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Master thesis

**Effect of Intercropping on the Growth and Grain Yield
of Common Buckwheat**

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Declaration

I declare that I am the author of this graduation thesis and that I used only sources and literature displayed in the list of references in its preparation.

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Abstrakt

V polním pokusu na dvou odrůdách pohanky (Zoe, Harpe) byl testován vliv tří systémů pěstování: čistá kultura, směs s čírkem a směs se svazenkou a bílou hořčicí. Výsledky ukázaly, že meziplodiny statisticky průkazně neovlivnily růstové parametry v pozdějších fázích (8 týdnů po výsevu), což svědčí o vysoké kompenzační schopnosti pohanky. Systém se svazenkou a hořčicí vedl k nejvyšší čerstvé biomase ($29,00 \text{ g} \cdot \text{rostlina}^{-1}$) a sušině ($72,94 \text{ t} \cdot \text{ha}^{-1}$), avšak výnos zrna se mezi ošetřeními významně nelišil. Parciální LER přesáhl 1,0 pouze u směsi se svazenkou a hořčicí (max. 1,378), což dokazuje lepší využití půdy. Naopak čírek vykazoval neutrální až mírně negativní účinek. Korelační analýza potvrdila silný vztah mezi biomasou a výnosem zrna ($r = 0,95\text{--}1,00$), zatímco výška rostlin s výnosem nesouvisela. Závěr: Pro produkci biomasy a zlepšení půdy je vhodnější směs se svazenkou a hořčicí, pro stabilní výnos zrna pak meziplodina s čírkem.

Klíčová slova: pohanka, meziplodinové systémy, čírek, svazenka, hořčice, LER

Abstract

A field experiment with two buckwheat varieties (Zoe, Harpe) tested three cropping systems: sole crop, buckwheat + sorghum, and buckwheat + phacelia + white mustard. Results showed that intercropping did not significantly affect vegetative growth parameters at later stages (8 weeks after planting), indicating buckwheat's strong compensatory ability. The phacelia+mustard system produced the highest fresh biomass ($29.00 \text{ g} \cdot \text{plant}^{-1}$) and dry matter yield ($72.94 \text{ t} \cdot \text{ha}^{-1}$), but grain yield did not differ significantly among treatments. Partial Land Equivalent Ratio exceeded 1.0 only for phacelia+mustard mixtures (max. 1.378), demonstrating better land-use efficiency. Sorghum-based systems showed neutral to slightly negative effects. Correlation analysis confirmed a strong relationship between biomass and grain yield ($r = 0.95\text{--}1.00$), while plant height was not correlated with yield. Conclusion: Phacelia+mustard mixtures are more suitable for biomass production and soil improvement, whereas sorghum intercropping can be used to maintain stable grain yield.

Keywords: buckwheat, intercropping systems, sorghum, phacelia, white mustard, LER

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Introduction

As the demand for sustainable and nutritious food sources rises, alternative crops are gaining renewed attention. There is an increasing interest in pseudocereals, such as quinoa, amaranth, and buckwheat, due to their nutritional potential and application in gluten-free products. Incorporating minor and pseudo cereals into cropping systems enhances biodiversity and reduces the environmental impact of arable crops, as these species are often well-suited to thrive in saline or nutrient-deficient soils.

Common buckwheat (*Fagopyrum esculentum* Moench) is a globally sought-after crop due to its nutritional, economic, and medicinal attributes. This pseudocereal serves as a valuable alternative to staple crops like rice, wheat, and maize. Buckwheat possesses advantageous agroecological characteristics, such as the ability to facilitate weed management through the allelopathic inhibition of couch grass, effective soil protection against water erosion, a high capacity for nitrogen and phosphorus assimilation, beneficial phytosanitary effects by controlling nematodes (specifically reducing potato cyst nematode populations), and advantages for insects during its flowering period.

Intercropping is one of the strategies to mitigate the effects of climate change and safeguard the soil from erosion. However, the impact of intercropping in agriculture has not been fully exploited. Intercropping is a practice that aims to achieve high production while also providing numerous ecosystem benefits.

Therefore, this thesis evaluates the impact of various intercropping strategies on the growth and yield components of common buckwheat in the field. The aim is to provide practical insights for utilizing intercropping in production systems, thereby improving food security and preserving the environment.

1 Literature Review

1.1 Buckwheat

1.1.1 Taxonomy and botanical characteristics

Fagopyrum (Polygonaceae) is a minor genus with fewer than 30 species, predominantly confined to southern China. *Fagopyrum* is distinctly differentiated from other genera in Polygonaceae by the central placement of the embryo within the achene (Ohsako & Li, 2020).

Among the 26 recognised species of the genus *Fagopyrum*, which include diploids ($2n = 2x = 16$) and tetraploids ($2n = 4x = 32$), the cultivated species are *F. esculentum* (common buckwheat) and *F. tataricum* (Tartary buckwheat) (Joshi et al., 2020). The genus comprises two cultivated species: common buckwheat (*F. esculentum*) and Tartary buckwheat (*F. tataricum*). The variable position of *Fagopyrum* within the Polygonaceae family has hindered the determination of evolutionary patterns and phylogenetic relationships among *Fagopyrum* species for an extended period (Ohnishi, 2016).

The genus is categorised into two principal groups: the *cymosum* group and the *urophyllum* group, determined by morphological characteristics and molecular systematics (Ohnishi & Matsuoka, 1996; Ohsako & Li, 2020).



Fig 1: Flowers and fruits in the two cultivated buckwheat species (A), (B) and (C) indicate flowering individuals of sweet buckwheat (*Fagopyrum esculentum*), a distylous crop, illustrating long-styled, and short-styled flower, respectively; (D) Fruiting individuals of bitter buckwheat (*F. tartaricum*), a homostylous crop. (Ohsako & Li, 2020).

The scientific name of buckwheat derives from the Latin term "fagus" (beech) and the Greek word "pyrus" (wheat), reflecting the similarity of the achene to a beech nut and its utilisation like to wheat. The term *esculentum* derives from Latin and signifies edible (Dictionary of Botanical ,2025). The term "buckwheat," of Dutch origin, denotes both beech-nut and wheat (Gondola and Peter, 2010).

Buckwheat is a herbaceous annual flowering plant, characterized by red stems and pink and white flowers.

The buckwheat plant possesses a branched root system featuring a primary taproot that extends deeply into damp soil. It grows to a height of 75 to 125 cm.

Buckwheat branches freely, facilitating a more thorough adaptation to its environment compared to other cereal crops. Buckwheat has a growth duration of about 10 to 12 weeks.

The leaves have an alternate growth pattern and are notably big and sagittate (heart-shaped). The upper leaves perfoliate, encircling the stem, while the lower leaves include a petiole that connects to the stem. Each stalk culminates in an inflorescence composed of small clusters or groups of flowers. Each flower comprising a corolla and calyx consisting of 5 petals and 5 sepals.

The inflorescence comprises enormous racemes featuring vari-ably dense clusters of flowers. The plant commences blooming 4-6 weeks post-seeding. The blooms exhibit dimorphism and are hence naturally cross-pollinated. The fruit is dark brown with a light brown triangular seed coat. The endosperm is white, opaque, and starchy in contrast to cereal grain endosperms. Seeds size variation across distinct types, ranging from approximately 4 mm in maximum width and 6 mm in length to 2 mm in width and 4 mm in length. The seed comprises an outer layer or hull, an inner layer known as the seed coat, and within it, a starchy endosperm and the germ (Kamili, 2023).

1.1.2 History of buckwheat cultivation

Buckwheat (*Fagopyrum spp.*), which originated in southwestern China, is among the oldest cultivated crops from Asia. Until recently, it was believed that buckwheat cultivation originated around 4000 years ago in the Yunnan province of Southwest China and subsequently disseminated westward into Tibet and the Himalayas. Recent archaeobotanical research has provided evidence of buckwheat in northern China, dating back approximately 6,000 years. Currently, we possess a preliminary narrative: buckwheat was cultivated in Northern China as early as 4000 BCE, and in southwestern China and the Tibetan/Himalaya region around 2000 BCE (Joosten et al., 2015).

Since the 1980s, agriculturists and buckwheat researchers have identified numerous wild buckwheat species in the southwestern region of China. According to research findings on common buckwheat and the historical context of Yunnan, it originated in southwestern China, on the eastern flank of the Himalayas, as documented by Li and Yang (1992). Specifically, Yunnan, Daliangshan, Xiaoli-angshan, and the border area of Yunnan and Sichuan constituted the epicentre of buckwheat's origin. Ye & Guo (1992) indicated that, from a botanical perspective, the southwestern region of China served as both the centre for divergence and spread.

The two diploid varieties, *F. cymosum* var. *pilus* and *F. cymosum* var. *megaspartanum*, within the large achene group exhibited considerable similarity to the two cultivated species, and were regarded as potential progenitors of common buckwheat (*F. esculentum*) (Steward, 1930; Ohnishi, 2016). Nevertheless, findings derived from morphological cladistics, iso-zyme analysis, and DNA polymorphism indicate that *F. cymosum* is not the direct progenitor of buckwheat (Ohnishi & Matsuoka, 1996; Kadyrova et al., 2010; Zhou et al., 2012). Wild relatives of *F. esculentum* ssp. *ancestral* served as the progenitors of the cultivated species *F. esculentum* Moench, as determined through morphological studies, reproductive biology, isozyme analysis, and marker assessments (RAPD and AFLP) (Ohnishi 1995, 1998a, 1998b, 2004).

Following the domestication of buckwheat in southwest China, it subsequently disseminated into other regions through two pathways: one extending from China to the Korean peninsula and later Japan; the other traversing from China through Tibet to Bhutan, Nepal, and India, and then via Kashmir to Poland (Murai and Ohnishi 1995).

The earliest documented mention of buckwheat appears in Klar-et's Versed Glossary, dated approximately 1365 AD. It was transported into Europe-an nations in the 13th century through the "Silk Road" during invasions by Mongoli-an, Turkish, and other forces. The soldiers effortlessly transported buckwheat seeds and prepared nutritious meals. Into Central Europe and the Bohemian lands, perhaps through two distinct routes: either across Polish territory outside the Carpathians or through the Danubian region (Pirzadah et al. 2020).

Subsequent to the 17th century, the Dutch introduced buckwheat to America, and it is presently extensively farmed globally, in Europe, the United States, Canada, Australia, and South Africa (Campbell 1997). In Asia, buckwheat is cultivated in Pakistan, India, China, Nepal, Bhutan, Mongolia, North Korea, the Russian Far East, and Japan. Recently, Japan has expanded the farmed areas of common buckwheat, especially in converted paddy fields (MAFF 2019).



Fig 1.2: World production of buckwheat (Source: Campbell, 1997)

1.1.3 The importance of buckwheat and its global production

Buckwheat offers a substantial supply of macronutrients, including carbohydrates (predominantly starch), high-quality proteins, and essential amino acids like lysine,

which is often lacking in most other cereals (Zhamel et al., 2023). Buckwheat, inherently gluten-free, is an exceptional dietary option for those with coeliac disease or gluten intolerance. Buckwheat, abundant in flavonoids, vitamins, minerals, and chlorophyll, is regarded as a natural food source suitable for health and dietary nutrition. Rutin, a flavonoid present in buckwheat, has shown efficacy in improving capillary resistance and reducing oxidative stress through the modulation of antioxidant enzyme activity (Singh et al., 2019). Next flavonoid, quercetin similarly engages in anti-inflammatory mechanisms by inhibiting NF- κ B signaling and improving mitochondrial activity (Cui et al., 2022).

Buckwheat is consumed either whole after boiling or steaming or crushed into gluten-free flour. Buckwheat has diverse applications in a range of culinary products, including buckwheat cakes and pastries, pasta, and even tea. Sprouts can even serve as a substitute for vegetables. It also serves as an exceptional feed for livestock, including sheep, cattle, and pigs. The stems, leaves, and seeds of buckwheat are utilized in traditional Chinese medicine. The Chinese pharmacopoeia records indicate that it is predominantly used for the treatment of indigestion, qi deficiency, diarrhoea, and various other conditions (Sun-Waterhouse et al., 2024). Additionally, buckwheat possesses purifying characteristics and is utilized in Japan for cleansing hair and garments (Danford et al., 2014). The husk of buckwheat is not only a source for potassium carbonate extraction but also functions effectively as a fuel (Pena, 2018; Kulokas et al., 2021).

Data from the Food and Agriculture Organisation (FAO) indicates that buckwheat output in 2022 totaled 2,231,443 tonnes. In comparison to 2021, buck-wheat production rose by 16.3%. Historically, buckwheat production peaked in 1992, achieving a global output of 4,975,23 tonnes. The lowest production was in 2010, at 1,454,590 tonnes. Since 1961, the average annual growth rate has been -0.170% (Kulokas et al., 2021). Common buckwheat is cultivated throughout Asia, Europe, and North America. Relative to Tartary buck-wheat (*F. tataricum* L.), common buckwheat exhibits a much greater cultivation area and yield (Dhakal et al., 2015).

The FAO (2020) indicates that 25 nations engage in buckwheat farming, with a total area of around 3,001,495 hectares, yielding 2,905,294 metric tonnes. The primary regions for buckwheat cultivation are Russia, China, Ukraine, the United States, Kazakhstan, Poland, Japan, Brazil, Lithuania, France, Tanzania, Belgium, Nepal, Latvia, Bhutan, South Korea, Slovenia, the Czech Republic, Estonia, Bosnia, South Africa, Hungary, Georgia, and Kyrgyzstan.

China leads in buckwheat production, followed by Russia, which cultivates 979,914 hectares and contributes around 892,322.58 metric tonnes (FAOSTAT 2020) (Figure 2.2). Countries such as Ukraine, the United States, Kazakhstan, Poland, Japan, Brazil, Lithuania, and France collectively allocate nearly 300,000 hectares for buckwheat cultivation. Figure 2.3 illustrates the ten leading global producers of buckwheat.

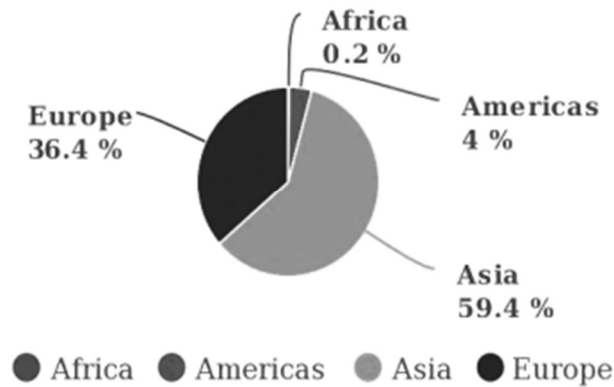


Fig 1.3: Average production share of buckwheat by region (1961–2028) (Source: FAOSTAT, November 2020).

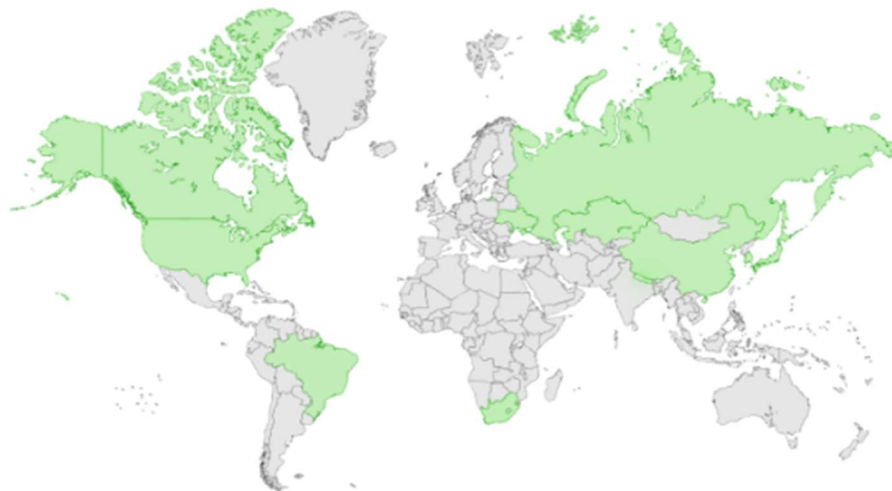


Fig 1.4 : Buckwheat global production in 2022 (Lițoiu et al., 2025).

1.1.4 Environmental requirements of buckwheat

Buckwheat thrives on soils with light to medium texture and good drainage (Clark, 2007) and can endure moderately acidic soils (up to a pH of 5) (Myers & Meinke, 1994). It will not thrive in compacted, water-saturated, or coarse soils, flooding, or soil crusting, (Clark, 2007; Bjorkman & Shail, 2010). Buckwheat is more suited to low-fertility soils than many other crops (Clark, 2007), and the residual nutrients from prior crops are frequently sufficient for its optimal growth (Bjorkman et al., 2008).

Buckwheat is intolerant to frost or excessive drought. Buckwheat thrives in a cool climate, particularly prevalent in some regions of the Northeast. While buckwheat may thrive in diverse environments, it is notably vulnerable to climate extremes. The optimal growth temperature is approximately 21°C. It produces optimal results on cool nights.

Buckwheat progresses through its life cycle rapidly, leaving less opportunity to compensate for developmental deficiencies. Seedlings appear for 3-5 days post-sowing. Most leaf production occurs between the third and sixth weeks. Buckwheat flowers produce seeds between the 6th and 7th weeks, with seed maturation commencing in the 8th week. The grain reaches maturity 10 to 12 weeks post-sowing.

F. esculentum is an insect-pollinated, obligate outbreeder (Cawoy et al. 2009). In expansive fields and regions lacking wild pollinators, the introduction of honeybees is recommended. The ideal stocking density is projected to be 2-5 hives per acre.

1.2 Intercropping:

1.2.1 Definition, Benefits, and Limitations

The simultaneous cultivation of two or more crop species that coexist for a substantial portion of the crop cycle is referred to as intercropping, which is also known as polyculture or mixed cropping (Li et al., 2018). The component crops are not seeded or harvested simultaneously; however, they coexist in the field for a significant duration of their growth periods. Intercropping generally involves a primary crop alongside

one or more companion crops, with the primary objective being the production of the main crop. Intercropping enhances the cropping system by ensuring higher productivity, efficient resource utilization, and increased income (Zhang & Wang, 2015; Kumar et al., 2017; FAO, 2019)

1.2.2 The role of intercropping in global agricultural production

Intercropping, the practice of cultivating two or more crops simultaneously in the same field, plays a vital role in global agricultural production by enhancing productivity, ensuring food security, and promoting environmental sustainability. (Hussen, 2021). While intensive monoculture is often favoured by large-scale farmers for its ease of mechanisation, intercropping remains a cornerstone for small-scale traditional farmers, particularly in tropical regions (Hussen, 2021). It is estimated that traditional multiple cropping systems still provide as much as 15–20% of the world's food supply (Hussen, 2021).

A primary role of intercropping in global production is the increase in productivity per unit area of land compared to sole cropping (Hussen, 2021). This yield advantage is largely attributed to resource complementarity, where component crops occupy different ecological niches, thereby minimizing competition (Hussen, 2021; Liu et al., 2025). Crops with different canopy structures and rooting depths can more completely absorb and convert growth resources such as light, water, and nutrients into biomass (Hussen, 2021). For example, deep-rooted species can access moisture and nutrients from deeper soil layers that are unavailable to shallow-rooted crops, while different canopy heights allow for more efficient light interception (Hussen, 2021; Liu, et al., 2025).

Globally, agricultural land use has shifted toward intensification and crop homogenization (monoculture), which has become a major driver of biodiversity decline (Rakotomalala, A.A.N.A., et al., 2023). Intercropping serves as an essential ecological intensification strategy to mitigate these adverse impacts (Rakotomalala, A.A.N.A., et al., 2023). By diversifying the field environment, intercropping significantly increases the abundance (36%) and species richness (27%) of beneficial arthropods, such as pollinators, predators, and parasitoids (Rakotomalala, A.A.N.A., et al., 2023). This biodi-

versity restoration provides critical ecosystem services, including natural pest control—reducing pest abundance by approximately 38%—and improved pollination for pollinator-dependent crops (Rakotomalala, A.A.N.A., et al., 2023).

1.2.3 Intercropping in different cropping systems

Intercropping enhances resource use efficiency and crop productivity while minimizing the need for synthetic inputs (Jordán, et al., 2026; Tripathi, et al., 2025). In tropical and subtropical regions, sugarcane-peanut intercropping has emerged as a promising strategy for ecological intensification (Fallah, et al., 2026). This system addresses the soil degradation and nutrient imbalances often caused by long-term sugarcane monoculture by promoting biological nitrogen (N₂) fixation and improving the availability of phosphorus and potassium (Fallah, et al., 2026). Research indicates that this configuration significantly enhances land-use efficiency, with Land Equivalent Ratios (LER) reaching as high as 1.42 (Fallah, et al., 2026). Beyond nutrient management, the system recruits beneficial plant growth- and stress-regulating bacteria (PGSRB), such as *Burkholderia* and *Bacillus*, which proliferate in the rhizosphere and contribute to the suppression of diseases like red stripe disease (Fallah, et al., 2026). While intercropping can lead to a reduction in the number of effective stems per hectare due to early-stage competition, the individual stem diameter and weight are often significantly improved (Fallah, et al., 2026).

In cereal-based systems, intercropping maize with legumes like alfalfa, red clover, or common beans provides a mechanism for associational resistance against pests (Jordán, et al., 2026). Unlike cover cropping, which relies on soil legacy effects, direct intercropping exploits immediate neighbourhood effects to alter the focal plant's secondary metabolism (Jordán, et al., 2026). For instance, maize intercropped with beans has been shown to upregulate defence-related metabolites, specifically benzoxazinoids (e.g., DIMBOA and MBOA), in both leaf and root tissues (Jordán, et al., 2026). These metabolic shifts result in tangible resistance benefits, such as significantly reduced leaf damage from herbivores like the fall armyworm (*Spodoptera frugiperda*) and increased larval mortality (Jordán, et al., 2026). These findings suggest that intercropping can be optimized to enhance constitutive pest resistance even in conventional genetically modified (Bt) varieties (Jordán, et al., 2026).

Intercropping is also highly effective in fibre-based systems, such as jute-based cropping in rainfed conditions (Tripathi, et al., 2025). Jute productivity often faces challenges from declining soil fertility and heavy weed infestation; however, integrating short-duration legumes such as cowpea or mung bean helps suppress weeds by competing for light and nutrients (Tripathi et al., 2025). Legume intercropping in these systems improves growth parameters, including plant height and basal diameter, leading to substantial increases in green fibre and dry fibre yields (Tripathi, et al., 2025). Specifically, the Jute Fibre Equivalent Yield (JFEY) can more than double in a jute-cowpea system compared to jute monoculture (Tripathi, et al., 2025). From an economic perspective, these diversified systems provide a critical risk-management strategy for smallholder farmers, as the additional legume yield significantly boosts net returns and overall system profitability (Tripathi, et al., 2025).

1.2.4 Most common companion crops in agriculture

Companion cropping is an essential practice within agronomy, defined as the application of scientific principles and practices to the cultivation of diverse crops (Sahoo et al., 2025).

The combination of cereal crops and pulses is a cornerstone of sustainable agriculture. Major cereals such as Maize (*Zea Mays L.*), sorghum, and pearl millet are frequently grown in association with various Pulses (Sahoo et al., 2025). Both sugarcane (*Saccharum Officinarum*) and potato (*Solanum Tuberosum*) are classified as significant commercial and industrial crops (Sahoo et al., 2025). In many agricultural systems, particularly in South Asia, the potato is a common companion crop for autumn-planted sugarcane. The potatoes are grown in the inter-row spaces between sugarcane rows, providing an additional harvest before the sugarcane canopy fully closes.

Wheat (*Triticum Aestivum.L*) is often grown alongside oilseed crops like mustard or rapeseed (Sahoo et al., 2025). This companion arrangement (often in a 9:1 row ratio) is used to diversify risk and manage pests. The mustard can act as a trap crop or simply provide a secondary source of income from the same land area.

Maize is also frequently paired with oilseeds such as soybean (*Glycine Max L.*) (Sahoo et al., 2025). Soybeans act as a ground cover, reducing weed growth and moisture loss, while providing nitrogen benefits to the maize crop.

1.2.5 Brassicaceae as a companion crop

The integration of Brassicaceae species as companion plants is a strategic approach to enhance pest management, disease regulation, and weed suppression through plant diversification (Seimandi-Corda et al., 2023). These species interact with primary crops and their environment through both physical presence and the release of secondary metabolites (Rehman et al., 2018).

Brassicaceae species can directly influence insect pest behaviour by acting as attractive trap crops or repellent barriers (Seimandi-Corda et al., 2023). For example, turnip rape (*Brassica rapa oleifera*) is often utilized as a trap crop because it is preferred by the cabbage stem flea beetle (CSFB) over oilseed rape (OSR) (Seimandi-Corda et al., 2023). In contrast, white mustard (*Sinapis alba*) is notably less preferred by CSFB and has been investigated for its potential to act as a repellent (Seimandi-Corda et al., 2023)

Certain Brassicaceae species serve as sacrificial bait plants to manage soil-borne pathogens, most notably clubroot disease caused by *Plasmodiophora brassicae* (Ma et al., 2024). Radishes (*Raphanus sativus*) are particularly effective in this role because they stimulate the germination of latent resting spores in the soil (Ma et al., 2024)

1.2.6 Lacy phacelia as a companion crop

Lacy phacelia (*Phacelia tanacetifolia* Benth.) is widely regarded as a versatile phyto-sanitary crop, particularly when utilized as a stubble crop in agricultural rotations. In these systems, it is commonly ploughed under to serve as green manure or left over the winter as mulch to improve soil health (Yakimovich et al., 2017). One of the most significant advantages of lacy phacelia is its intensive growth rate, which allows it to function as a robust natural competitor against various weed species. Under optimal environmental conditions, the crop's rapid biomass development is often sufficient to suppress weeds entirely, potentially making the application of herbicides unnecessary (Yakimovich et al., 2017). The competitive ability of lacy phacelia is notably higher

than that of many other herbal plants. However, this effectiveness is highly dependent on weather conditions; for example, a cold spring or periods of drought can hinder the growth of phacelia, allowing weeds to gain a competitive advantage and potentially crowd out the crop (Yakimovich et al., 2017). In addition to its role in weed suppression and soil improvement, lacy phacelia is a highly valued honey plant. It possesses a high honey potential, with annual yields ranging from 200 to 700 kg·ha⁻¹ depending on the specific region and prevailing weather (Yakimovich et al., 2017). Lacy phacelia is not only effective as a fodder crop but is also very suitable for intercropping. It functions efficiently in combinations with other species, such as Persian clover, buckwheat, oilseed radish, field vetch, or rye (Zarczyński et al., 2025). When cultivated as an intercrop, the sowing rate must be modified correspondingly; for instance, in a combination with winter rapeseed and peas, a phacelia planting rate of roughly 6 kg·ha⁻¹ is advised (Zarczyński et al., 2025). This method enables farmers to integrate the soil-enhancing and pollinator-supporting advantages of phacelia with the synergistic characteristics of companion crops, thereby fostering diversified and sustainable agricultural systems.

1.2.7 Uses of buckwheat as an intercrop

Common buckwheat (*Fagopyrum esculentum* Moench) is a fast-growing crop that is increasingly utilized as a cover crop or intercrop to promote sustainable agricultural production (Nwajei & Kalinová, 2026). Its inclusion in diversified crop management systems offers several ecological and agronomic advantages, ranging from soil conservation to yield enhancement.

Buckwheat plays a significant role in reducing soil degradation and supporting sustainable soil management (Nwajei & Pexová Kalinová, 2026). It enhances organic carbon levels, nutrient cycling, and microbial activities within the soil (Kato-Noguchi et al., 2007). Furthermore, its rapid growth helps mitigate raindrop impact and runoff, effectively reducing soil erosion and contributing to moisture conservation (Glaze-Corcoran et al., 2020)

A primary use of buckwheat as an intercrop is its ability to suppress weeds through a combination of root allelopathy and its specific leaf arrangement, which shades out

competitors (Woźniak et al., 2025; Falquet et al., 2015). Beyond weed control, buckwheat intercrops provide a habitat and food source for insect pollinators during the flowering stage, which is particularly beneficial when integrated into mixtures that provide canopy closure (Liszewski & Chorbiński, 2021; Nwajei & Pexová Kalinová, 2026)

2 Aims and Hypotheses

Main Aim

The overall aim of the study is to evaluate the effect of intercropping on the growth and grain yield parameters of common buckwheat.

Hypothesis

Intercropping common buckwheat with lacy phacelia and white mustard will enhance vegetative growth parameters (plant height, stem diameter, leaf area) and yield components (number of inflorescences, achenes per plant) compared to sole cropping and sorghum intercropping. This hypothesis is grounded in the complementary ecological roles of the intercrop species: lacy phacelia attracts pollinators, potentially improving fertilization efficiency in buckwheat's dimorphic flowers, while white mustard may suppress weeds or pests through allelopathic effects, reducing competition for resources.

Intercropping common buckwheat with sorghum will reduce vegetative growth (plant height, stem diameter, leaf area) and grain yield compared to sole cropping and mixed intercrop systems. This hypothesis posits that sorghum's taller stature and aggressive root system will intensify competition for light and soil nutrients, limiting buckwheat's access to critical resources during key growth stages. Reduced photosynthetic capacity and nutrient uptake are anticipated to lower the number of branches, inflorescences, and filled achenes, ultimately diminishing biomass accumulation and yield.

3 Materials and Methods

3.1 Location characteristics

The field experiment was conducted at the Teaching and Research Farm of the Faculty of Agriculture and Technology, University of South Bohemia in České Budějovice, Czech Republic (48°58'43" N, 14°26'54" E). The site is characterised by a temperate climate with an average annual temperature of approximately 8.5 °C and annual precipitation of around 620 mm. The experiment took place during the summer season of 2025. The previous crop was cereal.

The soil of the experimental field is a sandy-loam Cambisol, moderately acidic (pH 5.6), and well-drained. It contains approximately 1.9% organic matter, total nitrogen 0.11%, available phosphorus 72 mg kg⁻¹, and exchangeable potassium 142 mg kg⁻¹, with bulk density around 1.35 g cm⁻³.

Climatic data for the 2025 growing season (April–September) were obtained from the České Budějovice meteorological station (Czech Hydrometeorological Institute). Average daily temperature and total monthly precipitation are presented in Table 3.1

Table 3.1. Average daily temperature (°C) and monthly precipitation (mm) in České Budějovice, April–September 2025

Month	Avg. daily temperature (°C)	Precipitation (mm)
April	9.2	46
May	13.6	63
June	17.4	91
July	19.6	78
August	18.8	82
September	14.1	56

3.2 Material

The following plant species and varieties were used in the small-plot experiment: Common buckwheat (*Fagopyrum esculentum* Moench), variety Zoe and La Harpe Sorghum (*Sorghum bicolor* L. Moench) – variety Ruzrok, Lacy phacelia (*Phacelia tanacetifolia*) - variety Fiona), White mustard (*Sinapis alba*) - variety Sněženska.

3.3 Design of Field Experiment

The experiment was established as a randomized complete block design with three replications. Three cropping systems were compared: Sole buckwheat, buckwheat intercropped with sorghum, and buckwheat intercropped with lacy phacelia and white mustard (1:1). In the intercropping treatments, the component species (buckwheat to companion plant) were sown in a 100:100 seed ratio. The target plant population was 200 plants m⁻².

The seeds were sown on 19th June, 2025. Each plot measured 6 m × 1.25 m (7.50 m²), and a total of 36 plots were used (6 treatments × 3 replicates). The experiment was established with a precision seeder in 12.5 cm rows, where rows of buckwheat and companion crops were interspersed.

3.4 Determination of growth and yield parameters

Ten plants per plot were randomly selected and tagged for non-destructive measurements throughout the growing season. The collected data were divided into vegetative parameters (recorded three times during the growing period) and yield parameters (recorded at harvest). Data were collected at 4, 6, and 8 weeks after planting (WAP) and at final harvest, which took place 7th September

• 3.4.1 Vegetative parameters

- Plant height (cm): Measured from the base of the plant to the tip of the youngest fully expanded leaf using a measuring tape.

-
- Number of leaves per plant: Counted visually for the ten tagged plants.
 - Number of branches per plant: Counted visually for the ten tagged plants.
 - Leaf area per plant (cm²): Determined using a portable leaf area meter (Petiole pro application) for the ten tagged plants.
 - Stem diameter (mm): Measured 2 cm above ground level using a digital Vernier caliper for the ten tagged plants.

3.4.2 Yield parameters (determined at final harvest)

- Total number of achenes per plant: Counted using an electronic seed counter.
- Number of empty achenes per plant: Counted visually on one plant for the ten tagged plants and expressed as a percentage of the total number of achenes.
- Fresh biomass yield (g·plant⁻¹, t·ha⁻¹): After harvesting the grains, the ten whole plants were cut 2 cm above ground level and weighed fresh using a precision balance.
- Dry matter yield (t·ha⁻¹): Calculated according to dry plant weight and number plants per square meter.
- Dry matter percentage: Fresh plant samples were oven-dried at 70 °C to constant weight. Dry matter percentage was calculated according to the formula described:

$$\text{Dry matter (\%)} = \frac{\text{Dry weight}}{\text{Fresh weight}} \times 100$$

- Thousand achene weight (g): Measured twice using an electronic seed counter and sensitive scale.
- Seed weight per plant (g): Recorded using a weighing balance for ten plants.
- Total grain weight (t·ha⁻¹): Extrapolated from plot yield using the formula:

$$\text{Grain yield (t} \cdot \text{ha}^{-1}\text{)} = \frac{\text{Plot grain weight (g)}}{\text{Plot area (m}^2\text{)}} \times 0.01$$

-
- Partial Land equivalent ratio (PLER) was calculated as the dry matter yield of buckwheat in intercropping divided by its yield in monoculture. Calculated to assess intercropping efficiency using the formula:

$$\text{PLER} = \frac{Y_{ab}}{Y_{aa}}$$

where Y_{ab} is the dry matter yield of buckwheat in intercropping, and Y_{aa} is the dry matter yield of buckwheat in monoculture.

3.5 Data Analysis

ANOVA using JASP software and LSD for post-hoc test at 5% level of probability. Pearson correlation was used for the relationship between vegetative and grain yield data of common buckwheat.

4 Results

Effect of Intercropping on Growth Parameters of Common Buckwheat at Four, Six and Eight Weeks After Planting (Mean $\pm$ SD)

Tables 4.1–4.3 present the effects of intercropping treatments and varieties on the vegetative growth of buckwheat at 4, 6, and 8 weeks after planting. Across all treatments, plant height, number of branches, stem girth, leaf number, and leaf area increased from 4 to 6 WAP, reflecting active vegetative growth. By 8 WAP, most parameters either stabilised or showed slight declines, particularly leaf number and leaf area, indicating the onset of reproductive development and leaf senescence.

Intercropping influenced growth responses, with mixtures involving phacelia and mustard generally promoting greater leaf development and leaf area, while sorghum-based systems tended to enhance branching. Differences between the two varieties were relatively small, although Harpe showed slightly higher stem girth and leaf retention at later stages, whereas Zoe exhibited comparatively higher early growth. Statistical analysis indicated that some parameters varied significantly among treatments at earlier stages, while differences became less pronounced by 8 WAP.

Figures 4.6h–4.6l illustrate the mean values of plant height, number of branches, stem diameter, number of leaves, and leaf area for each intercropping system, providing a visual overview of the treatment effects on vegetative growth across both buckwheat varieties.

Table 4.1: Effect of Intercropping on Growth Parameters of Common Buck-Wheat at Four Weeks After Planting (Mean $\pm$ SD)

Treatment	Plant Height (cm)	No. of Branches	Stem Girth (mm)	No. of Leaves	Leaf Area (cm²/plant)
Zoe	55.5 $\pm$ 12.6 c	3.8 $\pm$ 0.9 ab	6.5 $\pm$ 1.0 a	5.8 $\pm$ 1.3 bc	34.5 $\pm$ 8.6 a
Harpe	46.5 $\pm$ 9.7 b	3.2 $\pm$ 0.8 a	6.0 $\pm$ 0.9 a	4.2 $\pm$ 1.1 a	35.4 $\pm$ 10.2 a
Zoe + Ruzrok	50.1 $\pm$ 8.9 bc	4.5 $\pm$ 1.1 b	6.7 $\pm$ 1.0 a	6.2 $\pm$ 1.4 c	45.8 $\pm$ 7.3 b
Harpe + Ruzrok	49.6 $\pm$ 6.9 bc	4.1 $\pm$ 1.0 ab	6.6 $\pm$ 1.2 a	5.6 $\pm$ 1.3 bc	37.9 $\pm$ 8.3 ab
Zoe + Phacelia + Mustard	38.7 $\pm$ 5.3 a	3.6 $\pm$ 0.9 ab	6.6 $\pm$ 1.4 a	5.1 $\pm$ 1.2 ab	43.2 $\pm$ 9.5 ab
Harpe + Phacelia + Mustard	43.7 $\pm$ 8.3 ab	3.9 $\pm$ 1.1 ab	6.5 $\pm$ 1.0 a	5.3 $\pm$ 1.3 b	41.8 $\pm$ 11.7 ab
Mean for Variety					
Zoe	48.1 $\pm$ 8.9	4.0 $\pm$ 1.0	6.6 $\pm$ 1.1	5.7 $\pm$ 1.3	41.2 $\pm$ 8.5
Harpe	46.6 $\pm$ 8.3	3.7 $\pm$ 0.9	6.4 $\pm$ 1.0	5.0 $\pm$ 1.2	38.4 $\pm$ 10.1
Mean for Treatment	47.4 $\pm$ 8.6	3.9 $\pm$ 1.0	6.5 $\pm$ 1.1	5.3 $\pm$ 1.2	39.8 $\pm$ 9.3
LSD(p=0.05)	5.05	0.85	NS	1.05	6.8

Means within a column followed by the same letter are not significantly different at $p=0.05$ (Tukey's HSD). NS = Not Significant

Table 4.2: Effect of Intercropping on Growth Parameters of Common Buckwheat at Six Weeks After Planting (WAP) (Mean $\pm$ SE)

Treatment	Plant Height (cm)	No. of Branches	Stem Girth (mm)	No. of Leaves	Leaf Area (cm²/plant)
Zoe	104.3 $\pm$ 23.5 b	7.2 $\pm$ 1.4 a	7.4 $\pm$ 1.0 a	9.1 $\pm$ 1.6 a	58.4 $\pm$ 10.2 ab
Harpe	98.8 $\pm$ 17.6 ab	7.6 $\pm$ 1.3 a	7.8 $\pm$ 0.9 ab	9.8 $\pm$ 1.8 ab	60.1 $\pm$ 9.5 ab
Zoe + Ruzrok	98.6 $\pm$ 17.6 ab	8.3 $\pm$ 1.5 a	7.3 $\pm$ 1.1 a	8.6 $\pm$ 1.5 a	52.8 $\pm$ 8.9 a
Harpe + Ruzrok	105.7 $\pm$ 11.7 b	8.9 $\pm$ 1.4 a	8.4 $\pm$ 0.9 b	9.2 $\pm$ 1.6 a	55.3 $\pm$ 9.2 ab
Zoe + Phacelia + Mustard	97.7 $\pm$ 16.3 ab	7.9 $\pm$ 1.5 a	8.6 $\pm$ 1.5 b	10.6 $\pm$ 1.4 b	71.2 $\pm$ 12.3 c
Harpe + Phacelia + Mustard	90.1 $\pm$ 17.7 a	7.8 $\pm$ 1.6 a	7.7 $\pm$ 1.3 ab	10.2 $\pm$ 1.5 b	67.5 $\pm$ 11.8 bc
Mean for Variety					
Zoe	100.2 $\pm$ 19.1	7.8 $\pm$ 1.5	7.8 $\pm$ 1.2	9.4 $\pm$ 1.5	60.8 $\pm$ 10.5
Harpe	98.2 $\pm$ 15.7	8.1 $\pm$ 1.4	8.0 $\pm$ 1.1	9.7 $\pm$ 1.6	60.9 $\pm$ 10.2
Mean for Treatment	99.2 $\pm$ 17.4	7.9 $\pm$ 1.5	7.9 $\pm$ 1.1	9.5 $\pm$ 1.6	60.9 $\pm$ 10.3
LSD(p=0.05)	9	NS	0.72	1.4	8.2

Means within a column followed by the same letter are not significantly different at $p=0.05$ (Tukey's HSD). NS = Not Significant.

Table 4.3: Effect of Intercropping on Growth Parameters of Common Buckwheat at Eight Weeks After Planting (Mean $\pm$ SD)

Treatment	Plant Height (cm)	No. of Branches	Stem Girth (mm)	No. of Leaves	Leaf Area (cm²/plant)
Zoe	122.3 $\pm$ 16.3 bc	8.6 $\pm$ 1.8 ab	7.8 $\pm$ 0.7 a	7.6 $\pm$ 1.2 a	52.1 $\pm$ 8.0 a
Harpe	131.3 $\pm$ 17.8 c	8.0 $\pm$ 2.0 ab	8.4 $\pm$ 0.7 b	8.2 $\pm$ 1.4 ab	53.4 $\pm$ 8.8 a
Zoe + Ruzrok	107.2 $\pm$ 12.5 ab	9.5 $\pm$ 1.9 b	7.4 $\pm$ 0.3 a	7.3 $\pm$ 1.1 a	50.6 $\pm$ 7.5 a
Harpe + Ruzrok	104.3 $\pm$ 11.6 a	8.2 $\pm$ 2.0 ab	8.4 $\pm$ 1.0 b	7.0 $\pm$ 1.2 a	51.3 $\pm$ 9.6 a
Zoe + Phacelia + Mustard	118.5 $\pm$ 31.4 abc	8.9 $\pm$ 2.3 ab	7.9 $\pm$ 0.6 ab	8.6 $\pm$ 1.3 b	55.0 $\pm$ 9.1 a
Harpe + Phacelia + Mustard	111.7 $\pm$ 18.9 ab	8.5 $\pm$ 2.5 ab	7.9 $\pm$ 0.7 ab	9.0 $\pm$ 1.4 b	55.8 $\pm$ 9.0 a
Mean for Variety					
Zoe	116.0 $\pm$ 0.1	9.0 $\pm$ 2.0	7.7 $\pm$ 0.5	7.8 $\pm$ 1.2	52.6 $\pm$ 8.2
Harpe	115.8 $\pm$ 16.1	8.2 $\pm$ 2.2	8.2 $\pm$ 0.8	8.1 $\pm$ 1.3	53.5 $\pm$ 9.1
Mean for Treatment	115.9 $\pm$ 8.1	8.6 $\pm$ 2.1	7.9 $\pm$ 0.7	8.0 $\pm$ 1.3	53.0 $\pm$ 8.7
LSD(p=0.05)	11.58	1.4	0.35	1.1	NS

Means within a column followed by the same letter are not significantly different at $p=0.05$ (Tukey's HSD). NS = Not Significant

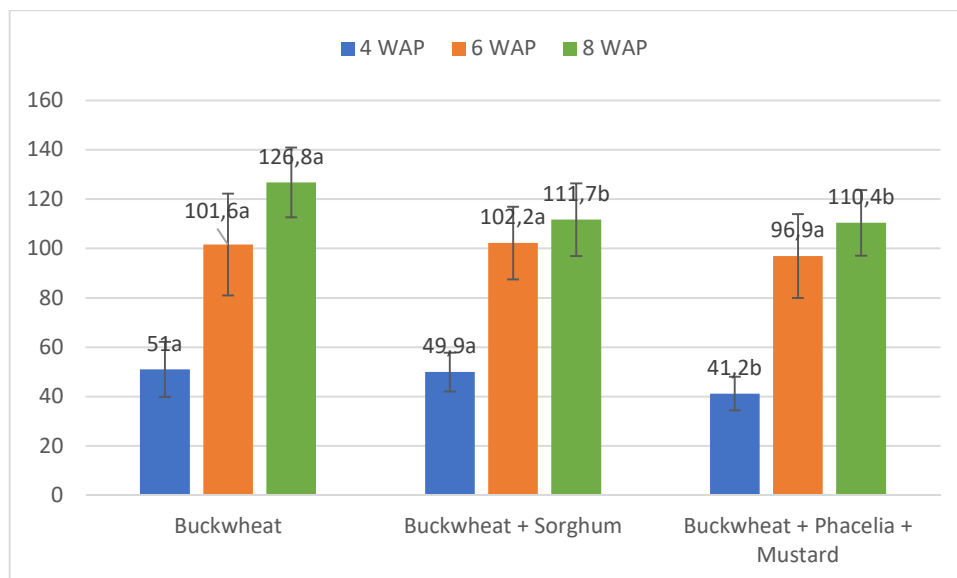


Fig 4.6h: Mean plant height of common buckwheat (cm) by companion plant system (mean of both varieties $\pm$ SD). Means followed by the same letter are not significantly different at $p = 0.05$ (Tukey's HSD).

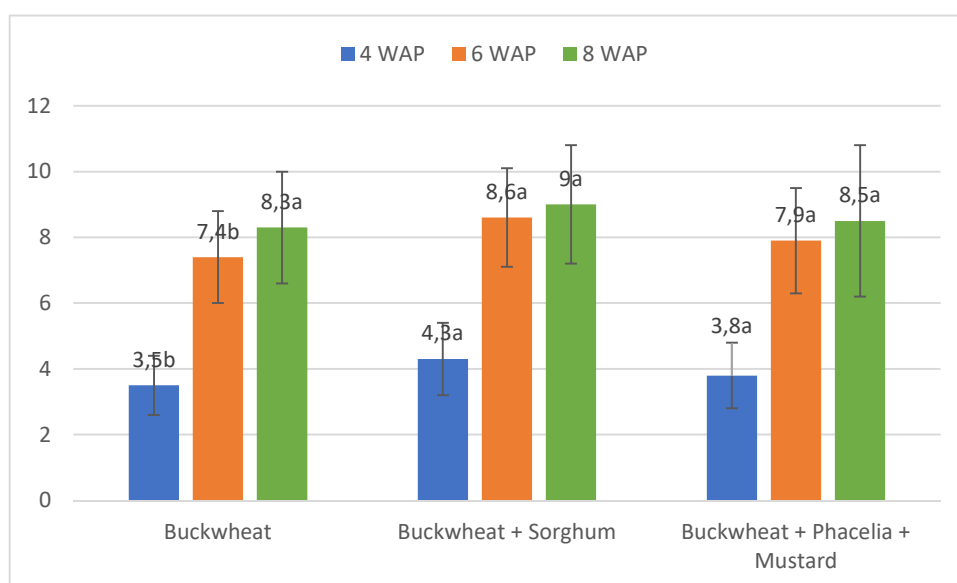


Fig 4.6i: Mean number of branches of buckwheat by companion plant system (mean of both varieties $\pm$ SD). Means followed by the same letter are not significantly different at $p = 0.05$ (Tukey's HSD).

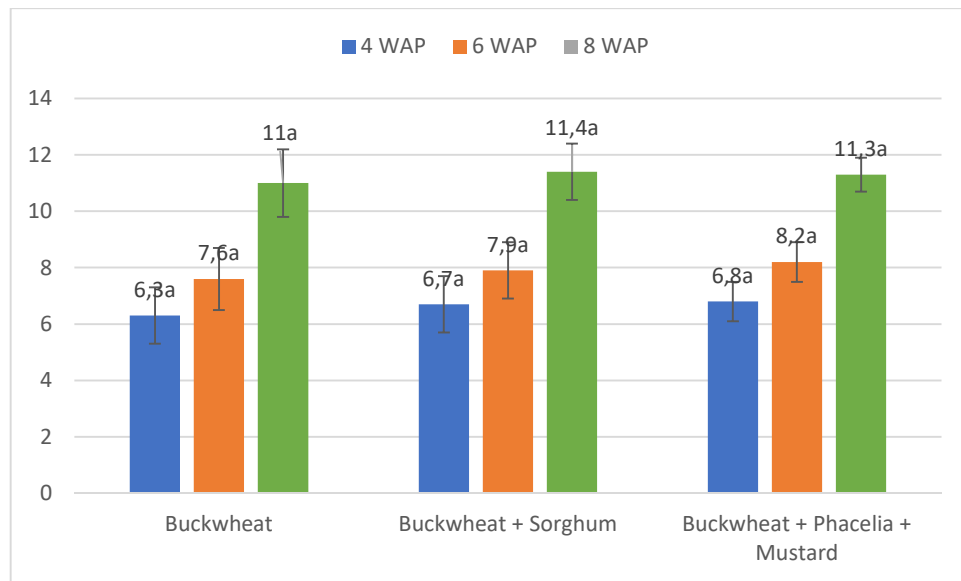


Fig 4.6j: Mean stem diameter (mm) of buckwheat by companion plant system (mean of both varieties $\pm$ SD). Means followed by the same letter are not significantly different at $p = 0.05$ (Tukey's HSD).

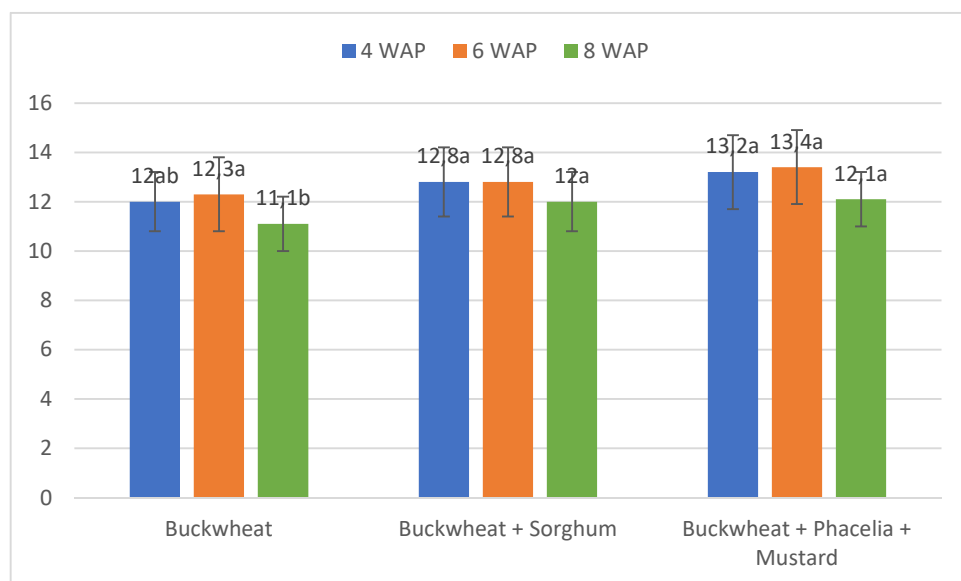


Fig 4.6k: Mean number of leaves of buckwheat by companion plant system (mean of both varieties $\pm$ SD). Means followed by the same letter are not significantly different at $p = 0.05$ (Tukey's HSD).

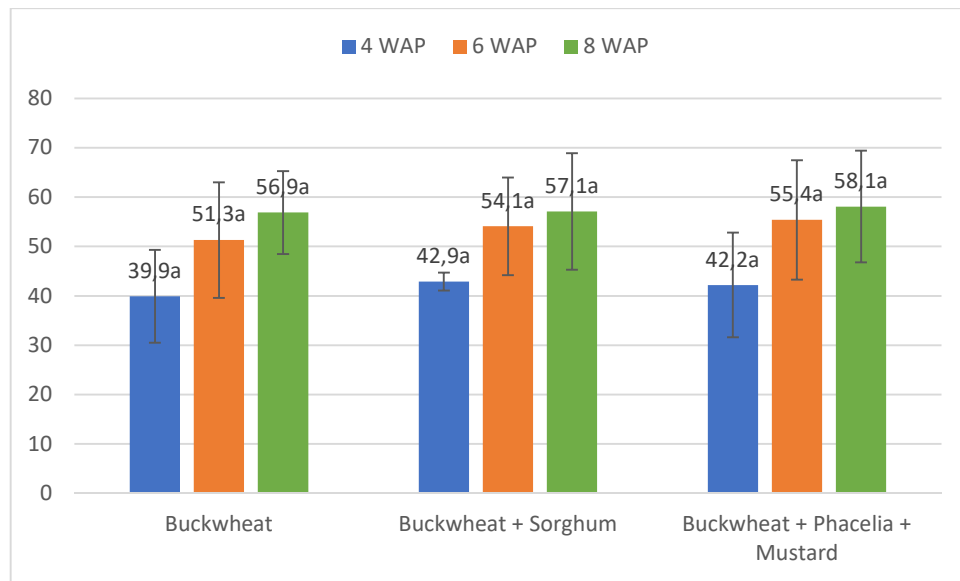


Fig 4.6l: Mean leaf area(cm²/plant) of buckwheat by companion plant system (mean of both varieties $\pm$ SD). Means followed by the same letter are not significantly different at $p = 0.05$ (Tukey's HSD).

Table 4.4 presents the effects of intercropping systems and varieties on yield and related parameters of buckwheat. The results indicate that yield varied across treatments, with intercropping combinations influencing productivity differently. Treatments involving mixed species showed either competitive or complementary effects, depending on the associated crops. In general, combinations that supported better vegetative growth also tended to produce relatively higher yield values. Varietal differences were observed but were not consistently significant across all parameters. Overall, the results suggest that intercropping can influence yield performance, although the magnitude of the effect depends on the specific crop combinations and their interactions.

Figures 4.6c–4.6g present the mean values of total achene count, number of fully developed achenes, percentage of empty achenes, thousand achene weight, and seed weight per plant for each intercropping system. As shown in Fig. 4.6c, Harpe + Phacelia + Mustard recorded the highest total achene count, while Fig. 4.6d confirms that this treatment also produced the greatest number of fully developed achenes per plant.

Table 4.4: Yield Components Under Different Intercropping Systems at harvest time (Mean $\pm$ SD)

Treat- ment	Total No. Achenes/ Plant	Fully Devel- oped Achenes/ Plant	Empty Achenes (%)	Thousand Achene Weight (g)	Seed Weight/Pla nt (g)
Zoe	87.3 $\pm$ 27.60ab	64.6 $\pm$ 35.98ab	22.7 $\pm$ 3.08b	19.5 $\pm$ 10.32a	1.65 $\pm$ 0.859a
Harpe	73.9 $\pm$ 24.05a	62.0 $\pm$ 24.60a	11.9 $\pm$ 5.16a	24.4 $\pm$ 16.10a	2.12 $\pm$ 1.858a
Zoe + Ruzrok	69.8 $\pm$ 41.66a	58.8 $\pm$ 41.93a	11.0 $\pm$ 4.75a	25.9 $\pm$ 8.89a	2.03 $\pm$ 1.482a
Harpe + Ruzrok	80.0 $\pm$ 46.48a	72.9 $\pm$ 46.70a	7.07 $\pm$ 4.51a	24.8 $\pm$ 10.47a	2.24 $\pm$ 1.665a
Zoe + Ph. + Mustard	95.6 $\pm$ 30.16ab	85.6 $\pm$ 30.34ab	10.0 $\pm$ 3.26a	17.6 $\pm$ 0.21a	1.68 $\pm$ 0.538a
Harpe+Ph. .+ Mustard	118.3 $\pm$ 37.82b	108.5 $\pm$ 37.94b	9.8 $\pm$ 3.03a	19.9 $\pm$ 0.40a	2.36 $\pm$ 0.765a
Mean for Variety					
Zoe	84.2 $\pm$ 33.14	69.6 $\pm$ 36.08	14.6 $\pm$ 10.36	21.0 $\pm$ 6.47	1.79 $\pm$ 0.960
Harpe	90.7 $\pm$ 36.12	81.1 $\pm$ 36.41	9.6 $\pm$ 4.23	23.0 $\pm$ 8.99	2.24 $\pm$ 1.429
Mean for Treatment					
Mean	87.5 $\pm$ 34.63	75.4 $\pm$ 36.25	12.1 $\pm$ 7.30	22.0 $\pm$ 7.73	2.01 $\pm$ 1.194
LSD (p=0.05)	24.17	24.17	4.86	NS	NS

Means within a column followed by the same letter are not significantly different at $p=0.05$ (Tukey's HSD). NS = Not Significant.

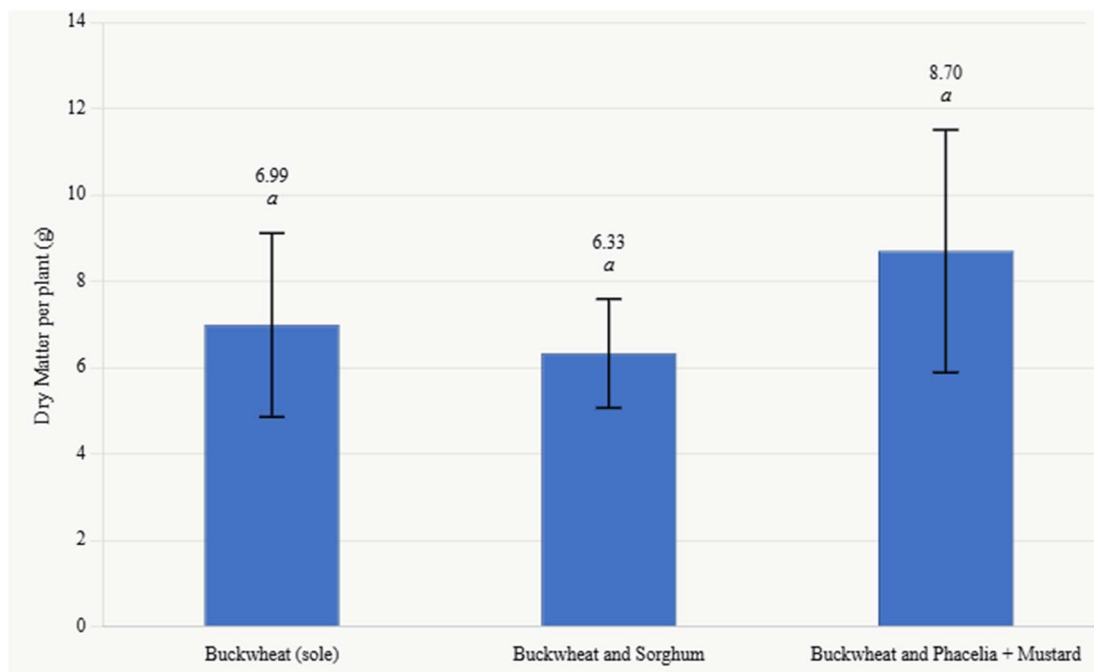


Fig. 4.6c: Mean dry matter per plant of common buckwheat by companion plant system (mean of both varieties $\pm$ SD). Means followed by the same letter are not significantly different at $p = 0.05$ (Tukey's HSD).

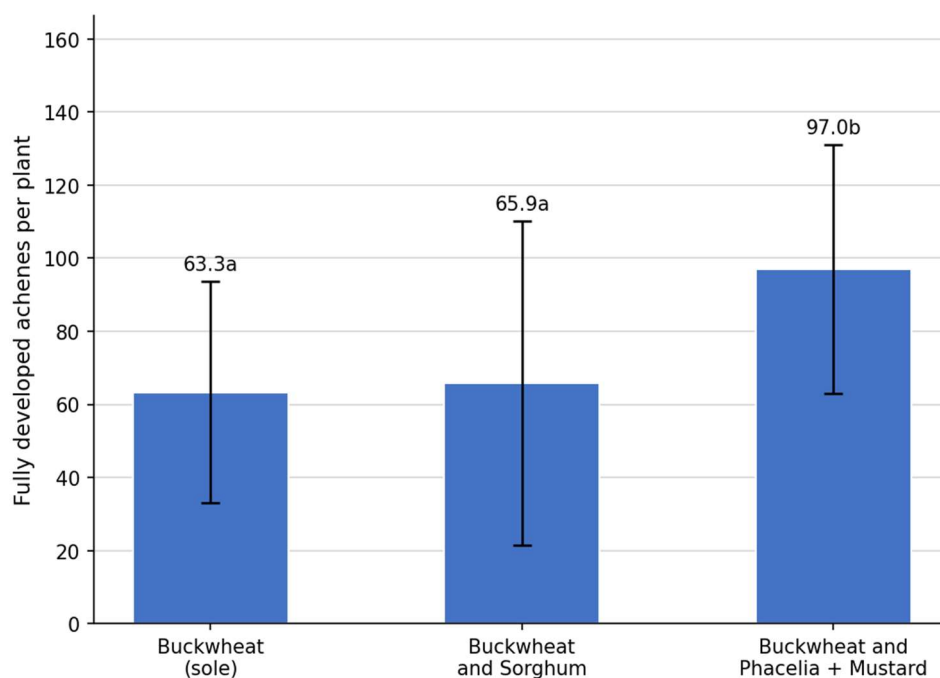


Fig. 4.6d: Mean number of fully developed achenes per plant of common buckwheat by companion plant system (mean of both varieties $\pm$ SD). Means followed by the same letter are not significantly different at $p = 0.05$ (Tukey's HSD).

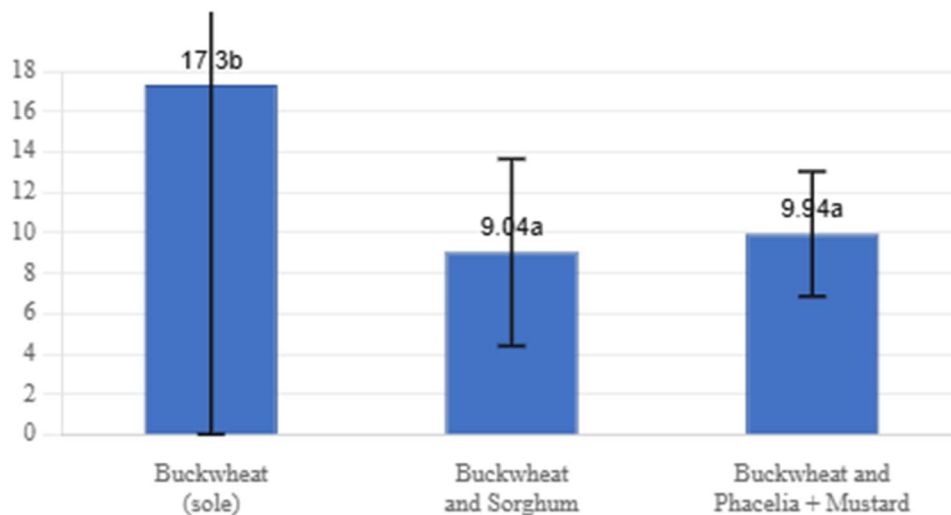


Fig. 4.6e: Mean empty achenes per plant of common buckwheat by companion plant system (mean of both varieties $\pm$ SD). Means followed by the same letter are not significantly different at $p = 0.05$ (Tukey's HSD).

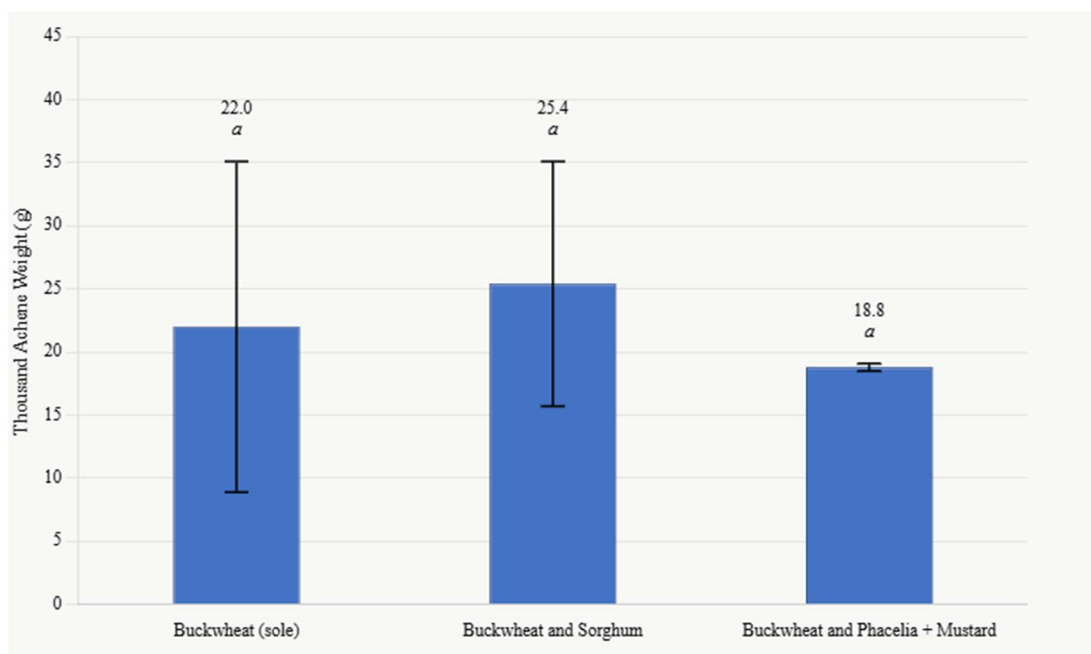


Fig. 4.6f: Mean thousand achene weight of common buckwheat by companion plant system (mean of both varieties $\pm$ SD). Means followed by the same letter are not significantly different at $p = 0.05$ (Tukey's HSD).

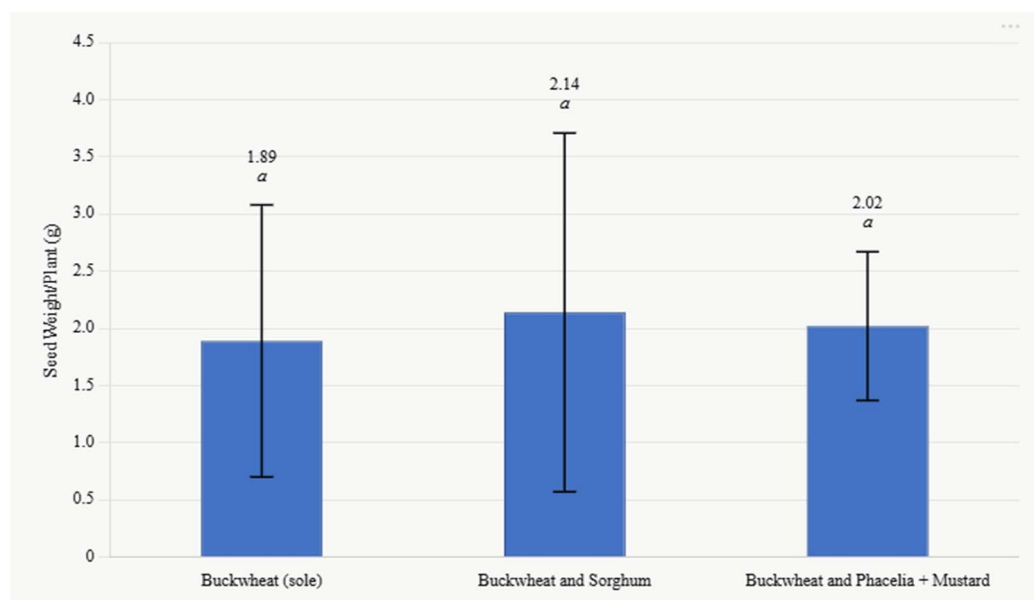


Fig. 4.6g: Mean seed weight/plant of buckwheat by companion plant system (mean of both varieties $\pm$ SD). Means followed by the same letter are not significantly different at $p = 0.05$ (Tukey's HSD).

In Table 4.5, Zoe + Phacelia + Mustard produced the highest fresh biomass per plant (29.00 ± 10.04 g), followed closely by Harpe + Phacelia + Mustard (28.27 ± 4.82 g), though these did not differ significantly from Zoe (23.43 ± 6.80 g) and Harpe + Ruzrok (23.78 ± 7.28 g). Harpe alone and Zoe + Ruzrok recorded the lowest fresh biomass (21.98 and 20.60 g/plant, respectively), both differing significantly from Zoe + Phacelia + Mustard ($p \leq 0.05$). For dry matter yield (t/ha), Zoe + Phacelia + Mustard again recorded the highest value (72.94 t/ha), which was significantly greater than all other treatments except Harpe + Phacelia + Mustard (66.26 t/ha). The remaining four treatments ranged from 50.11 to 61.72 t/ha with no significant differences among them. Dry matter percentage was highest in Zoe (33.02%) and lowest in Harpe + Ruzrok (26.54%), which differed significantly from all other treatments. Across varieties, Zoe consistently outperformed Harpe in both fresh biomass (24.35 vs. 24.68 g/plant) and dry matter percentage (31.81 vs. 28.22%).

Figures 4.6a and 4.6b illustrate the mean dry matter yield and fresh biomass per plant across the six intercropping systems. As shown in Fig. 4.6a, Zoe + Phacelia + Mustard achieved the highest dry matter yield ($72.94 \text{ t} \cdot \text{ha}^{-1}$), while Fig. 4.6b confirms that both Phacelia + Mustard combinations produced the greatest fresh biomass per plant compared to the sorghum-based and sole crop treatments.

Table 4.5: Biomass Production Under Different Intercropping Systems at harvest time (Mean $\pm$ SD)

Treatment	Fresh Biomass per plant (g)	Dry Matter per plant (g)	Dry Matter Yield (t/ha)	Dry Matter (%)
Zoe	$23.43 \pm 6.80\text{ab}$	$7.72 \pm 2.13\text{a}$	61.72ab	33.02a
Harpe	$21.98 \pm 6.48\text{b}$	$6.26 \pm 1.77\text{a}$	50.11b	28.62b
Zoe + Ruzrok	$20.60 \pm 3.84\text{b}$	$6.32 \pm 1.26\text{a}$	50.58b	30.65ab
Harpe + Ruzrok	$23.78 \pm 7.28\text{ab}$	$6.35 \pm 2.12\text{a}$	50.79b	26.54c
Zoe + Phacelia + Mustard	$29.00 \pm 10.04\text{a}$	$9.12 \pm 2.81\text{a}$	72.94a	31.77a
Harpe + Phacelia + Mustard	$28.27 \pm 4.82\text{a}$	$8.28 \pm 1.02\text{a}$	66.26ab	29.50b
Mean for Variety				
Zoe	24.35 ± 7.36	7.72 ± 2.23	61.75	31.81
Harpe	24.68 ± 6.12	6.97 ± 1.77	55.72	28.22
Mean for Treatment				
Mean	24.51 ± 6.57	7.34 ± 1.99	58.73	30.02
LSD (0.05)	12.155	3.458	27.6657	3.038

Dry Matter Yield ($\text{t} \cdot \text{ha}^{-1}$): Mean only — $\text{DW}(\text{g/plant}) \times 80 \text{ plants/m}^2 \times 10 \div 1000$

*** $p < 0.01$ * $p < 0.05$ ns = not significant*

Partial Land Equivalent Ratio (PLER) and Grain Yield (Mean $\pm$ SD)

Fig. 4.6a: Mean dry matter yield of common buckwheat by companion plant system (mean of both varieties $\pm$ SD). Means followed by the same letter are not significantly different at $p = 0.05$ (Tukey's HSD).

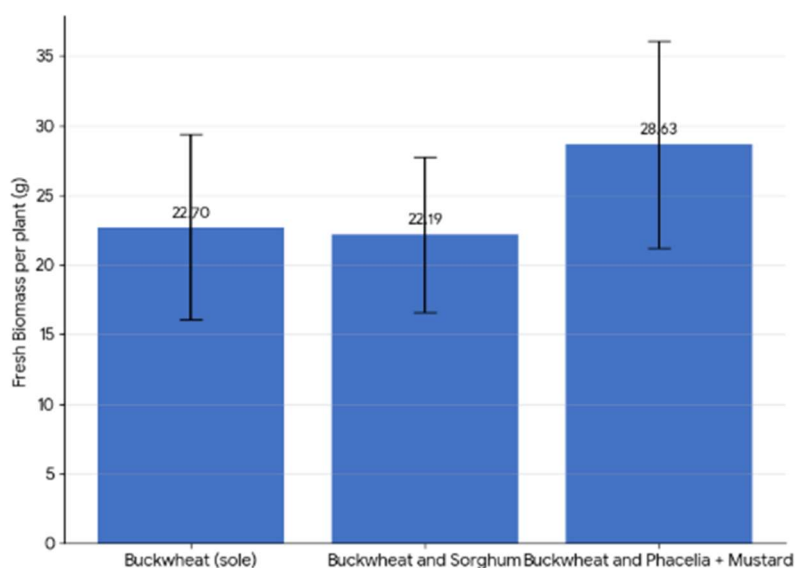


Fig. 4.6b: Mean fresh biomass per plant (g) of common buckwheat by companion plant system (mean of both varieties $\pm$ SD). Means followed by the same letter are not significantly different at $p = 0.05$ (Tukey's HSD).

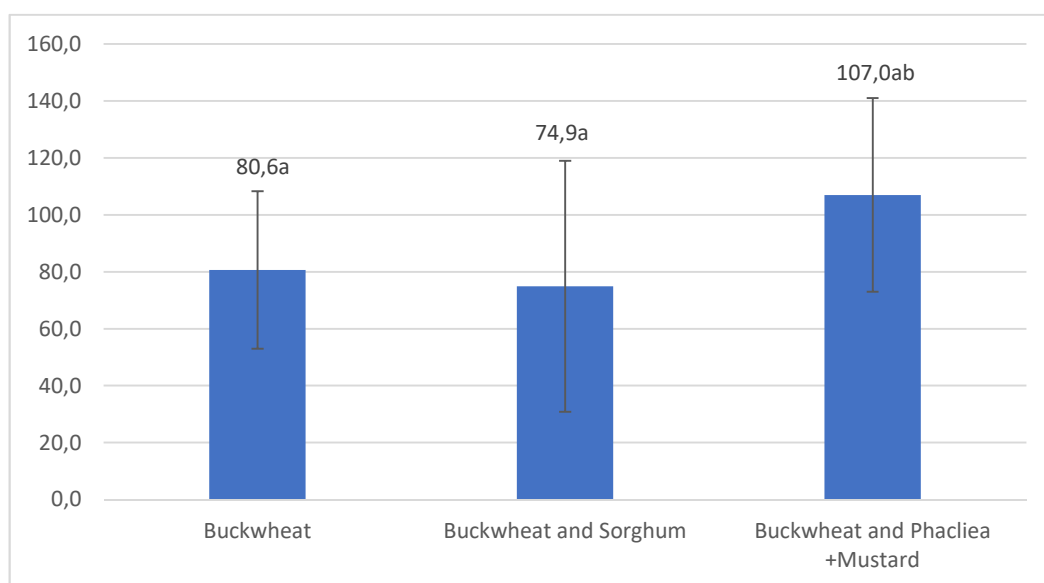


Table 4.6 presents the Partial Land Equivalent Ratio (PLER) and estimated grain yield for six buckwheat cropping systems. PLER was calculated as the dry matter yield of buckwheat in intercropping divided by its yield in monoculture, with sole crop treatments serving as the reference. A value above 1.0 indicates that buckwheat performed better under intercropping than alone. Harpe + Phacelia + Mustard recorded the highest PLER (1.378), followed by Zoe + Phacelia + Mustard (1.242), demonstrating a clear intercropping advantage for both Phacelia and mustard combinations. In contrast, Zoe + Ruzrok (0.900) slightly underperformed relative to monoculture, while Harpe + Ruzrok (1.004) was effectively equal to the sole crop. The highest estimated grain yield was recorded in Zoe + Ruzrok (sorghum) ($2.59 \pm 1.64 \text{ t} \cdot \text{ha}^{-1}$), followed by Sole Zoe ($2.36 \pm 0.24 \text{ t} \cdot \text{ha}^{-1}$) and Harpe + Phacelia + Mustard ($2.32 \pm 0.03 \text{ t} \cdot \text{ha}^{-1}$). Although differences between treatments were not statistically significant at the 5% level. The results consistently indicate that Phacelia and white mustard are more compatible companion plants for buckwheat than sorghum under the conditions of this experiment.

Figure 4.8.3 visualises the Partial Land Equivalent Ratio for each intercropping system, with the reference line at $\text{PLER} = 1.0$ indicating the threshold of intercropping advantage. Figure 4.8.4 shows the total grain yield ($\text{t} \cdot \text{ha}^{-1}$) across all treatments.

Table 4.6: Partial Land Equivalent Ratio (PLER) and Grain Yield (Mean $\pm$ SD)

Intercropping System	Partial LER ^a	Grain Yield ($\text{t} \cdot \text{ha}^{-1}$)
Sole Zoe (buckwheat)	—	2.36 ± 0.24
Sole Harpe (buckwheat)	—	2.10 ± 0.47
Zoe + Ruzrok (sorghum)	0.82	2.59 ± 1.64
Harpe + Ruzrok (sorghum)	1.01	1.84 ± 0.85
Zoe + Phacelia + Mustard	1.18	1.66 ± 0.04
Harpe + Phacelia + Mustard	1.32	2.32 ± 0.03
LSD (0.05)	NS	0.75

Correlation Matrix Between Selected Growth and Yield Parameters

Table 4.7: Correlation Matrix Between Selected Growth and Yield Parameters

Parameter	Plant Height	Fresh Bio-mass	Dry Matter	Grain Yield	Total Achenes	Fully Developed Achenes	1000 Seed Weight
Fresh Biomass	+0.16 ns	1.00	—	—	—	—	—
Dry Matter	+0.17 ns	+0.95**	1	—	—	—	—
Grain Yield	+0.17 ns	+0.95**	+1.00**	1	—	—	—
Total Achenes	+0.08 ns	-0.06 ns	—	+0.71**	1	—	—
Fully Developed Achenes	—	—	—	+0.71**	+0.95**	1	—
1000 Seed Weight	-0.09 ns	—	—	+0.75**	+0.21 ns	+0.21 ns	1.00
Seed Weight per Plant	-0.03 ns	—	—	+0.98**	+0.72**	+0.72**	+0.77**

*Pearson correlation coefficients are shown, where ** indicates significance at $p \leq 0.01$, and ns denotes non-significant relationships.*

5 Discussions

Vegetative Growth

Plant height showed significant differences among treatments at 4 WAP and 8 WAP, but not at 6 WAP (Table 4.1; Fig. 4.6h). At 4 WAP, sole buckwheat (51.0 cm) and buckwheat + sorghum (49.9 cm) were significantly taller than buckwheat + phacelia + mustard (41.2 cm), which carried letter “b” while the other two shared letter “a”. This early suppression in the phacelia and mustard system likely reflects establishment competition, as both phacelia and white mustard are fast-germinating species that develop quickly and may reduce light availability to young buckwheat seedlings (Yakimovich et al., 2017). By 6 WAP, all three systems were statistically indistinguishable (all letter “a”; means: 96.9–102.2 cm), demonstrating the strong compensatory growth capacity of buckwheat. This recovery is consistent with the observations of Willey (1979), who noted that component crops in intercropping systems frequently adjust their growth patterns to minimise interspecific competition over time. By 8 WAP, however, sole buckwheat (126.8 cm, letter “a”) grew significantly taller than both intercrop systems (111.7 cm and 110.4 cm, both letter “b”), suggesting that sustained resource competition from companion crops limited the final vegetative height of buckwheat even when earlier growth differences had resolved.

The number of branches was significantly affected at 4 WAP and 6 WAP, but not at 8 WAP (Table 4.1; Fig. 4.6i). At both 4 and 6 WAP, buckwheat + sorghum recorded the highest branch counts (4.3 and 8.6, letter “a”), while sole buckwheat was significantly lower (3.5 and 7.4, letter “b”). Buckwheat + phacelia + mustard shared letter “a” with the sorghum intercrop at both time points. The enhanced branching under sorghum intercropping may represent a compensatory response to reduced apical dominance caused by light competition from the taller sorghum canopy, stimulating axillary bud development in buckwheat (Huss et al., 2022). By 8 WAP, all treatments converged with no significant differences (all letter “a”), coinciding with the onset of reproductive development when resources are increasingly redirected away from vegetative branching.

Stem girth showed no significant differences among treatments at any measurement period (all letter “a”; Tables 4.1–4.3; Fig. 4.6j). Means ranged from 6.3 to 8.2 mm

across time points, but within-group variation was sufficiently large to render these differences non-significant. The uniformity in stem development across all cropping systems indicates that the structural growth of buckwheat is relatively robust to inter-specific competition under the conditions of this experiment. This is broadly consistent with Salehi et al. (2018), who reported that stem girth in buckwheat is primarily governed by genotypic factors and early establishment conditions rather than competitive pressure from companion crops.

Leaf number per plant showed a distinct treatment-dependent pattern across measurement periods (Tables 4.1–4.3; Fig. 4.6k). At 4 WAP, buckwheat + phacelia + mustard (13.2 leaves, letter “a”) had significantly more leaves than sole buckwheat (12.0 leaves, letter “b”), while buckwheat + sorghum (12.8) was intermediate (letter “ab”). The greater early leaf production under the phacelia and mustard system may reflect reduced above-ground competition at this stage relative to the sorghum intercrop, allowing more resources to be directed toward leaf initiation. At 6 WAP, no significant differences were detected among treatments (all letter “a”), corresponding to peak vegetative growth where all systems reached similar leaf counts between 12.3 and 13.4. By 8 WAP, however, a reversal was observed: sole buckwheat recorded significantly fewer leaves (11.1, letter “b”) than both intercrop systems (12.0 and 12.1, letter “a”). This late-stage retention of leaves in the intercropped treatments may reflect delayed senescence or altered source–sink dynamics under competition, whereby buckwheat maintains photosynthetically active leaf area for longer to compensate for reduced assimilate availability (Lithourgidis et al., 2011).

Leaf area per plant was not significantly affected by intercropping at any time point (all letter “a”; Tables 4.1–4.3; Fig. 4.6l), with means ranging from 39.9 to 58.1 cm²·plant⁻¹ across all treatments and periods. Although the phacelia and mustard system numerically recorded slightly higher values at most time points, none of these differences reached statistical significance. This finding suggests that individual leaf expansion in buckwheat is not strongly modified by companion crop presence, possibly because the species’ large sagittate leaf morphology allows adequate light interception even under moderate canopy competition. Varietal differences in vegetative parameters were minor overall, with Harpe recording slightly greater final plant height and Zoe showing marginally higher branching in early growth stages, consistent with

known genotypic variation in buckwheat growth strategies described by Kolaríć et al. (2021).

Yield Components

The number of achenes per plant was the yield component most clearly differentiated by intercropping (Table 4.4; Figs. 4.6c and 4.6d). Harpe + phacelia + mustard recorded the highest total achene count (118.3 per plant, letter “b”) and the most fully developed achenes (108.5, letter “b”), both significantly greater than all sorghum and sole crop treatments (letter “a”), except Zoe + phacelia + mustard (95.6 and 85.6, letter “ab”). This advantage in achene production under the phacelia and mustard intercrop is most plausibly explained by enhanced pollinator activity. Buckwheat is an obligate out-crossing species with dimorphic flowers entirely dependent on insect pollinators for fertilisation (Cawoy et al., 2009). The simultaneous flowering of lacy phacelia, a highly attractive honey plant yielding up to 700 kg·ha⁻¹ (Yakimovich et al., 2017), alongside white mustard would substantially increase floral diversity and draw greater pollinator abundance to the experimental plots. This mechanism is strongly supported by Chorbiński et al. (2024), who demonstrated that buckwheat mixed with high-nectar companion species significantly improved pollinator visits and achene set. The higher percentage of empty achenes observed only in sole Zoe (22.7%, letter “b”; Table 4.4; Fig. 4.6e), compared to all intercropped treatments (letter “a”), further corroborates the pollination benefit conferred by companion flowering species.

Despite the significant improvement in achene number, neither thousand achene weight nor seed weight per plant differed significantly among treatments (Table 4.4; Figs. 4.6f and 4.6g; all letter “a”), with thousand achene weights ranging from 17.6 to 25.9 g and seed weight per plant from 1.65 to 2.36 g. The failure of greater achene counts to produce correspondingly heavier individual achenes points to a source–sink limitation during grain filling. When a large number of fertilised ovules compete for a finite supply of photosynthates, individual achene weight tends to decline, resulting in higher counts of lighter seeds rather than fewer, heavier ones. This compensatory pattern under competitive conditions has been reported by Ghanbari et al. (2010) and Rotili et al. (2023) in buckwheat and related crops. The practical outcome is that the

gain in achene number under phacelia and mustard intercropping was effectively neutralised at the level of total grain weight, as confirmed by the absence of significant differences in grain yield across treatments (Table 4.6; Fig. 4.8.4), where values ranged narrowly from 1.66 to 2.59 t·ha⁻¹.

Sorghum intercropping did not enhance achene number relative to sole cropping but maintained grain yield at a comparable level (Zoe + sorghum: 2.59 t·ha⁻¹; sole Zoe: 2.36 t·ha⁻¹; Table 4.6). The taller sorghum canopy likely imposed a degree of shading on buckwheat, potentially reducing photosynthetic assimilation. However, buckwheat's deep taproot may have facilitated access to soil moisture and nutrients in deeper horizons not fully exploited by sorghum, providing a degree of belowground niche complementarity. This resource partitioning between crops with contrasting rooting architectures is recognised as a central mechanism in yield maintenance in cereal-based intercrops (Ofori and Stern, 1987; Liu et al., 2025).

Biomass Production

Biomass production was the parameter most clearly differentiated by intercropping system (Table 4.5; Figs. 4.6a and 4.6b). Both phacelia and mustard treatments recorded the highest fresh biomass per plant (Zoe + phacelia + mustard: 29.00 g·plant⁻¹; Harpe + phacelia + mustard: 28.27 g·plant⁻¹, letter “a”), significantly greater than sole Harpe (21.98 g·plant⁻¹, letter “b”) and Zoe + sorghum (20.60 g·plant⁻¹, letter “b”). Dry matter yield followed the same pattern, with Zoe + phacelia + mustard achieving the highest value of 72.94 t·ha⁻¹, significantly exceeding all sorghum and sole crop treatments except Harpe + phacelia + mustard (66.26 t·ha⁻¹). Dry matter per plant showed no significant differences among treatments (Fig. 4.6c), indicating that the yield advantage at the hectare scale arose from population-level effects rather than differences in individual plant assimilation efficiency.

The superior biomass accumulation in the phacelia and mustard system likely reflects synergistic canopy development between the component species. Lacy phacelia forms a relatively low, dense canopy while buckwheat grows taller and more erect, creating a two-layer structure that intercepts a greater proportion of incoming radiation than either species alone (Gou et al., 2017). Furthermore, the rapid early growth of phacelia

and mustard would suppress weed emergence (Yakimovich et al., 2017), reducing competition for soil resources and contributing to higher overall plot productivity. These dynamics are consistent across both buckwheat varieties, as shown in Figs. 4.6a and 4.6b. The elevated dry matter percentage in the Zoe sole treatment (33.02%) compared to all Harpe-based systems further suggests varietal differences in the efficiency of carbon assimilation and water-use during biomass accumulation, in agreement with Bedoussac et al. (2015) and Brooker et al. (2015), who highlighted complementary canopy architecture and weed suppression as primary drivers of biomass gains in diversified cropping systems.

Land Use Efficiency

The Partial Land Equivalent Ratio (PLER) results presented in Table 4.6 and illustrated in Fig. 4.8.3 clearly demonstrate the relative land-use efficiency of each intercropping system. Both phacelia and mustard combinations exceeded the PLER threshold of 1.0 that denotes an intercropping advantage: Harpe + phacelia + mustard achieved the highest PLER of 1.378, followed by Zoe + phacelia + mustard at 1.242. This means that approximately 38% more land under sole cropping would be required to produce the same dry matter output as the Harpe + phacelia + mustard system. In contrast, Zoe + sorghum returned a PLER of only 0.82, indicating that buckwheat performed below its monoculture potential under this combination, likely due to competitive suppression by the taller sorghum canopy. Harpe + sorghum (PLER = 1.01) was effectively equivalent to sole cropping. These findings are in agreement with Mead and Willey (1980), who established that a PLER above 1.0 is a clear indicator of intercropping advantage, and with Žalac et al. (2022) and Li et al. (2023), who reported similar efficiency gains in buckwheat-based systems where companion species occupied complementary ecological niches.

It must be noted, however, that the PLER values in this study were calculated using dry matter yield of buckwheat only, as sole companion crop yields were not measured. This prevents calculation of a full LER accounting for the productivity of both component species, which is a recognised limitation of the current experimental design. Future studies should include sole-cropped reference plots for sorghum, phacelia, and

mustard to enable a complete and internationally comparable assessment of system-level land use efficiency.

Relationships Between Growth, Biomass, and Yield

The Pearson correlation analysis presented in Table 4.7 revealed that vegetative parameters — plant height ($r = +0.17$, ns) and fresh biomass ($r = +0.16$, ns) — were not significantly correlated with grain yield. In contrast, reproductive traits showed strong associations: dry matter yield was perfectly correlated with grain yield ($r = +1.00$, $p \leq 0.01$), seed weight per plant was strongly correlated ($r = +0.98$, $p \leq 0.01$), and total achene count was moderately correlated ($r = +0.71$, $p \leq 0.01$). These relationships confirm that the ability of buckwheat to produce and fill achenes was the primary determinant of economic yield, rather than the degree of vegetative growth attained during earlier stages. This is consistent with Rotili et al. (2023) and Kolaric et al. (2021), who reported that reproductive efficiency rather than vegetative vigour is the key driver of yield variation across growing conditions in buckwheat.

The strong correlation between biomass and grain yield ($r = +0.95$, $p \leq 0.01$; Table 4.7) also has practical implications for the choice of intercropping system. As illustrated in Figs. 4.6a and 4.6b, the phacelia and mustard intercrop produced the highest dry matter yield, yet as shown in Fig. 4.8.4, its grain yield was not significantly higher than other treatments despite the markedly elevated achene counts shown in Figs. 4.6c and 4.6d. Taken together, these relationships suggest that the phacelia and mustard intercrop drives biomass accumulation and pollination-mediated achene number, but the increased reproductive load under resource competition during grain filling limits the conversion of additional achenes into harvestable grain mass. This trade-off between achene number and individual achene weight is a recognised constraint in buckwheat production under dense or competitive canopies (Biszcak et al., 2020), and has direct implications when selecting companion crop combinations for grain-oriented versus biomass or green manure production objectives.

6 Conclusion

This study evaluated the effect of intercropping common buckwheat (*Fagopyrum esculentum* Moench) with sorghum or a mixture of white mustard and lacy phacelia on growth, yield, biomass, and land-use efficiency under field conditions in the Czech Republic. Two varieties (Zoe and Harpe) were compared. The main conclusions are as follows:

- Intercropping systems influenced the growth, yield, and biomass production of buckwheat, although the effects varied depending on the type of companion crops used.
- Vegetative growth parameters, including plant height, number of branches, stem girth, leaf number, and leaf area, were not significantly affected at later growth stages, indicating the strong compensatory ability of buckwheat under intercropping conditions.
- Intercropping with phacelia and mustard enhanced yield components, particularly the number of achenes per plant, likely due to improved pollination associated with increased floral diversity.
- Despite improved yield components, the phacelia and mustard intercrop did not result in higher grain yield, suggesting limitations in assimilate partitioning and grain filling under competitive conditions.
- Sorghum intercropping maintained grain yield comparable to sole buckwheat, indicating better compatibility and more balanced resource use between the component crops.
- Biomass production was highest in the phacelia and mustard intercrop (up to 29.00 g·plant⁻¹ fresh biomass; 72.94 t·ha⁻¹ dry matter yield), demonstrating its suitability for biomass-oriented purposes such as green manure and soil fertility improvement.

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- Land use efficiency was improved in intercropping systems, particularly in the phacelia and mustard combination, where PLER values exceeded 1.0, indicating more efficient use of available resources compared to monocropping.
 - Yield in buckwheat was more closely associated with reproductive traits such as achene number and seed weight rather than vegetative growth parameters.
 - Overall, the results indicate that intercropping can be beneficial, but its effectiveness depends on the production objective. Phacelia and mustard mixtures are more suitable for biomass production, while sorghum intercropping is recommended for maintaining stable grain yield.

Limitations and future research: This study was conducted over a single season; multi-year trials are needed. Sole companion crop yields were not measured, preventing full LER calculation.

Recommendations for future research: (i) Measure sole sorghum grain yield within the same experimental framework to enable full LER calculation; (ii) assess pollinator abundance and species diversity in each intercropping treatment to quantify the pollination mechanism; (iii) investigate multi-year soil fertility effects of weed-buckwheat green manure treatments; and (iv) replicate the study across multiple sites and seasons to assess the generalisability of these findings to broader agro-climatic conditions in Central Europe.

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List of abbreviations

Abbreviations are listed alphabetically. Statistical significance symbols follow standard convention.

AD	Anno Domini
AFLP	Amplified Fragment Length Polymorphism
ANOVA	Analysis of Variance
BCE	Before the Common Era
cm	Centimetre(s)
cm²	Square centimetre(s)
CSFB	Cabbage Stem Flea Beetle (<i>Psylliodes chrysocephala</i>)
DIMBOA	2,4-dihydroxy-7-methoxy-2H-1,4-benzoxazin-3(4H)-one
DNA	Deoxyribonucleic Acid
F.	Fagopyrum (genus abbreviation used in binomial nomenclature)
FAO	Food and Agriculture Organisation of the United Nations
FAOSTAT	FAO Statistical Database
g	Gram(s)
g·plant⁻¹	Grams per plant
ha	Hectare(s)
ha⁻¹	Per hectare
kg	Kilogram(s)
kg·ha⁻¹	Kilograms per hectare
LER	Land Equivalent Ratio
LSD	Least Significant Difference (post-hoc test)

MAFF	Ministry of Agriculture, Forestry and Fisheries (Japan)
MBOA	6-methoxy-2-benzoxazolinone
mm	Millimetre(s)
n	Number of observations / sample size
NF-κB	Nuclear Factor kappa-light-chain-enhancer of activated B cells
ns	Not significant ($p > 0.05$)
OSR	Oilseed Rape (<i>Brassica napus</i>)
p	Probability value (statistical significance)
r	Pearson correlation coefficient
RAPD	Random Amplified Polymorphic DNA
RCBD	Randomised Complete Block Design
RUE	Radiation Use Efficiency
SD	Standard Deviation
SE	Standard Error
spp.	Species (plural, taxonomic abbreviation)
t	Tonne(s) (metric ton = 1,000 kg)
t·ha⁻¹	Tonnes per hectare
WAP	Weeks After Planting
°C	Degrees Celsius
*	$p < 0.05$ (statistically significant)
**	$p < 0.01$ (highly significant)
***	$p < 0.001$ (very highly significant)
