro-climatic conditions, attempts are made to improve the productivity of oilseed rape through irrigation, increased nitrogen fertilization, and breeding of new varieties – solutions previously used in Europe.

## Biological and environmental yield determinants

Extensive research revealed that radiation, temperature, and drought stress significantly affected yield of winter oilseed rape during the onset of pods and seeds when the number of seeds per $m^2$ was determined by assimilate availability. After flowering, only temperature was found to significantly influence the yield [18]. Furthermore, the authors of this study estimated that besides maximum seed yield ($Y_{max}$) and average daily mean temperature during seed development ($T_{seed}$) also influenced the correlation between the number of seeds per unit area and the weight of 1000 seeds. However, in the conditions of Warmia (northern Poland), in the case of a water shortage during the seed ripening stage of winter oilseed rape of the 'Californium' variety, the 1000-seed weight decreased, fluctuating around 4.5 g. The field data showed the number of seeds per $m^2$ and the 1000-seed weight to be negatively correlated, providing that $T_{seed}$ was not higher than 17°C. When $T_{seed}$ exceeded 17°C, 1000-seed weight remained independent of the number of seeds per $m^2$ [26]. The seed of the oilseed rape plant, regarded as the edible part, can amount to 25% of the total plant weight (75% is inedible). Enzymatic hydrolysis has been found to significantly enhance the use of such crops as oilseed rape, which are generally regarded as low-yield but fulfill a particularly dietary need. For this reason, oilseed rape is regarded as a raw material for oil production, while post-extraction meal is used as fodder.

Resistance to drought is an important characteristic of adaptation to environmental conditions, as confirmed by Gunasekera et al. [27] in a study on Indian mustard and canola (spring oilseed rape) in the Mediterranean-like conditions of southwestern Australia. In this study, mustard yielded significantly higher dry matter than canola (3.91 t $ha^{-1}$ vs. 2.63 t $ha^{-1}$), but this level is still low in comparison with the typical WOR yield in Central Europe, which is indicative of the importance of a lack of water as a limiting factor for these plants, perceived as resistant to drought stress. Water stress causes a significant decrease in metabolic factors such as leaf area index, nitrogen nutrition index, and leaf chlorophyll (SPAD) in rapeseed plants [23]. In a study conducted by Bouchereau et al. [28], all the traits studied that were associated with the biochemical composition of the seed were shown to be severely modified in plants exposed to drought during the flowering phase. While the variability of total lipid content was limited, changes were noted in the fatty acid composition, particularly in the erucic acid metabolic pathway (oleic, gadoleic, and erucic acids). In a study by Hamzei and Soltani [23] conducted in Iran, the level of irrigation of oilseed rape was 7500 $m^3$ water $ha^{-1}$, and the plants responded with a yield of aboveground dry matter of 1671 g $m^{-2}$ and a seed yield of 351 g $m^{-2}$. However, such high water consumption itself limits the feasibility of such a measure in an arid zone. Jabbari et al. [24] emphasize that where there is a water deficit in the soil, oilseed rape germination and seedling establishment are crucial stages for production, which are still poorly understood. In a pot experiment, when soil moisture content was decreased from 50% to 20% soil field capacity, total final emergence decreased from 94.3% to 82.7%.

It is currently emphasized as a certainty that nitrogen availability is crucial in determining the yield of winter oilseed rape [29]. The growth and development of winter oilseed rape, which is widely cultivated in temperate climates, is most commonly limited by nitrogen (N) availability, particularly in the early stage of vegetative growth [6,8,30]. Behrens and Diepenbrock [31] established that the highest fresh mass was attained by winter oilseed rape 'Lirajet' on day 280 or 300 of ontogenesis where the total nitrogen application was 210 kg N $ha^{-1}$. This also depended on the weather, which induced faster development in warmer years and delayed it in cooler years. In 2003 and 2004, the fresh weight of the WOR canopy was 53 and 88 t $ha^{-1}$, respectively. In this study, the dry matter yield of WOR on day 320 of ontogenesis (full maturity) in 2003 was about 9 t $ha^{-1}$, while in 2004, a wetter year, it was about 21 t $ha^{-1}$. Such a wide range of WOR productivity demonstrates the developmental plasticity of the winter form, which efficiently utilizes the resources of the environment. Colnenne et al. [32] estimated that in the soil and climate conditions of Western Europe, which are favorable to WOR, as early as fall this oilseed plant produces dry matter in an amount of about 6 t $ha^{-1}$, in which it accumulates up to 350 kg N $ha^{-1}$. Justes et al. [33] showed that high levels of nitrogen fertilization are imperative for oilseed rape productivity; when the application rate was very high, at 272 kg N $ha^{-1}$, at the end of the growing season (full maturity) the dry matter yield was 2250 g $m^{-2}$, which was twice as high as when no nitrogen was applied (control). As observed by Scott et al. [34], canopy size was reduced by reducing the number of pods, but the improved survival of seeds per pod more than offset this, and the weight of individual seed weight was not affected. In a study by Scott et al. [34], the total dry weight of a crop of oilseed rape 'Apex' at full maturity was 15.5 t $ha^{-1}$, while the seed yield was 4.4 t $ha^{-1}$. In a cause-and-effect design, Hamzei and Soltani [23] found that increases in grain yield were relatively strongly correlated with biomass ($R^2 = 0.73$).

Using a DAISY model, Petersen et al. [35] found that applied nitrogen determines the leaf area index (LAI). In this study, an increase in the LAI of the canopy led to an increase in the dry matter yield of WOR, measured at the end of the growing season. Kotecki et al. [36] emphasize that oilseed rape responds strongly to changing climate conditions as well as to the level of cost inputs. The authors showed that in the habitat conditions of Lower Silesia, the application of nitrogen at the intensive A2 agricultural technology level caused an 11% increase in seed yield with respect to the basic A1 level. Some studies have assessed the significance of high nitrogen application not only for yield, but also from an agroecological perspective [37]. These researchers state that the maximum WOR seed yields ranged from 4.79 to 4.90 t $ha^{-1}$ in the case of a high mineral fertilizer rate (240 kg N $ha^{-1}$), while storage of energy and $CO_2$ by the seeds varied from 13.6 to 13.9 GJ $ha^{-1}$ and 13.2 to 13.5 t $ha^{-1}$. Comparison of productivity for nitrogen application rates of 120 and 240 kg $ha^{-1}$ in the conditions of Warmia shows a seed yield of 4.19 t $ha^{-1}$ for the lower rate and 4.72 t $ha^{-1}$ for the rate of 240 kg $ha^{-1}$. In the case of the higher application rate, the winter oilseed rape plants formed more siliques and the 1000-seed weight increased as well [38]. However, many studies have found a solution making it possible to reduce the tendency towards high rates of nitrogen application, as nitrogen management has been shown to be an important driver of environmental impact. High levels of nitrogen application for WOR, particularly when there is plenty of water, result in intensive growth of the plants, which in these conditions leads to severe lodging and thereby to a 16–50% reduction in seed yield [39]. Later observations by Peltonen-Sainio and Jauhiainen [11] indicated that lodging likely affected seed yield when analyzed on the basis of yield grouping. In general, high-yielding plants showed a tendency to lodge less, supporting the idea that lodging is linked to a failure to attain yield potential.

An important phase for the oilseed yield and canopy is the flowering stage, in which the number of siliques per plant, and thus per unit area, is determined. The final number of pods and seeds is determined over a 4-week period and is highly dependent on a continuous supply of assimilates. Diepenbrock [8] emphasizes that the number of pods per plant is decisive for seed yield, which ultimately depends on the survival of branches, buds, flowers, and young pods, and not the potential number of flowers and pods. The ranking of treatments according to the number of siliques and yield usually corresponds to the fertilization level [29].

Diversified crop rotations in combination with improved nitrogen management can result in more ecologically efficient cropping systems. For this reason, in three regions in France (Beauce, Burgundy, and Moselle) spring and winter forms of pea were used as forecrops in order to compare the efficiency of WOR cultivation in conventional and integrated systems [7]. Legumes may potentially reduce the environmental impact by fixing nitrogen from the air in symbiosis with *Rhizobium* bacteria, thereby reducing the use of mineral N fertilizers as well as diversifying the crop rotation [40]. Nemecek et al. [7] observed that the introduction of pea made it possible to reduce the total eutrophication over the entire crop rotation. In one treatment, the first barley crop was replaced by pea: winter pea in Beauce and spring pea following a catch crop in Burgundy and Moselle. The catch crop was non-leguminous, e.g., *Phacelia*. The catch crops had beneficial effects on nutrient leaching and slightly beneficial effects on biodiversity and soil quality. Previously, in the conditions of northern Germany, Sieling et al. [41] established empirically that seed yield was more affected by the cropping sequence, with the greatest yield observed following the sequence peas–wheat (694 g $m^{-2}$), and the smallest after 2 years of WOR cropping (371 g $m^{-2}$). In this study, rapeseed grown after the combination of peas followed by wheat produced 1727 g $m^{-2}$ of biomass at full maturity, as compared to only 984 g $m^{-2}$ of aboveground biomass for WOR grown after 2 years of oilseed rape. It is stressed that oilseed rape is the most important of all winter–spring oil crops, known worldwide as an alternative to temperate cereals in winter–spring growing regions.

## Components of seed yield and canopy of rapeseed

Tab. 3 presents data from 1997–2016 included in selected studies devoted to oilseed rape. Analysis of data pertaining to plant density reveals a clear downward trend. In the past (the 1990s), density exceeded 70 plants per $m^2$. Currently, density is decreasing to 30–40 plants per $m^2$, which is a consequence of a reduction in the number of seeds sown, mainly in new hybrids. There is a visible tendency towards formation of a greater number of siliques by individual oilseed rape plants. This phenomenon can be seen in studies conducted under European conditions, in the temperate climate zone. In the arid zone, the number of siliques formed by the rape plant is much smaller. The number of seeds per silique ranges from 20 to 30. Siliques formed on the main stem contain more fruits. Sieling et al. [41] and Kwiatkowski [42] showed that fewer seeds in the fruits were observed when they were located on the lateral branches.

Tab. 4 presents three production categories of WOR plants distinguished during ontogenesis in southern Poland, small, medium, and large, which differed highly significantly in the number of lateral branches formed and therefore also in the number of siliques. Before harvest, the mean plant density of heterosis varieties of WOR was 30 plants per $m^2$. It is worth emphasizing that the large plants produced a high seed yield that was over four times greater than that of the small plants. The large plants, forming 304.1 ±87.6 siliques, produced a record-high seed yield of 39.68 ±11.32 g, rarely reported in the literature, which clearly illustrates the production potential of heterosis varieties [4]. Moreover, the seeds from the medium and large WOR plants showed a tendency towards increased weight per unit area. A factor determining the increasing weight of one seed may be the increase in the redistribution of nutrients to the seeds from the main stem and lateral branches during the ripening period, which in this plant category is significantly higher than in the case of the small plants. It is emphasized that the seed yield of a single oilseed rape plant is strictly determined by the number of siliques, the number of seeds per silique and the individual weight of the seed. Furthermore, buds, flowers, and in consequence pods are lost more quickly on lateral branches.

Under intensive cultivation conditions, heterosis varieties of WOR formed a large number of siliques: the traditional variety formed 278 and the semi-dwarf variety 259 (Tab. 5). The plants of both varieties formed more siliques on the main shoot and fewer on the lateral branches. Moreover, the semi-dwarf variety, 'PR45 D03', had greater fruit density, calculated for 10 cm of the fruiting part of the main shoot.

The long-stem rapeseed 'Visby' produced the highest yield (4.73 t $ha^{-1}$), which was 120 and 620 kg $ha^{-1}$ higher than for the semi-dwarf rapeseed 'Avenir' and 'PR45 D03', respectively [38]. These tendencies are confirmed by the results of other authors conducting research in the temperate climate zone. In a study of Clarke et al. [43] on hybrid WOR cultivars in Great Britain (Norfolk and North Yorkshire), the yield of the semi-dwarf rapeseed 'PR45 D03' was 0.52–0.84 t $ha^{-1}$ lower than that of the long-stem rapeseed 'Excalibur'. In northwestern Germany, the yield of the semi-dwarf WOR

**Tab. 3** Comparison of seed yield (SY), plant density (PD), number of siliques (NOS), seeds per silique (SP), and 1000-seed weight (1000 SM) depending on the level of factors applied in rapeseed cultivation.

| | | | | | Primary yield components | | | |
|---|---|---|---|---|---|---|---|---|
| **Author(s)** | **Factor** | **Level** | **Country** | **SY (units)** | **PD (pcs. m$^{-2}$)** | **NOS (pcs. plant$^{-2}$)** | **SP (pcs.)** | **1000 SM (g)** |
| Sieling et al. [41] | Previous crop | Wheat | Germany | 781 (g m$^{-2}$) | 73.0 | 127.0 | 19.8/17.4$^{A}$ | 4.18 |
| Leach et al. [53] | Sowing date | Sown early | United Kingdom | - | 74.3 | 69.8 | - | 4.46 |
| Özer [20] | Nitrogen rate | 240 kg ha$^{-1}$ | Turkey | 1.33 (t ha$^{-1}$) | - | 254.0 | - | 4.17 |
| Fargue et al. [54] | Cultivars | 'Lutin' | France | 8.1 (g plants$^{-1}$) | - | - | - | 5.90 |
| Kotecki et al. [36] | Cultivars | 'Kronos' | Poland | 3.92 (t ha$^{-1}$) | - | 125.0 | 27.8 | 4.36 |
| Jankowski and Budzyński [55] | Sowing density | 60 seeds m$^{-1}$ | Poland | 5.90 (t ha$^{-1}$) | 46.0 | 106.0 | 28.0 | 5.39 |
| Tuncturk and Çiftici [56] | 16 cultivars | Average | Turkey | 1.16 (t ha$^{-1}$) | - | 75.9 | 22.9 | 3.20 |
| Sieling and Kage [6] | Cultivars | 'Talent' | Germany | 692 (g m$^{-2}$) | - | - | 21.4 | 4.38 |
| Kwiatkowski [42] | Sowing rate | 70 seeds m$^{-1}$ | Poland | 3.64 (t ha$^{-1}$) | - | 136.0 | 18.9/12.0$^{A}$ | 4.71 |
| Śmiatacz [44] | Sowing date | Optimal | Poland | - | 47.9 | 121.2 | 25.2 | 6.07 |
| Zając et al. [4] | Cultivars | 'Adam' | Poland | 20.3 (g plants$^{-1}$) | 41.9 | 177.9 | - | - |
| Rad et al. [25] | Irrigation | - | Iran | 3.01 (t ha$^{-1}$) | - | 70.4 | 25.3 | 3.89 |
| Jankowski et al. [5] | S fertilization | 'Californium' | Poland | 4.76 (t ha$^{-1}$) | - | - | 22.2 | 4.49 |
| Jankowski et al. [38] | Cultivar | 'Visby' | Poland | 4.73 (t ha$^{-1}$) | 30.0 | 134.0 | 24.5 | 5.90 |

$^{A}$ Main shoot / lateral branches.

**Tab. 4** Comparison of the density and production potential of groups of WOR plants, heterosis cultivars 'Adam', and 'Poznaniak' – means from three locations and three growing seasons (unpublished data).

| Plant category | Plant density (plants per m$^2$) | Number per plant | | Seed yield per plant (g) | Weight of one seed (mg) |
|---|---|---|---|---|---|
| | | lateral branches | siliques | | |
| Small | 13.90 ±2.80 | 3.40 ±0.80 | 90.10 ±26.80 | 8.96 ±3.44 | 4.53 ±0.77 |
| Medium | 8.00 ±3.20 | 6.30 ±1.10 | 169.70 ±38.50 | 19.98 ±5.47 | 4.66 ±0.66 |
| Large | 6.00 ±2.40 | 9.50 ±1.50 | 304.10 ±87.60 | 39.68 ±11.32 | 5.03 ±0.75 |
| LSD | 2.43*** | 1.02*** | 51.71*** | 6.92*** | ns |

LSD and probability level: 0.001 (***); ns – not significant.

**Tab. 5** Differences in the morphological traits of WOR plants – height to the lowest branch (HLB), number of primary branches (NPB), length of main shoot with lateral branches (LMLB) – in different heterosis cultivars – traditional 'SY Kolumb' and semi-dwarf 'PR45 D03'; averages from six locations (unpublished data).

| Cultivar | Plants | | HLB (cm) | LMLB (cm) | NPB (pcs.) | Number of siliques per plant or plant parts | | | Number of siliques per 10 cm length | |
|---|---|---|---|---|---|---|---|---|---|---|
| | density (pcs. m$^{-1}$) | height (cm) | | | | whole plant | main shoot | lateral branch | main shoot | lateral branch |
| 'SY Kolumb' | 41 | 134.7 | 43.40 | 39.1 | 6.43 | 278.2 | 43.70 | 36.5 | 9.83 | 8.25 |
| 'PR45 D03' | 39 | 128.5 | 36.70 | 41.5 | 5.82 | 259.4 | 48.80 | 36.2 | 12.34 | 10.63 |
| LSD | ns | ns | 3.22* | ns | 0.57* | ns | 4.31** | ns | 1.98** | ns |

LSD and probability level: 0.05 (*), 0.01 (**); ns – not significant.

rapeseed 'Belcanto' was 0.21–0.44 t ha$^{-1}$ lower than that of long-stem cultivars [6]. In Poland, the semi-dwarf rapeseed 'Avenir', 'PR45 D01', and 'PR45 D03', produced yields that were 0.12–0.62 t ha$^{-1}$ lower than the yield of the standard-long stem rapeseed 'Visby', 'Poznaniak', and 'PR46 W31' [44].

Efforts are currently being made to breed plants with a reduced tendency towards pod shattering. Jia et al. [45] demonstrated wide variation between varieties with respect to resistance to pod shattering during harvest.

## Root distribution

Root distribution of oilseed rape in the soil profile is an important determinant of the ability of the plants to take up water and nutrients [46]. The spatial arrangement of the roots reflects the response of the plants to soil environment conditions. The morphological and physiological traits of the root system are characterized by high plasticity, which influences penetration of soil layers and, in consequence, the root distribution in the soil profile [47]. However, as demonstrated by Yu et al. [47], oilseed plants have varied root system morphology in the same growth conditions. Among oilseed plants, rape has the most developed root system and a larger root area than mustard or linseed [47]. The extensive root system of winter oilseed rape takes up water and nutrients from the soil intensively even in drought conditions [48]. Gan et al. [49] demonstrated that oilseed rape grown in semiarid conditions is able to take up more nitrogen from the soil than mustard.

Vamerali et al. [50], in a study in the Legnaro region (Padua, Italy), compared different varieties of rape ('Synergy' and 'Ceres') sown at high and varied densities from 100 to 300 seeds per m$^2$, in terms of yield, efficiency of nitrogen uptake, and root system size. The authors demonstrated that although the new hybrid variety of rape did not increase yield in comparison with the old variety, greater accumulation of biomass was observed in the winter together with greater nitrogen uptake capability. The rapeseed 'Synergy' exhibited greater vigour, typical of oilseed rape hybrids, together with faster root system growth, particularly at the initial phase of growth (the rosette stage). Both the length of the root system and its physiological efficiency are conditions for better nitrogen uptake from the soil. Breeders creating new varieties should devote attention to increasing the efficiency of nitrogen utilization by the root system of hybrid rape.

A similar study was conducted by Zanetti et al. [51] in the same region of northern Italy (Legnaro, Padua), comparing the semi-dwarf hybrid 'PR45 D01' (Pioneer Hi-Breed®, DuPont, USA) with the conventional hybrid 'Excalibur' (Dekalb®, Monsanto, USA) during the rosette-forming stage, in relation to the efficiency of nitrogen uptake. The authors showed that the semi-dwarf variety had a higher root length density in the upper soil layer and greater nitrogen utilization during the rainy winter. These results are of great importance for groundwater protection, as leaching of N from the soil is reduced due to its better utilization by plants.

## Conclusions

- As an agricultural plant, rapeseed is an important crop all over the world. The seed yield per unit area by 3.4% yr$^{-1}$ systematically increased during the last 40 years. In temperate climate zone, the winter rapeseed has no competitors in terms of yield per unit area.
- The warmer climate currently enables cultivation of oilseed rape instead of winter turnip rape in the conditions of Scandinavia.
- In semiarid conditions (Iran, Turkey), the enlargement of acreage and increase in yield have currently been observed, which is resulted from the irrigation system applied.
- Winter rape yield in the field conditions of the temperate climate zone is mainly determined by agro-climatic conditions during the growing period, the level of nitrogen fertilization, and the production potential of varieties, which is currently higher in hybrids.
- In cultivation, the plant density of the winter form of rapeseed has decreased to about 30–40 plants per m$^2$, which is due to the decrease in the number of seeds sown. There is a noticeable tendency towards formation of more siliques by individual rape plants in hybrids.
- In Europe, hybrid varieties of winter rapeseed of the semi-dwarf type are distinguished by greater silique density, particularly on the main shoot.
- Hybrid rape varieties of the traditional and semi-dwarf growth type are characterized by faster root system growth than traditional varieties, particularly at the initial stage of plant growth (rosette stage). Both the greater extent of the root system and its physiological efficiency are factors causing better nitrogen uptake from the soil.

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## Analiza plonowania i cech morfologicznych rzepaku (*Brassica napus* L.) uprawianego w strefie klimatu umiarkowanego, w świetle możliwości siewu w klimacie suchym

### Streszczenie

Praca stanowi przegląd wybranych pozycji literatury poświęconej uprawnym gatunkom z rodzaju *Brassica*. Skoncentrowana jest na wiodącym gospodarczo gatunku – kapusta rzepak (*Brassica napus* L. ssp. *oleifera*). Aktualnie rzepak to 3-cia roślina oleista świata, a najważniejsza dla umiarkowanej strefy klimatycznej. Głównym sposobem wykorzystania rzepaku jest przemysł spożywczy, ale wykorzystuje się również śrutę poekstrakcyjną w żywieniu zwierząt. Ważne jest również zastosowanie przemysłowe jako źródła bioenergii lub celulozy. Poprawa pozycji gospodarczej rzepaku wśród roślin rolniczych wynika także z podwojenia poziomu plonowania

w okresie 1970–2009, gdy średnioroczny wzrost plonu nasion w skali świata wyniósł 27 kg ha$^{-1}$ rok$^{-1}$. W Polsce areał rzepaku w latach 1965–2013 wzrósł 3–4 krotnie, a coroczny przyrost plonu nasion zwiększał się o 29 kg ha$^{-1}$ rok$^{-1}$. W Europie poziom plonowania jest wyższy niż w świecie, a zwłaszcza w Azji. W ostatnim czasie podjęto uprawę rzepaku w Iranie, gdzie na stosunkowo dużym areale uzyskano plony nasion w wysokości 2.1 t ha$^{-1}$, co przewyższa poziom plonowania w Chinach i Indiach. Plonowanie rzepaku ozimego w warunkach polowych strefy klimatu umiarkowanego determinują głównie warunki agroklimatyczne okresu wegetacji, poziom nawożenia azotem i potencjał produkcyjny odmian – aktualnie najwyższy u odmian mieszańcowych. Odmiany półkarłowe rzepaku ozimego odznaczają się większym zagęszczeniem łuszczyn, zwłaszcza na pędzie głównym. Ponadto mieszańce cechują się szybszym wzrostem systemu korzeniowego, który ma zdolność do lepszego pobierania azotu z gleby.