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Research article

Assessing the quality and grain yield of winter wheat in the organic farming management under wheat-legume intercropping practice

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A R T I C L E I N F O

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A B S T R A C T

Intercropping is an alternative farming method that maximizes crop yield and resource usage effectiveness, especially in low-input agricultural systems. Legume-based intercropping systems can effectively boost the quality and wheat yield by promoting soil functions and microbial activities. However, changes in the types of legumes and field management can alter the response of crop functions. A three-year field study was conducted on intercropping cultivation of winter wheat variety (Butterfly and Lorien) and legume species (faba bean, incarnate clover, spring pea, winter pea) to assess grain yield and wheat quality in organic farming. Based on the results, Butterfly showed higher grain quality but lower grain yield and yield components than Lorien. Mixtures of legume crops with winter wheat did not significantly differ in wheat grain yield, but grain quality variables were significantly affected. Protein content (PC) was significantly higher in wheat and legume mixtures than in sole wheat by 4 %. PC in wheat + winter pea (Wheat + Wi) and wheat + faba bean (Wheat + Fa) were higher than wheat sown alone. Wet gluten (WG) was higher in Wheat + Wi than in sole wheat and wheat + incarnate clover mixtures (Wheat + In). The rheological parameters evaluated by the Mixolab showed greater wheat quality in Butterfly and legume mixtures. Mixed and row-row intercropping of wheat and legume species did not significantly influence rheological properties. To conclude, customizing wheat yield and grain quality under the effect of winter wheat and legume mixtures requires considering the optimal solution based on different cultivates, wheat varieties and legume species to achieve the desired response.

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1. Introduction

Organic wheat farming, despite its many advantages, is characterized by low soluble nitrogen (N) availability, especially in early spring in Central Europe. This is due to the limitation of soil organic matter mineralization caused by cold temperatures or high rainfall, and erosion causes either N-deficiency or soil N losses via nitrate (NO3) leaching and N volatilization [1,2]. However, N is one of the crucial macroelements, as it notably influences wheat yield and baking quality [3]. To meet crop N requirements while reducing the risk of high N loss, mineral N fertilizers are sometimes used in split applications during the growing season. However, this practice is not permitted in organic cereal farming, including wheat production. Splitting the rate of organic fertilizers is often not feasible in organic wheat cultivation, as most organic fertilizers need to be broadcast all at once before sowing, resulting in an insufficient N supply to wheat, which can be detrimental to plant growth, yield, and grain quality [4]. Even in the case of top-dress application, the N availability could limited because soil organic matter mineralization is slow and late, so it cannot provide the nutrients needs for wheat in the springtime [2]. The low winter N accumulation in vegetative organs of winter wheat predisposes the grain protein content to be low [5].

The diversity of cropping systems in agriculture practices is becoming an attractive option for enhancing natural interactions and increasing agroecosystem resilience. Strategies to increase sustainable crop growth, N self-sufficiency, and N use efficiency are necessary [6,7]. Cereal-legume intercropping is a practical agronomic solution for wheat production [7], especially in low-input agriculture conditions. Intercropping is a multiple cropping practice that involves the cultivation of two or more crops simultaneously in the same field with the advantage mainly of the complementary use of N sources by the species used in the system [8,9]. A high amount of fixed N is provided into the system through the N-fixation of legume, which is available for cereals [7,10,11].

The results of the intercropping system depend on factors such as environmental conditions, crop species, sowing, and management practices [7,12]. According to previous studies, using a diversity of legume species in the wheat-legume intercropping system is considered a notable advantage [13,14]. In the case of simultaneous intercropping, it may be necessary to consider additional

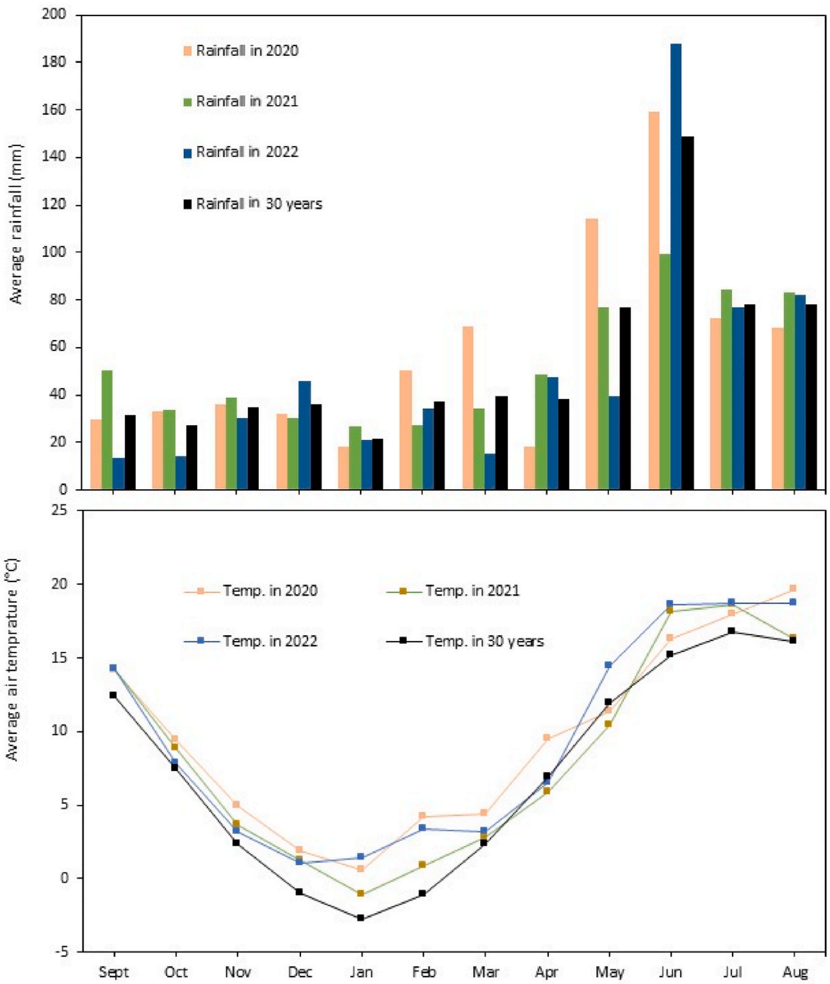

Fig. 1. Monthly air temperature and precipitation during three growing seasons and 30-year periods in the experiment site.

management practices to address potential competition between legumes and cereal crops [15] because this appears mainly suitable for increased grain yield and quality through an increased protein at harvest for animal feed [16]. Some authors have shown that competition for nutrients and light in simultaneous intercropping might limit or reduce the cereal yield in the case of vigorous growth or high legume crop density [11,17]. An alternate technique may be considered where the cereal and legume are sown in separate rows alternately [18]. Intercropping of winter wheat and legumes enhances diversity in the ecosystem, positively affecting weed control, enhancing soil fertility, and increasing the N use efficiency. This contributes to the concentration of crude protein and cereal quality compared to the monoculture systems [11,19,20]. Cereal-legume intercropping can effectively increase grain yield through the years and improve grain quality [21].

Studies on wheat and legume mixtures efficiency had limited, especially in our case. A long-term field study can better understand the relationship between wheat cultivars and legume species to assess yield stability and enhanced grain quality. We aimed to provide insights into the potential of different wheat and legume mixtures as an effective strategy for achieving sustainable organic farming and high-quality food production. Farmers and policymakers could make informed decisions that promote and achieve high efficiency in winter wheat organic agriculture.

2. Materials and methods

2.1. Site description

Three growing seasons of consecutive field experiments were carried out during 2019/20, 2020/21, and 2021/22 in an organic certified farm located in the Ceske Budejovice, South Bohemia region of the Czech Republic (48°58′26.4″N, 14°37′43.5″E, at an altitude of 460 m). The soil texture of the experimental field is Silt Loam following USDA with 18 % of sand (0.05–2 mm), 59 % of silt (0.05–0.002 mm), and 23 % of clay (<0.002 mm); pH(H_2O): 5.7, pH($CaCl_2$): 5.1, bulk density: 1.3 g cm^{-3}, total organic carbon (TOC): 1.97 %, $NO3^-$: 48 mg kg^{-1}, $NH4^+$: 16.2 mg kg^{-1}, P: 59 mg kg^{-1}, K: 235 mg kg^{-1}, electrical conductivity: 0.0932 dS/m. The monthly air temperature and precipitation throughout the three growing seasons and long term are presented in Fig. 1. Mean annual temperature from 1989 to 2019 was 7.2 °C, and the mean annual precipitation was 633 mm. The mean annual air temperature during three years experiment was 9.5 °C in 2019/20 growing season; 8.4 °C in 2020/21 growing season; and 9.3 °C in 2021/22. The total precipitation was 699 mm, 633 mm, and 607 mm in the 2019/20, 2020/21, and 2021/22 growing seasons. In the 2020/21 growing season, heavy rain was recorded after sowing, and the temperature was lower than in January and February 2021, comparing the 2019/20 and 2021/22 growing seasons.

2.2. Experimental design and treatments

Field trials were performed under organic farming using red clover as a preceding crop for the growing seasons. Pesticides and herbicides were not used for the experiment. The soil was fertilized with composted sheep manure of 4 t ha^{-1} before plowing, characteristics of organic fertilizer with 28 % content dry matter: 8.9 kg N t^{-1}, 5.4 kg P_2O_5 t^{-1}, 17.7 kg K_2O t^{-1}. Field management practices of wheat cultivation in each growing season are given in Table 1.

The small plot experiment was conducted with the randomized complete block design in three replicates with a plot size of 15 m^2. Two winter wheat varieties (Butterfly and Lorien) and four legume species were used. Butterfly has good resistance to lodging, good frost resistance and winter hardiness, good resistance to *Fusarium head blight* (FHB) and *Septoria tritici blotch* (STB) (*Mycospharella graminicola*), high resistance to brown rust (*Puccinia triticina*). Lorien is suitable for dry and warm regions and has good resistance to lodging, medium frost resistance, and good resistance to FHB. The leguminous species included faba bean (*Vicia faba* L., cv. Merkur), incarnate clover (*Trifolium incarnatum* L., cv. Kardinál), spring pea (*Pisum sativum* L., cv. Avatar), winter pea (*Pisum sativum* L., cv. Balltrap) [22]. Winter wheat varieties were sown at the same rate of 400 seeds m^{-2}, faba bean at 30 seeds m^{-2}, spring pea and winter pea at 50 seeds m^{-2}, and incarnate clover at 300 seeds m^{-2}.

The small plot experiment with the randomized complete block design in three blocks (replications) with a plot size of 15 m^2 was adopted: two winter wheat varieties (Butterfly and Lorien), two sowing methods (mixed and row-row intercropping), and four legume species (faba bean, incarnate clover, spring pea and winter pea). In the mixed intercropping, wheat and legume seeds were blended and sown in the same row, and legume crops remained in the plots for the entire growing season. In row-row intercropping, wheat and legume seeds were sown in separate rows, and the legume crops were removed in the springtime. Winter wheat varieties were sown alone as a control. The details of variants of the experiment are presented in Table 2 and Fig. S1.

Table 1
Dates of field management practices in the growing seasons.

Growing season	Manure fertilizer	Rate (t ha^{-1})	Ploughing	Harrowing	Sowing date	Harvest date
2019/20	Sheep manure	4	26/9/19	5/10/19	7/10/19	10/8/20
2020/21	Sheep manure	4	21/9/20	5/10/20	8/10/20	10/8/21
2021/22	Sheep manure	4	26/9/21	3/10/21	5/10/21	3/8/22

2.3. Evaluation of grain yield and quality parameters

Plant height (PH) and the number of spikes m^{-2} (Spike) were determined, and wheat grain yield was recorded at the final harvest for each plot. A thousand kernel weight (TKW) also was determined.

PSY 20 (Mezos, Hradec Kralove, Czech Republic) was used to mill wheat flour samples. PC was measured by the Kjeldahl method (Kjeltec 1002 System, Tecator AB, Hoganas, Sweden), based on N * 5.7 (in dry matter). According to ICC Standard No. 137/1, WG and gluten index (GI) were determined by Glutomatic 2200 and Centrifuge 2015 (Perten Instruments, Hägersten, Sweden). FN was measured on FN 1100 (Perten Inst., Sweden), according to ICC standard No. 107/1, AACC International method 56–81 B.

According to the ICC standard method No. 173-ICC 2006, Mixolab (CHOPIN Technologies Mixolab 2, Villeneuve-la-Garenne, France) was used to evaluate the rheological properties of wheat flour, such as the consistency of the dough during mixing and analyze the quality of the protein and starch, as well as assess the impact of enzymes. Mixolab curves were made from wheat flour. Stability (Stab): Resistance to dough kneading. The longer the duration, the stronger the flour. Time of C1 (TimeC1): Dough development. Torque C2 (TC2): Attenuation of protein due to mechanical work and temperature. Torque C3 (TC3): The gelatinization of starch. Torque C4 (TC4): Stability of hot gel. Torque C5 (TC5): Measured starch retrogradation in the cooling phase. Slope α: to evaluate the protein weakening speed under the effect of heat between the end of at 30 °C and TC2. Slope β: to calculate starch gelatinization speeds between TC2 and TC3. Slope γ: enzymatic degradation speeds the period of TC3 and TC4.

2.4. Statistical analysis

Statistical analysis was performed to determine the effect of growing season, winter wheat varieties, sowing method, and legume species. Dunnett's test was used to analyze the combined effect of sowing method and wheat + legume species mixtures relative to wheat sown alone as the control for grain yield, PC, and WG in each year. Dunnett's test was used to analyze the effect of Butterfly/Lorien and legume species mixtures relative to Butterfly/Lorien sown alone as the control for PC. Principal component analysis (PCA) and correlation analysis were used to determine parameters' correlations between grain yield, yield components and grain quality. All statistical analyses were performed using the STATISTICA program (version 13.2, StatSoft, Inc., California, USA) and JMP v. 14 (SAS, NC, USA) software were used. Tukey's HSD (Honest Significant Difference) test was performed with a significance level of $P < 0.05$.

3. Results

3.1. Wheat grain yield and quality parameters

Growing season and wheat cultivars significantly affected grain yield, yield components and grain quality (Table 3). In general, the trend of season performance was as follows: 2019/20 > 2021/22 > 2020/21 for grain yield and yield components. The grain yield, TKW, PH, and Spike were lower in the 2020/21 growth season than other growth seasons caused by the effect of weather conditions. Falling number was higher in the first growing season than in the second and third growing seasons. PC, WG, and GI were higher in the 2020/21 growing season, followed by the 2019/20 and 2021/22 growing seasons (Table 3).

Sowing method did not significantly affect grain yield, yield components and grain quality (Table 3). Grain yield value was lower in wheat and legume species mixtures than in control (wheat was sown alone). Protein content, WG, and FN were higher in wheat and legume mixtures than in control by 3.3 %, 3.6 %, and 2.6 %, respectively.

Wheat cultivars (WC) significantly affected grain yield, yield components, and grain quality (Table 3). Butterfly cultivar performed greater in PC than Lorien (Fig. 3). It was similar for WG, GI, and FN, however, PH, Spike, TKW, and grain yield in the Lorien cultivar

Table 2
Winter wheat/legume mixtures tested and the corresponding code.

	Code	Winter wheat + legume	Sowing method
1	Butterfly	Butterfly seeded alone	Control
2	BuFaMi	Butterfly + Faba bean	Mixed
3	BuInMi	Butterfly + Incarnate clover	Mixed
4	BuSpMi	Butterfly + Spring pea	Mixed
5	BuWiMi	Butterfly + Winter pea	Mixed
6	BuFaRo	Butterfly + Faba bean	Row-row
7	BuInRo	Butterfly + Incarnate clover	Row-row
8	BuSpRo	Butterfly + Spring pea	Row-row
9	BuWiRo	Butterfly + Winter pea	Row-row
1	Lorien	Lorien seeded alone	Control
2	LoFaMi	Lorien + Faba bean	Mixed
3	LoInMi	Lorien + Incarnate clover	Mixed
4	LoSpMi	Lorien + Spring pea	Mixed
5	LoWiMi	Lorien + Winter pea	Mixed
6	LoFaRo	Lorien + Faba bean	Row-row
7	LoInRo	Lorien + Incarnate clover	Row-row
8	LoSpRo	Lorien + Spring pea	Row-row
9	LoWiRo	Lorien + Winter pea	Row-row

Table 3
Effect of the harvest year, sowing method, wheat cultivar, and leguminous crop on production and quality parameters of winter wheat.

Variants	Plant height (cm)	Spikes number m^{-2}	TKW (g)	Yield (t ha^{-1})	Protein content (%)	Wet gluten (%)	Gluten index (%)	Falling number (s)
Season (S)								
2019/20	96.63^{a}	372.07^{a}	52.51^{a}	6.20^{a}	9.79^{b}	18.13^{ab}	73.86^{b}	277.55^{a}
2020/21	71.05^{c}	221.69^{c}	43.78^{b}	2.31^{c}	10.01^{a}	18.50^{a}	85.49^{a}	242.80^{b}
2021/22	87.71^{b}	327.36^{b}	44.58^{b}	4.89^{b}	9.20^{c}	17.39^{b}	69.85^{c}	242.80^{b}
Sowing method (SM)								
Control	84.56	305.15	47.25	5.57	9.41	17.39	78.42	249.00
Mixed	84.01	300.36	46.47	4.42	9.77	18.58	73.88	260.04
Row-row	86.54	313.16	47.30	4.45	9.69	17.50	77.91	251.41
Wheat cultivar (WC)								
Butterfly	82.22^{b}	295.65^{b}	46.42^{b}	4.24^{b}	10.02^{a}	18.94^{a}	79.21^{a}	260.36^{a}
Lorien	88.04^{a}	318.43^{a}	47.59^{a}	4.69^{a}	9.31^{b}	17.08^{b}	73.59^{b}	248.41^{b}
Leguminous crop (LC)								
Wheat control	84.56	308.16	47.25	4.58	9.41^{b}	17.39^{b}	78.43^{ab}	249.00
Wheat + Fa	86.00	301.74	47.22	4.52	9.77^{a}	18.25^{ab}	73.58^{ab}	256.31
Wheat + In	85.21	307.53	46.69	4.40	9.62^{ab}	17.45^{b}	79.53^{a}	250.03
Wheat + Sp	85.03	315.27	47.01	4.48	9.71^{ab}	17.98^{ab}	77.95^{ab}	255.44
Wheat + Wi	84.87	302.51	46.62	4.34	9.82^{a}	18.96^{a}	72.51^{b}	261.14
ANOVA								
S	***	***	***	***	*	*	*	**
SM	ns	ns	ns	ns	ns	*	ns	ns
WC	***	*	***	*	***	***	*	***
LC	ns	ns	ns	ns	*	*	*	ns
S*SM	***	***	ns	***	***	***	***	***
S*WC	ns	***	***	ns	ns	ns	ns	***
S*LC	ns	ns	ns	ns	ns	ns	*	ns
S*SM*WC	ns	*	ns	*	*	ns	*	ns
S*SM*LC	ns	ns	ns	ns	ns	ns	ns	ns
S*WC*LC	ns	ns	ns	ns	ns	ns	ns	ns
SM*WC	ns	ns	ns	*	*	ns	ns	ns
SM*LC	ns	ns	ns	ns	ns	ns	ns	ns
WC*LC	ns	ns	*	ns	ns	ns	ns	ns
S*SM*WC*LC	ns	ns	ns	ns	ns	ns	ns	ns

Wheat control = wheat sown alone; Wheat+Fa = winter wheat + faba bean; Wheat+In = winter wheat + incarnate clover; Wheat+Sp = winter wheat + spring pea; Wheat+Wi = winter wheat + winter pea; TKW, thousand kernel weight; different letters within the column show a statistical difference at *p-Value* < 0.05, Tukey HSD test.
ns (non-significant); *$p < 0.05$; **$p < 0.01$; and ***$p < 0.001$.

were significantly higher than in the Butterfly cultivar (Table 3).

In the case of leguminous crop (LC), baking quality, i.e., PC, WG, and GI were significantly affected by a change in the mixtures of wheat and legume species while agronomy traits (PH, Spike, and TKW) and grain yield were no significant different (Tables 3, 5 and 6 and Fig. 2). Winter wheat and legume mixtures significantly increased PC by 4 % compared to the wheat sown alone (Table 3). A higher PC in wheat and faba bean mixture (Wheat + Fa) and wheat and winter pea mixtures (Wheat + Wi) than in control, while wheat and incarnate clover mixtures (Wheat + In) and wheat and spring pea mixtures (Wheat + Sp) were not affected. WG were lower in sole wheat than wheat intercropped with winter pea. The GI was lower in Wheat + Wi than in Wheat + In.

In individual winter wheat cultivars combined of Butterfly and Lorien (Tables 5 and 6, Fig. 2), the grain yield and yield components did not significantly differ; however, grain quality was higher in some mixtures of wheat and different legume species than wheat was sown alone, e.g., in the mixtures of Butterfly and different legume species, PC was higher in Butterfly + Winter pea + Mixed (BuWiMi) and Butterfly + Spring pea + Row-row (BuSpRo) than Butterfly sown alone. In the mixtures of Lorien and different legume species, PC did not significantly affect, but WG was higher than in Lorien + Winter pea + Mixed (LoWiMi) than wheat sown alone.

3.2. Mixolab analysis

Season and cultivar significantly affected rheological parameters and their interaction but were not significantly affected by sowing method and wheat and legume species mixtures (Table 4). WA ranged from 62.54 to 64.69 %, and the highest value was found in the 2020/21 growing season, followed by the 2021/22 and 2019/20 growing seasons. On the contrary, TimeC1 was highest in the 2019/20 growing season (2.54 min) and the lowest (1.86 min) in the 2020/21 growing season. The Stab indicated the highest in the 2020/21 growing season (6.06 min), then the 2019/20 growing season (5.48 min), and lowest in the 2021/22 growing season (4.77 min). The alfa values showed that in the first season (−0.08) and the third growing season (−0.077) were similar and higher than in the second growing season (−0.084). Similar results were obtained for TC2, TC3, TC4, and beta, with higher values in the 2019/20 growing season than those in the 2020/21 and 2021/22 growing seasons. Also, the lowest gamma is indicated in the 2019/20 growing season (−0.095) compared to the 2020/21 (−0.082) and 2021/22 growing seasons (−0.084) (Table 4).

The difference in wheat cultivar significantly affected the rheological properties of dough (except gamma). The higher number was

Table 4
Effect of the harvest year, sowing method, wheat cultivar, and leguminous crop on rheological parameters evaluated by the Mixolab.

Variants	WA (%)	Time of C1 (min)	Stability (min)	Torque C2 (Nm)	Torque C3 (Nm)	Torque C4 (Nm)	Torque C5 (Nm)	α	β	γ
Season (S)										
2019/20	62.54[c]	2.54[a]	5.48[b]	0.38[a]	1.60[a]	0.945[a]	1.623[a]	-0.080[a]	0.50[a]	-0.095[b]
2020/21	64.69[a]	1.86[c]	6.06[a]	0.36[b]	1.43[b]	0.732[c]	1.344[c]	-0.084[b]	0.43[b]	-0.082[a]
2021/22	63.15[b]	2.19[b]	4.77[c]	0.35[b]	1.43[b]	0.794[b]	1.437[b]	-0.077[a]	0.43[b]	-0.084[a]
Sowing method (SM)										
Control	63.15	2.04	5.21	0.36	1.50	0.828	1.415	-0.080	0.47	-0.095
Mixed	63.50	2.23	5.56	0.36	1.49	0.844	1.508	-0.081	0.45	-0.086
Row-Row	63.57	2.24	5.31	0.35	1.48	0.802	1.454	-0.081	0.44	-0.085
Wheat cultivar (WC)										
Butterfly	66.97[a]	2.32[a]	5.76[a]	0.37[a]	1.36[b]	0.664[b]	1.124[b]	-0.078[a]	0.40[b]	-0.086
Lorien	59.95[b]	2.07[b]	5.11[b]	0.36[b]	1.62[a]	0.994[a]	1.811[a]	-0.082[b]	0.51[a]	-0.089
Leguminous crop (LC)										
Wheat control	63.15	2.04	5.21	0.36	1.50	0.828	1.415	-0.079	0.47	-0.095
Wheat + Faba	63.64	2.31	5.26	0.36	1.49	0.825	1.485	-0.081	0.46	-0.084
Wheat + In	63.55	2.04	5.60	0.36	1.50	0.817	1.473	-0.081	0.45	-0.088
Wheat + Sp	63.51	2.30	5.51	0.37	1.47	0.824	1.470	-0.081	0.44	-0.090
Wheat + Wi	63.44	2.28	5.60	0.37	1.49	0.826	1.497	-0.080	0.44	-0.079
ANOVA										
S	*	***	**	***	***	***	**	***	***	*
SM	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
WC	***	*	***	***	***	***	***	**	***	ns
LC	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
S*SM	***	*	ns	***	***	***	***	**	ns	*
S*WC	***	**	*	***	***	***	***	***	***	ns
S*LC	ns	ns	ns	ns	*	*	*	ns	ns	*
S*SM*WC	ns	ns	***	ns	ns	ns	*	ns	ns	ns
S*SM*LC	ns	*	*	ns	ns	ns	ns	ns	ns	ns
S*WC*LC	ns	ns	ns	ns	***	ns	*	ns	ns	ns
SM*WC	ns	ns	ns	ns	ns	*	ns	ns	ns	ns
SM*LC	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
WC*LC	ns	ns	ns	ns	*	ns	ns	ns	*	ns
S*SM*WC*LC	ns	*	*	ns	ns	ns	ns	ns	ns	ns

Wheat control = wheat sown alone; Wheat+Fa = winter wheat + faba bean; Wheat+In = winter wheat + incarnate clover; Wheat+Sp = winter wheat + spring pea; Wheat+Wi = winter wheat + winter pea; TKW, thousand kernel weight; different letters within the column show a statistical difference at *p-Value* < 0.05, Tukey HSD test.
ns (non-significant); *p < 0.05; **p < 0.01; and ***p < 0.001.

indicated in Butterfly on WA, TimeC1, alfa, Stab, and TC2 at 7.02 %, 0.25 min, 0.004, 0.65 min, and 0.018 Nm than in Lorien, respectively. TC3, TC4, TC5, and beta in Butterfly were 0.255 Nm, 0.33 Nm, 0.687 Nm, and 0.11 lower than in Lorien (Table 4).

In the combination of individual cultivars, there were no significant differences in rheological parameters evaluated by Mixolab for Butterfly and Lorien cultivars intercropped with legume in different sowing methods (Tables 5 and 6).

3.3. Principal component analysis (PCA)

PCA was used to visualize the variation in yield, yield components, and rheological properties of wheat by simplifying many traits, with PC1 and PC2 describing 60.4 % and 11.4 % of the overall variance, respectively (Fig. 4). Yield and yield components were strongly positively correlated with PC1. Baking quality PC, WG, GI, and FN were negatively correlated with PC1. The rheological properties of wheat evaluated by Mixolab as TC3, TC4, TC5, and beta strongly positively correlated with PC1, and WA negatively correlated with PC1. TimeC1 and alfa were positively correlated with PC2. Compared to cultivar, there was a difference between Butterfly and Lorien; Butterfly was strongly positively correlated with PC, WG, and WA. Lorien was positively correlated with TC3, TC4, TC5, and beta due to the lower grain quality but higher grain yield in Lorien compared to Butterfly.

3.4. Correlation analysis

Correlation coefficients between the Mixolab parameters and flour characteristics were calculated and are given in Table 7. There were positive significant correlations between grain yield and yield components. Higher yield components increased grain yield. Negative and significant correlations were found between yield and grain quality, except for WG. PC, WG, and GI had positive correlations with the WA. Overall, the results indicated that the correlation between baking quality and rheological characteristics could be used to predict flour quality.

Table 5
Evaluated the production of wheat, grain yield and grain quality parameters of Butterfly under sowing method and legume species combined.

Variant	Plant height (cm)	Number of spikes m^{-2}	TKW (g)	Yield (t ha^{-1})	Protein content (%)	Wet gluten (%)	Gluten index (%)	Falling number (s)	WA (%)
Butterfly	82.54	304.47	45.89	4.37	9.60^{b}	18.12	81.15	258.33	66.49
BuFaMi	82.49	300.37	46.69	4.50	10.26^{ab}	19.34	74.70	262.11	67.23
BuInMi	80.25	288.49	46.74	4.41	9.86^{ab}	18.38	82.93	258.11	66.94
BuSpMi	81.20	313.68	47.12	4.47	10.05^{ab}	19.41	77.32	257.56	67.08
BuWiMi	79.87	284.01	44.73	4.03	10.35^{a}	20.17	74.09	278.89	66.81
BuFaRo	82.22	288.94	46.61	4.06	9.95^{ab}	18.27	80.56	256.78	67.48
BuInRo	84.36	284.56	47.11	4.10	10.01^{ab}	18.76	79.96	250.67	67.47
BuSpRo	84.47	302.51	46.77	4.01	10.35^{a}	18.89	81.57	259.67	66.76
BuWiRo	82.29	285.00	46.60	4.10	10.18^{ab}	19.93	78.63	263.11	66.91
p-Value	ns	ns	ns	ns	*	ns	ns	ns	ns
Variant	Time of C1 (min)	Torque C2 (Nm)	Torque C3 (Nm)	Torque C4 (Nm)	Torque C5 (Nm)	α	β	γ	Stability (min)
Butterfly	2.15	0.38	1.38	0.70	1.13	-0.077	0.405	-0.099	5.77
BuFaMi	2.63	0.37	1.36	0.64	1.11	-0.080	0.394	-0.083	5.61
BuInMi	1.85	0.38	1.41	0.68	1.20	-0.079	0.424	-0.079	6.50
BuSpMi	2.81	0.37	1.32	0.65	1.09	-0.079	0.370	-0.097	5.52
BuWiMi	2.36	0.38	1.37	0.67	1.17	-0.080	0.404	-0.074	5.82
BuFaRo	2.29	0.36	1.36	0.63	1.12	-0.079	0.406	-0.080	5.30
BuInRo	2.45	0.36	1.36	0.61	1.08	-0.081	0.407	-0.087	5.47
BuSpRo	2.10	0.37	1.31	0.62	1.04	-0.078	0.364	-0.088	5.86
BuWiRo	2.40	0.38	1.38	0.65	1.16	-0.075	0.394	-0.076	6.00
p-Value	ns	ns	ns	ns	ns	ns	ns	ns	ns

TKW, thousand kernel weight; WA, water absorption; α, slope α: attenuating rate of protein in warming; β, slope β: starch gelatinization rate; γ, slope γ: enzymatic degradation rate. Different letters within the column show a statistical difference at *p-Value* < 0.05, Tukey HSD test. ns (non-significant); *$p < 0.05$.

Table 6
Evaluated production of wheat, grain yield and grain quality parameters of Lorien under sowing method and legume species combined.

Variant	Plant height (cm)	Number of spikes m^{-2}	TKW (g)	Yield (t ha^{-1})	Protein content (%)	Wet gluten (%)	Gluten index (%)	Falling number (s)	WA (%)
Lorien	86.57	311.84	48.61	4.78	9.22	16.65^{b}	75.70^{a}	239.67	59.81
LoFaMi	89.29	299.89	47.85	4.76	9.55	18.45^{ab}	71.33^{ab}	257.11	59.78
LoInMi	85.56	302.09	45.27	4.25	9.34	16.50^{b}	73.78^{ab}	245.56	59.84
LoSpMi	85.94	308.93	45.93	4.66	9.21	17.07^{ab}	78.45^{a}	263.22	60.26
LoWiMi	87.46	305.45	47.41	4.32	9.56	19.33^{a}	58.43^{b}	257.78	60.06
LoFaRo	89.99	317.74	47.73	4.78	9.30	16.95^{ab}	67.75^{ab}	249.22	60.06
LoInRo	90.64	354.98	47.64	4.86	9.25	16.18^{b}	81.44^{a}	245.78	59.96
LoSpRo	88.49	335.97	48.21	4.78	9.24	16.60^{ab}	74.46^{ab}	241.33	59.93
LoWiRo	89.87	335.57	47.74	4.91	9.20	16.43^{b}	78.89^{a}	244.78	59.98
p-Value	ns	ns	ns	ns	ns	*	*	ns	ns
Variant	Time of C1 (min)	Torque C2 (Nm)	Torque C3 (Nm)	Torque C4 (Nm)	Torque C5 (Nm)	α	β	γ	Stability (min)
Lorien	1.92	0.35	1.63	0.96	1.70	-0.081	0.530	-0.091	4.66
LoFaMi	2.35	0.38	1.65	1.05	1.90	-0.084	0.517	-0.091	5.61
LoInMi	1.86	0.36	1.62	1.01	1.81	-0.078	0.485	-0.095	4.64
LoSpMi	1.97	0.37	1.64	1.05	1.93	-0.082	0.545	-0.081	5.68
LoWiMi	2.04	0.35	1.61	1.01	1.84	-0.083	0.491	-0.085	5.78
LoFaRo	1.99	0.35	1.61	0.99	1.81	-0.082	0.527	-0.082	4.53
LoInRo	1.98	0.35	1.60	0.97	1.80	-0.085	0.481	-0.092	5.78
LoSpRo	2.33	0.35	1.60	0.98	1.81	-0.084	0.497	-0.096	4.99
LoWiRo	2.34	0.35	1.59	0.98	1.82	-0.082	0.463	-0.082	4.79
p-Value	ns	ns	ns	ns	ns	ns	ns	ns	ns

TKW, thousand kernel weight; WA, water absorption; α, slope α: attenuating rate of protein in warming; β, slope β: starch gelatinization rate; γ, slope γ: enzymatic degradation rate. Different letters within the column show a statistical difference at *p-Value* < 0.05, Tukey HSD test. ns (non-significant); *$p < 0.05$.

4. Discussion

4.1. Grain yield and baking quality

The yield components are the factors that influence winter wheat crop productivity [23]. Though controlled by the genetic features of a specific cultivar, the contribution of each of these components in determining grain yield can fluctuate based on growth and

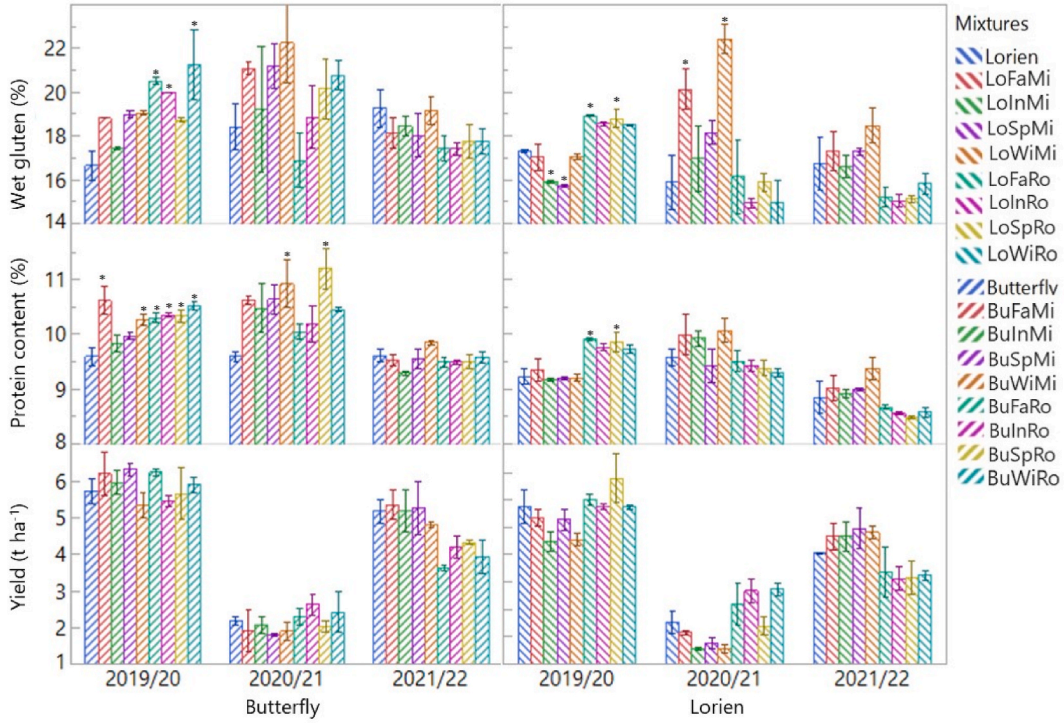

Fig. 2. Effect of Butterfly/Lorien and legume species mixtures on grain yield, protein content, and wet gluten in the three growing seasons. Error bar indicates the standard error (n = 3). Symbols indicate a significant difference from control (wheat sown alone) at *p < 0.05 by Dunnett's test. The abbreviation is indicated in Table 2.

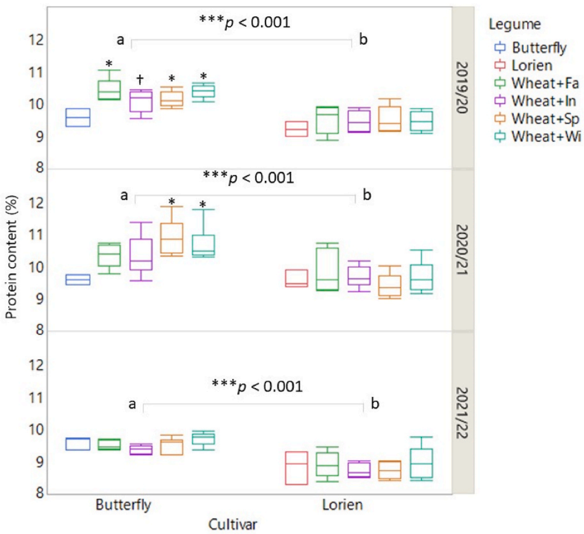

Fig. 3. Effect of Butterfly/Lorien and legume species mixtures on protein content. Wheat + Fa = winter wheat + faba bean; Wheat + In = winter wheat + incarnate clover; Wheat + Sp = winter wheat + spring pea; Wheat + Wi = winter wheat + winter pea. Error bar indicates the standard error. Symbols indicate a significant difference from control (wheat sown alone) at *p < 0.05, †p < 0.1 by Dunnett's test. Different letters show a statistical difference between cultivars (Butterfly and Lorien) at ***p < 0.001.

development conditions under the different effects of habitat and agronomic variables [24]. Heavy rain was recorded in the 2020/21 growing season, resulting in topsoil erosion, reducing nutrients and seeds, and causing a low germination rate. On the other hand, the temperature was lower in January and February 2021 compared to the 2019/20 and 2021/22 growing seasons, causing them to be killed, affecting plant density, plant growth, and grain yield. PH was lowest in the 2020/21 growing season, indicating that weather

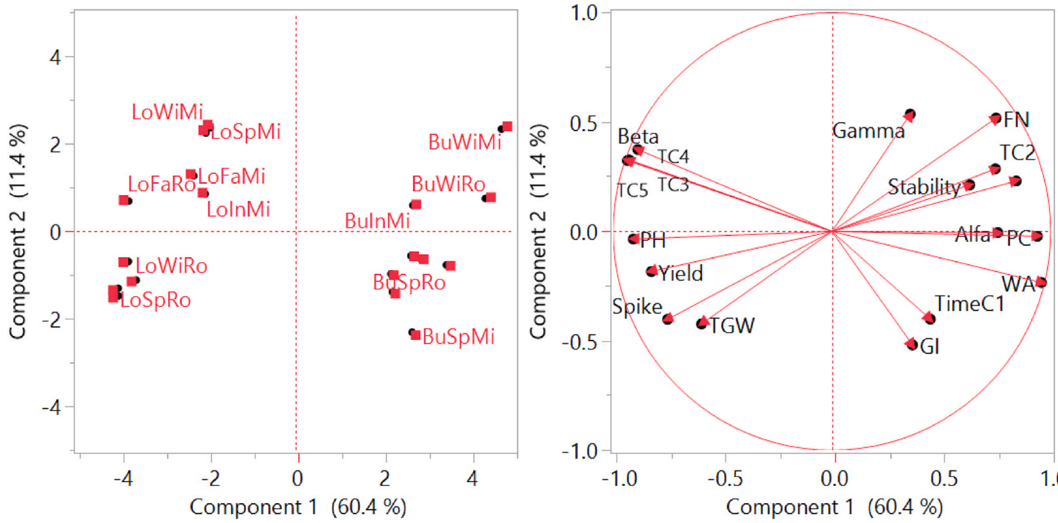

Fig. 4. PCA is based upon various production and quality parameters of wheat under the effect of winter wheat and legume mixtures. PH, plant height; TKW, thousand kernel weight; HW, hectoliter weight; PC, protein content; WG, wet gluten; GI, gluten index; FN, falling number; WA, water absorption; TimeC1, time of C1; TC2, Torque C2; TC3, torque C3; TC4, torque C4; TC5, torque C5.

Table 7
Correlations are significant at $p < 0.05$ between wheat yield, baking quality, and rheological parameters of dough evaluated by Mixolab (N = 54).

Variable	Yield	WA	Time of C1	Torque C2	Torque C3	Torque C4	Torque C5	α	β	γ	Stability
Yield	-	-0.34*	0.45**	ns	0.42**	0.38**	0.31*	0.30*	0.40**	-0.35*	-0.30*
PH	0.94**	-0.49**	0.41**	ns	0.53**	0.48**	0.43**	ns	0.48**	-0.39**	-0.38**
Spike	0.88**	-0.40**	0.51**	0.27*	0.46**	0.46**	0.40**	0.38**	0.44**	-0.34*	ns
TKW	0.71**	ns	ns	ns	0.32*	ns	ns	ns	0.32*	-0.35**	ns
PC	-0.28*	0.68**	ns	ns	-0.44**	-0.50**	-0.55**	ns	-0.37**	ns	0.60**
WG	ns	0.59**	ns	ns	-0.44**	-0.44**	-0.48**	ns	-0.36**	0.35**	0.50**
GI	-0.55**	0.32*	-0.30*	ns	-0.24	-0.30*	-0.29*	-0.32*	ns	ns	ns
FN	0.27*	ns	0.44**	0.84**	0.37**	0.45**	0.34*	0.34*	0.37**	ns	0.29*

PH, plant height; Spike, the number of spikes m^{-2}; TKW, thousand kernel weight; PC, protein content; WG, wet gluten; GI, gluten index; FN, Falling number; WA, water absorption; α, slope α: attenuating rate of protein in warming; β, slope β: starch gelatinization rate; γ, slope γ: enzymatic degradation rate.
ns (non-significant); $*p < 0.05$; $**p < 0.01$.

conditions influenced the growth and development of winter wheat, which in turn affected yield components and grain yield. The number of spikes per unit area and TKW are commonly thought to be the critical yield components [25,26]. The increase of spikes m^{-2} increased the wheat grain yield [27]. However, many authors reported that a higher spike number per unit area did not result in a higher yield level [28] and that a decrease in the value of one yield trait can be compensated by a more beneficial effect of another trait, resulting in a minimal change in grain yield [29]. Compared with previous studies, the lower number of spikes m^{-2} reduced grain yield in this study. A substantial year effect was observed for the yield and yield components. The PH, Spike, TKW and yield were considerably higher in the 2019/20 growing season than in the other years (Table 3). The lowest spike in the 2020/21 growing season (Table 3) was observed because of the lower germination rate (data not shown). Besides, the drought that began in spring greatly reduced the number of grains per spike because that drought during flowering led to poorer seed setting and, consequently, a lower grain number per spike [28,30]. On the other hand, in agreement with Konvalina et al. (2009, 2007), who reported that differences in variety and growing season influenced wheat yield [1,31].

Weather conditions influence growth, development, grain yield, and grain quality. Numerous prior research indicated that the growing condition could significantly impact gluten composition, quality, and overall kernel protein composition. These effects are connected to the impact of high temperatures on reducing the duration of dry matter accumulation, shortening the grain-filling period, and finally reducing kernel weight [32]. On the other hand, agree with the previous studies indicated that there was a negative correlation between yield and grain quality [33,34], grain yield was higher but PC lower was found in this study (Tables 3 and 7; Fig. 2). The effect of the wheat cultivars also indicates this, the Lorien variety was a higher grain yield but lower grain quality than the Butterfly variety.

Other factors, such as leguminous species and cultivation practices, influence yield formation, Stab, and grain quality. Legumes in well-chosen mixed cultivation can contribute to a positive balance of available nitrogen in the soil [35], which makes nitrogen available to the legumes and companion crops because they improve soil fertility through the symbiotic association with rhizobia [36].

This can lead to higher yields of the main crop compared to monoculture [37,38] and higher grain quality of the main crop [11,20,21] compared to monoculture. There are, however, conflicting reports on the impact of legumes in wheat and legume intercropping on wheat yields and grain quality. In the case of mixed intercropping, the competition of legumes with cereal may need to be considered in further management practices [15], such as weed and disease control and mechanization of cultivation practices [12]. Intercropping can reduce the yield of mixtures compared to monoculture cereal crops [38] because simultaneous intercropping might limit or reduce the cereal yield in a case of high growth and high density of the legume and the resulting competition for nutrient resources and light [11,17]. This alternative cropping may be considered where the cereal and legume are sown in separate rows alternately [2] to reduce competition between the main crop and intercropped. In our study, the legume crops killed in the springtime might reduce their competition. However, the remaining residue legume plants underground may have enhanced soil fertility, then improved growth plant, grain yield and quality. The soil and legume crop results were limited, but our findings showed that grain yield was not reduced while grain quality increased in wheat and legume intercropping. This is similar to Refs. [10,39] findings, who reported no significant changes in wheat yield; the intercropping of legumes had no influence on wheat grain production in general. Agreed with Guiducci et al. (2018), who found that intercropping winter wheat and legumes is an efficient tool for the sustainable management of N nutrition in winter wheat. The grain yield was not changed, and the N concentration was recommended better in the legume crops ploughed in the soil compared to keeping the whole growth season. In our site, grain yield and PC were unaffected by removing (row intercropping) and keeping legume (mixed intercropping) crops, but other baking parameter such as WG and FN were better in mixed intercropping than row intercropping. This showed wheat quality in mixed intercrop could be apply to improve the baking quality of winter wheat in organic farming.

4.2. Rheological parameters evaluated by Mixolab

The assessment of the rheological parameters of wheat flour dough during mechanical handling is critical because it affects the effective manufacture of the bakery and the quality of the finished products. Mixolab can assess physical dough parameters such as dough strength and stability, and the pasting capabilities of starch on the actual dough in a single test. There was no significant difference in almost all the rheological properties evaluated by Mixolab in this site under the effect of sowing method and wheat and legume mixtures (Table 4), a high correlation between baking quality and rheological properties (Table 7, Fig. 4).

The dough mixing parameters such as stability and WA can be assessed in the first stage of the Mixolab test. An increase in the torque is observed until a maximum is reached and the dough can resist the deformation for some time. The higher the index, the higher the quality of the flour. The second stage indicates the consistency of the dough when mixing, in other words, protein weakening. The more significant the decrease in consistency, the lower the protein quality. There was no significant difference in correlation between protein and gluten quality with the TC2 in our study (Table 7). The starch gelatinization indicated in the third stage under the temperature increases, starch granules absorb water and amylose molecules leach out, increasing viscosity. The consistency decreases due to the amylolytic activity indicated in the fourth stage. The intensity of the decrease depends on amylase activity; the higher the index, the lower the amylase activity. At the fifth stage, the temperature reduction increases consistency due to gel formation; a greater TC5 value indicates a higher amount of starch retrogradation; and it appears able to assess the texture of the cakes [40,41]. The rheological parameters found in this study did not affect different leguminous species and management, TC4. A highly positive correlation was found between PC with WA and stability ($r = 0.68$ and $r = 0.60$), and a negative correlation with TC3, TC4, and TC5 ($r = -0,44$, -0.50, and -0.55, respectively) (Table 7), this is in agreement with the previous study by Ref. [42]. Therefore, a significant difference in the effect of the growing season and cultivar on the rheological properties of flour is mainly influenced by weather conditions and different types of variety.

5. Conclusions

Finding strategies to deal with abiotic stresses in agricultural environments has always been difficult since they are detrimental limiting factors for grain yield and quality. The key to fixing this issue is to draw attention to suitable farming systems, such as intercropping systems comprising legumes. In this study, after conducting different intercropping systems using various legumes, wheat varieties, and sowing management during three growing seasons, it shows that the intercropping of winter wheat and legume caused no grain yield variation and rheological properties of dough evaluated by Mixolab, but an increased grain quality. This study is an opening for further research on the effect of changing leguminous species on baking quality and nutrient content in many standard and strategic wheat varieties. Butterfly shows greater grain quality but lower grain yield than Lorien, so a study blending Butterfly with Lorien and legume mixtures could be an option in a future study to improve simultaneous grain yield and grain quality.

Data availability

Data will be made available on request.

CRediT authorship contribution statement

Trong Nghia Hoang: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Data curation, Conceptualization. **Petr Konvalina:** Writing – review & editing, Supervision, Project administration, Methodology. **Marek Kopecký:** Writing – review & editing, Methodology. **Mohammad Ghorbani:** Writing – review & editing. **Thi Giang Nguyen:**

Investigation. **Jaroslav Bernas:** Investigation. **Yves Theoneste Murindangabo:** Investigation. **Ivana Capouchová:** Writing – review & editing. **Sangin Shim:** Writing – review & editing. **Petra Hlásná Čepková:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2024.e31234.

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