Effects of crop mixtures on rust development on faba bean grown in Mediterranean climates

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Abstract

Faba bean (*Vicia faba*) is a temperate grain legume of major importance in Mediterranean agriculture. Faba bean production can be severely constrained in the area by rust incited by *Uromyces viciae-fabae*. Control with fungicides is possible, but there is a growing interest on alternative control methods, compatible with organic agriculture. Intercropping faba bean with cereals has been suggested as an alternative to maximize land use and increase crop resilience, with potential beneficial effects reducing weeds and diseases. In the present work, we studied the effect of intercropping faba bean with barley, triticale or wheat on faba bean rust development. Field studies performed over two consecutive seasons in two different countries showed that faba bean rust is significantly reduced when faba bean is intercropped with cereals confirming the value of faba bean-cereal intercropping for the management of faba bean rust. These results confirm that, under our conditions, intercropping faba bean with cereals (oat, barley, wheat or triticale) could usefully contribute to the management of faba bean rust.

Keywords: Intercropping, Organic farming, Disease management, *Uromyces viciae-fabae*, *Vicia faba*

Introduction

Faba bean (*Vicia faba* L.) is a temperate annual legume crop cultivated worldwide. It is an important source of protein in developing countries and is used as a human food and feed (Karkanis et al., 2018). It is also grown for green manure and can significantly improve yields of cereals and other crops. Faba bean needs a cool season for better growth and the optimum temperatures for production range from 18 to 27°C. It is well adapted to Mediterranean-type climates, where it is sown in autumn, and to cold-temperature regions where it is sown in spring (Mínguez and Rubiales, 2020).

Faba bean rust (*Uromyces viciae-fabae* Pers.) is one of the main diseases of faba bean in nearly every area in the world where faba bean is grown and can cause yield loss up to 70% in early infection (Stoddard et al., 2010). Control is possible by the use of fungicides (Emeran et al., 2012) and resistant cultivars (Ijaz et al., 2017; Sillero et al., 2017). However, there is an increasing demand for unconventional management practices as fungicides are expensive, unfriendly for the environment and people, and can lose effectivity against pathogens. At the same time, resistant cultivars are limited and resistance available so far is only incomplete (Sillero et al., 2000).

Intercropping, consisting of growing different crops together simultaneously in the same piece of land at different mixing rates was a common practice in the past, being currently reevaluated for its potential to increase crop resilience (Finckh et al., 2000; Hauggard-Nielson et al., 2006; Mikić et al., 2015). Intercropping is believed to have beneficial effects providing a degree of weeds, pests and disease reduction. This protection use however to be incomplete and to be influenced by environmental factors (Boudreau, 2007; Malézieux et al., 2009), therefore needing monitoring and case by case adjustments.

Cereal-legume combinations are among the most common intercropping systems practiced worldwide (Willey, 1979) providing advantages in yield particularly in low-input systems (Bedoussac et al., 2015). The increased N use efficiency in cereal/ legume intercrops can reduce the need of fossil-based fertilizer N by about 26% on a global scale (Jensen et al., 2020). Intercropping with cereals has already been reported to improve alternaria leaf spot, chocolate spot, fusarium wilt and broomrape control in faba bean (Sharaiha et al., 1989; Fernández-Aparicio et al., 2007, 2011; Sahile et al., 2008a; Yang et al., 2014; Zhang et al., 2019) as well as on diseases of the cereals (Luo et al., 2021). However, negative (Zhang et al., 2019) or insufficiently quantified reports are available on the potential of intercropping for faba bean rust management (Terefe et al., 2016; Ijaz et al., 2017; Villegas-Fernández et al., 2017). However, even for the diseases in which significant reduction was reported, this was incomplete and variable among environments. The objective of the current study was to quantify the effect of intercropping faba bean with cereal species on the development of *U. viciae-fabae* in faba bean in Mediterranean environments.

Materials and methods

Sites and soil

The experiments were conducted in two countries with long tradition of faba bean cultivation in which rust is a major limiting factor, but in which cultivation practice are very contrasting. These were Palestine where rain fed faba beans are grown and Egypt where they are grown under flood irrigation. Locations were selected based on their known history of high and uniform infestation of *U. viciae-fabae*. These were Tulkarm at Palestine (32.31519º N, 35.02033º E, 75 m altitude), with light clay chromic luvisol with a pH of 7.0-7.5, in Kafr El-

Sheik, Egypt (30º470 N, 30º590 E, 0 m altitude) with loamy calcaric entisol with a pH of 7.5-8.0 during 2006-2007 and 2007-2008 seasons. In all these locations, due to their mild winter and hot spring, faba beans are autumn sown.

Validation of optimal crop mixtures

Four intercrop mixtures were used in this study: faba bean (cultivars Nobaria 1 at Egypt, and Baladi at Palestine) intercropped either with barley, with durum wheat, with oat or with triticale (cultivars Cory, Meridiano, Aspen and Peñarroya, respectively). The experimental unit consisted of 1.8 x 10 m plots, with 6 rows 10 m long, separated 0.3 m (Figure 1). Plots were laid out in a randomized complete block design with 4 replicates. Faba bean monocrop with a plant density of 100 faba bean plants m^{-2} was used as a control. Species were mixed intercropped within rows. All species were sown by hand at the 1st of November in all environments. No chemical fertilizers or pesticides were applied across the experiment. Weeds were removed by hand weeding when needed. No irrigation was applied at Tulkarm whereas surface irrigation took place four times at Kafr El-Sheikh (400 m^3 ha^{-1} were applied each time). The first irrigation was done after sowing, the second one during December the third during March, and the fourth during April.

The rust susceptible faba bean cv. Brocal was grown in a single, long row perpendicular to the rows of the tested plots to act as rust spreader. No artificial inoculation was performed as faba bean rust was known to occur every year naturally on both sites.

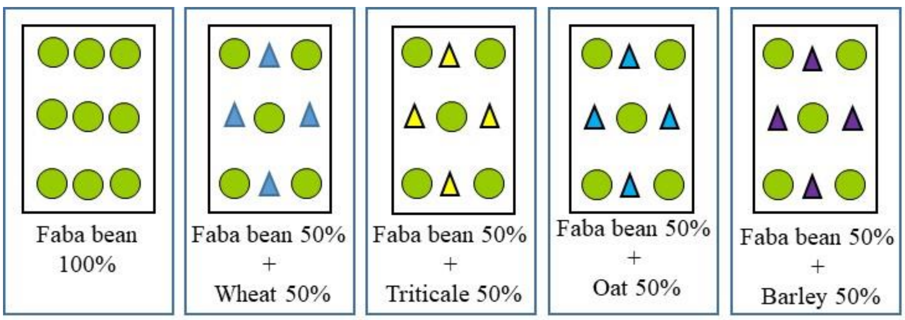

Figure 1: *Diagram of planting patterns in the field experiments*

Disease assessment

Disease severity (DS) was evaluated by visual estimation of the percentage of leaf area covered with rust pustules. DS evaluation was estimated using 10 randomly chosen plants per plot. First DS evaluations were made four weeks after onset of the first symptoms on the spreader rows of faba bean cv. Brocal. This was followed by two additional DS evaluations, at two weeks interval. The third DS evaluation was used as final disease severity (DSf). DS data were used to calculate the area under the disease progress curve (AUDPC) using the formula:

$$\mathrm{AUDPC} = \sum_{i=1}^{k} 1/2[(DSi + DS_{i+1})(t_{i+1} + t_i)]$$

Where *DSi* is the rust severity at evaluation date *i*, *ti* is the number of days after the first observation on evaluation date i and k is the number of consecutive evaluations. The epidemic growth rate (r) was obtained by linear regression of the transformed DS against time: trans(DS) = logit(DS) + 10 = ln(DS/100 - DS) + 10 (10 was added to obtain a positive number). Time of the first pustule's appearance (t0) was calculated from the straight line slope equation y = mx + b, and was measured as number of days from sowing to first pustule's appearance on the leaves (Barilli et al., 2009).

Plant stature and biomass assessments

To study the effect of plant height on rust development, the height of 10 randomly chosen plants per plot, was measured for faba bean and the associated crop. Measurements were recorded at faba bean pod filling stage. The averages of the 10 plants were used for statistical analysis.

To study the effect of plant biomass on rust development, all plants within 0.5 m^2 of each plots were collected by cutting the plants at soil level when the faba bean was at pod filling stage. Then, baba bean plants were separated from the associated crop and then fresh biomass of each crop was weighted separately.

Statistical analysis

Analysis of variance (Two-way ANOVA) was conducted using PROC MIXED of SAS/STAT software (version 9.0 for Windows) (SAS institute 2002). The analysis was carried out for each season and each location separately. The terms fitted in the analysis model included the effects of block and intercrop mixture. The residuals (errors) were obtained and investigated for any departure from normality using Shapiro-Wilk test. The results of this test showed no significant deviations from normality for all studied variables ($P > 0.05$) indicating that ANOVA is appropriate for the analysis of the data. Multiple comparisons among pairs of intercrop mixtures were made by the Tukey-test.

Results

Uniform rust infection was observed in both seasons at both locations. Infection started earlier in Egypt than in Palestine in both seasons (Fig. 2) which could be explained by cooler winters in Palestine (Table 1 and 2). Onset of symptoms (t_0) occurred around 107-109 days after sowing in Egypt and 115-116 days in Palestine in both seasons. No year x treatment interaction effect was observed.

Table 1*: Average temperature (°C) at each growing season and site of experimentation.*

Location	Season	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.
Tulkarm, Palestine*	2006-2007	21.6	17.9	13	15.1	21.7	24.6
	2007-2008	23.7	18	14.9	15.2	15.5	19.2
Kafr El-Sheikh, Egypt**	2006-2007	23.2	20.1	19.3	20.2	22.8	25.3
	2007-2008	25.9	21.7	18.1	19.2	25.4	27.8

Table 2*: Total rain fall (mm) at each growing season and site of experimentation.*

Location	Season	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	Total
Tulkarm, Palestine*	2006-2007	148.3	82	77.8	104	10.5	0.0	422.6
	2007-2008	32.7	151	22.7	151.5	105.9	6.2	470
Kafr El-Sheikh, Egypt**	2006-2007	3.2	10	17.5	44.1	9	11.5	95.3
	2007-2008	28	12.5	37.8	38	0.0	0.0	116.3

**rain fed, **irrigated*

There was a general trend for slight retardation on the onset of infection (longer t_0) in the studied intercrops, although these were seldom significant (Table 3). Apparent growth rate (r) in monocrops was 0.167 and 0.114 respectively for Palestine and Egypt in 2006-2007 and 0.166 and 0.236 in 2007-2008. A general non-significant trend of reduction was observed in the intercrops ranging in Palestine from 0.161 to 0.164 in 2006-2007 and 0.154 to 0.158 during 2007-2008 and in Egypt from 0.088 to 0.114 during 2006-2007 and 0.223 to 0.228 during 2007-2008.

Table 3. *The effect of intercropping faba bean with cereals on rust development: time of the first pustule's appearance (t_0), apparent growth rate (r), final disease severity (DSf) and AUDPC*

Intercrops[1]	**Tulkarm, Palestine**								**Kafr El-Sheikh, Egypt**							
	2006-2007[2]				**2007-2008**[2]				**2006-2007**[2]				**2007-2008**[2]			
	t_0[3,4]	**r**	**DSf**	**AUDPC**	**t_0**	**r**	**DSf**	**AUDPC**	**t_0**	**r**	**DSf**	**AUDPC**	**t_0**	**r**	**DSf**	**AUDPC**
FB 100%	115.1^{b}	0.167^{a}	35.8^{a}	765.4^{a}	119.3^{a}	0.166^{a}	39.8^{a}	724.4^{a}	109.4^{a}	0.114^{a}	47.5^{a}	782.3^{a}	107.2^{b}	0.236^{a}	54.6^{a}	1012.8^{a}
FB50% + B50%	117.8^{b}	0.163^{a}	23.9^{b}	522.9^{b}	117.2^{a}	0.154^{a}	20.0^{b}	505.1^{b}	111.5^{a}	0.114^{a}	34.0^{b}	472.0^{b}	109.7^{a}	0.223^{a}	38.0^{b}	573.5^{b}
FB50% + O50%	117.3^{b}	0.163^{a}	23.1^{b}	539.0^{b}	116.5^{b}	0.154^{a}	19.3^{b}	533.0^{b}	119.5^{a}	0.088^{a}	34.3^{b}	500.7^{b}	107.7^{b}	0.225^{a}	42.8^{ab}	760.4^{ab}
FB50% + T50%	115.3^{b}	0.161^{a}	26.1^{b}	629.4^{b}	117.0^{a}	0.158^{a}	23.5^{b}	614.4^{ab}	111.1^{a}	0.114^{a}	29.9^{b}	434.9^{b}	108.2^{b}	0.228^{a}	45.1^{ab}	779.1^{ab}
FB50% + W50%	118.7^{a}	0.164^{a}	24.9^{b}	586.2^{b}	117.9^{a}	0.157^{a}	24.1^{b}	526.4^{b}	110.2^{a}	0.132^{a}	33.3^{b}	541.3^{b}	108.5^{b}	0.226^{a}	42.4^{ab}	714.7^{b}

[1] *FB100%: faba bean monocrop, FB+B: faba bean 50% intercropped with barley 50%, FB+O: faba bean 50% intercropped with oat 50%, FB+T: faba bean 50% intercropped with triticale 50%, FB+W: faba bean 50% intercropped with wheat 50%.*

[2] *Per each year, column with the same superscripts are not statistically different (Tukey test, $p < 0.05$).*

[3] *t_0 was calculated from the straight line slope equation $y = mx + b$.*

[4] *r: the epidemic growth rate, t_0: time of the first pustule's appearance, AUDPC: area under the disease progress curve, DS: the percentage of leaf area covered with rust pustules. DSf: the final disease severity.*

Faba bean rust developed during the months of March and April in Palestinian trials under warmer and drier conditions in 2007 than in 2008 and reached maximum values of diseased tissue (DSf) in monocropped faba bean plots (maximum DS of 35.8% in 2007 and 39.8% in 2008). However, as disease started a few days later in 2008, AUDPC was slightly lower in 2008 in spite of a slightly higher final DS. All cereal in intercrop mixtures showed significantly less faba bean rust in comparison with monocropped faba beans. This cereal-mediated reduction being higher in 2007-2008 (average AUPDC reduction of 25.6%) than in 2006-2007 (23.5%), with all cereals having similar effects except for barley (Table 3).

Higher rust severities were achieved in Egyptian trials, with 47.5% and 54.6% final DS in faba bean monocrops in 2007 and 2008, respectively. Rust started a few days earlier in 2008, and reached higher DS, resulting in a much larger ADPC in 2008 than is 2007. All intercrops reduced faba bean rust significantly in comparison with monocrops, with an overall reduction of 30.2% in 2007 and of 37.7% in 2008.

Faba bean plant stature varied with the environment, being taller in 2006-2007 in both locations (Table 5). There was no effect of the various intercrops on faba bean height in both locations except a significant reduction in faba bean height when it was mixed with barley at Kafr El-Sheikh during 2006-2007 season. The associated crop was higher in 2006-2007 in both locations.

***Table 5**: The effect of intercropping on plant height*

Intercrops[1]	Tulkarm, Palestine		Kafr El-Sheikh, Egypt	
	2006-2007	**2007-2008**	**2006-2007**	**2007-2008**
FB100%	118.1^{a}	99.0^{a}	147.3^{a}	101.1^{a}
FB50% + B50%	116.3^{a} (94.6)*	104.0^{a} (85.6)	125.0^{b} (85.5)	100.8^{a} (63.1)
FB50% + O50%	115.3^{a} (135)	98.9^{a} (107.8)	141.7^{ab} (112.4)	101.8^{a} (62.5)
FB50% + T50%	114.1^{a} (106.5)	97.0^{a} (89.4)	144.9^{a} (128)	102.6^{a} (90.6)
FB50% + W50%	114.3^{a} (84.4)	98.9^{a} (94.1)	137.1^{ab} (92.5)	92.2^{a} (63.7)

[1] FB100%: faba bean monocrops, FB+B: faba bean 50% intercropped with barley 50%, FB+O: faba bean 50% intercropped with oat 50%, FB+T: faba bean 50% intercropped with triticale 50%, FB+W: faba bean 50% intercropped with wheat 50%.

** Faba bean plant height and in brackets the height of the associated cereal crop.*

Means in the same column with similar superscripts are not statistically different (Tukey test, $p < 0.05$).

When faba bean fresh biomass was assessed no significant reduction was observed in both seasons and both locations except intercropping with barley in Egypt in 2006-2007 season (Fig. 2). Intercropping faba bean with triticale gave the highest accumulative faba bean fresh biomass in Egypt during 2008.

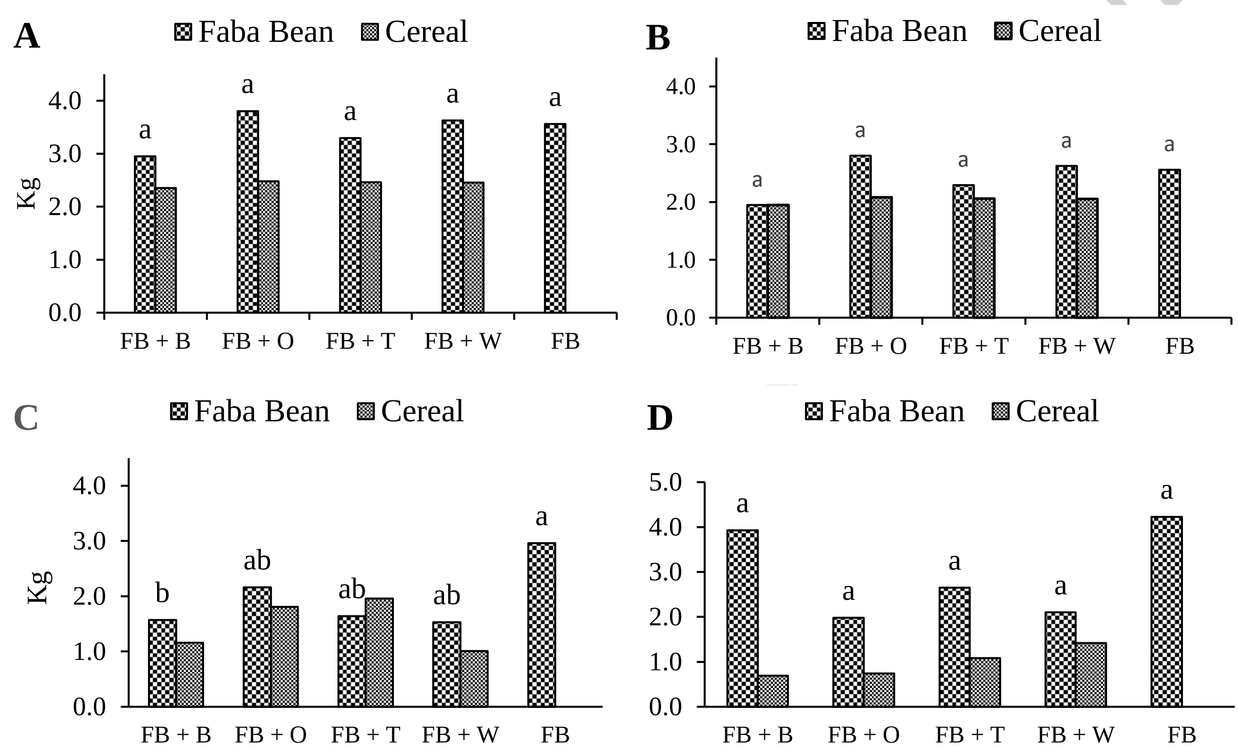

Figure 2: *Plant fresh biomass of monocropped faba bean at full plant densities and when intercropped with oat (O), barley (B), wheat (W) and triticale (T). Data correspond to the mean values in kg/m*^{2} *made at Tulkarm, Palestine 2007 and 2008 (Fig. A and B.), and at Kafr El-Sheikh, Egypt 2007 and 2008 (Fig. C and D). Data are mean (n = 4). Treatments with the same letter are not statistically significant different (Tukey test, p < 0.05).*

Simple correlation coefficients between disease severity and plant height and plant fresh weight were computed and presented in Table (4). Significant positive correlation was found between DSf in each season in both countries. High negative significant correlation was found between DSf on faba bean and the height and fresh biomass of the associated crop in both seasons and both countries. Positive non-significant correlation was found between DSf and faba bean plant fresh weight.

__Table 4:__ Correlation coefficients for final disease severity (DSf) and plant fresh weight and plant height.

Palestine					
	DSf 2008	**Weight of faba bean 2007**	**Height of faba bean 2007**	**Weight of associated crop 2007**	**Height of associated crop 2007**
DSf 2007	0.922 (0.000)	0.114 (0.631)	0.135 (0.570)	-0.908 (0.000)	-0.898 (0.000)
		Weight of faba bean 2008	**Height of faba bean 2008**	**Weight of associated crop 2008**	**Height of associated crop 2008**
DSf 2008		0.208 (0.379)	-0.146 (0.540)	-0.905 (0.000)	-0.906 (0.000)
Egypt					
	DSf 2008	**Weight of faba bean 2007**	**Height of faba bean 2007**	**Weight of associated crop 2007**	**Height of associated crop 2007**
DSf 2007	0.620 (0.000)	0.410 (0.073)	0.293 (0.210)	-0.529 (0.016)	-0.866 (0.000)
		Weight of faba bean 2008	**Height of faba bean 2008**	**Weight of associated crop 2008**	**Height of associated crop 2008**
DSf 2008		0.008 (0.975)	0.049 (0.836)	-0.385 (0.094)	-0.620 (0.004)

Actual P values are between brackets.

Discussion

Intercropping is useful for agriculture in terms of yield stability, increase in total yield, pest and disease management, weed management, erosion control, and soil fertility amongst others (Hauggard-Nielson et al., 2006). The results of this study, obtained over two growing seasons in two countries, confirm that intercropping faba bean with cereals is an effective strategy for controlling faba bean rust. The experiment was designed based on replacing half of the host plant species (faba bean) with the associated cereal crop. Reducing host plant density and increasing the distance between faba bean plants resulted in reduction of the amount of susceptible plant tissue per field area unit leading to reduction in the likelihood of spore deposition (Fernández-Aparicio et al., 2011).

The reduction in rust severity due to intercropping with cereals observed in this study is in agreement with a number of occasional reports of reductions on faba bean rust in Denmark (Fernández-Aparicio et al., 2006), highland Ethiopia (Terefe et al., 2016; Eshesu et al., 2018) and Spain (Villegas-Fernández et al., 2017). On the contrary Zhang et al. (2019) reported a reduction in other faba bean diseases, but not significant for rust. Reduction has been reported for other aerial diseases of faba bean such as chocolate spot and alternaria spot (Sharaiha et al., 1989; Sahile et al., 2008b; Fernández-Aparicio et al., 2011). The cereals in the intercropping system might work as a natural barrier that intercept rust urediospores carried by wind from infecting faba bean plants resulting in reducing the amount of available effective inoculums to infect other faba bean plants. This hypothesis of barrier effect of the accompanying crops is supported by the significant association of the reduction of rust severity on faba bean with the plant stature and fresh biomass of the accompanying crop. Nutritive status of the plant is known to affect disease severity, with increased application of nitrogen fertilizer favouring rust and other diseases. Luo et al. (2021) found that the relative control effect of intercropping on diseases of wheat intercropped with faba bean increased as application of N increased, suggesting that rational application of nitrogen fertilizer in intercrops contributes to disease control. As long as we focus on low input agriculture, we did not study fertilization effects, but following the studies of Luo et al. (2021) we hypothesise that faba bean rust reduction effects of intercrops would increase with nitrogen fertilization.

The stratified dispersal of faba bean rust was modelled by Sapoukhina et al. (2010) to identify the spatial patterns of cultivar mixtures that could slow epidemic spread, showing that mixtures creates a natural barrier to the progression of a smooth epidemic wave. Besides reduction in dispersal phase of rust, additional effects on rust life cycle other than dispersal could be derived from alterations in faba bean nutritive status and changes in microclimate inside canopy promoted by the cereal component (Boudreau and Mundt, 1992). Similar effects have been reported for pea ascochyta blight spores in pea intercropped with cereal (Schoeny et al., 2010), chocolate spot reduction in faba bean-maize and faba bean-barley intercrops (Sahile et al., 2008 a,b; Guo et al., 2020) and powdery mildew reduction in pea-cereals intercrops (Villegas-Fernández et al., 2021).

In this study, faba bean rust development was significantly affected by intercropping of faba bean with cereals. These results confirm that, under our conditions, intercropping faba bean with cereals (oat, barley, wheat or triticale) at 50:50% seeding ratio could usefully contribute to the management of faba bean rust. In this study, the effect of intercropping on yield and yield losses due to leaf rust was not evaluated

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References

Barilli, E., Sillero, J.C., Fernández-Aparicio, M., Rubiales, D., 2009. Identification of resistance to *Uromyces pisi* (Pers.) Wint. in *Pisum* spp. germplasm. Field Crops Res. 114: 198–203.

Bedoussac, L., Journet, E.P., Hauggaard-Nielsen, H., Naudin, C., Corre-Hellou, G., Jensen, E.S., Prieur, L., Justes, E., 2015. Ecological principles underlying the increase of productivity achieved by cereal-grain legume intercrops in organic farming. A review. Agron. Sustain. Dev. 35: 911–935. doi: 10.1007/ s13593-014-0277-7

Boudreau, M.A., 2007. Effect of intercropping beans with maize on the severity of angular leaf spot of beans in Kenya. Plant Pathol. 42: 16-25.

Boudreau, M.A., Mundt C.C., 1992. Mechanisms of alteration in bean rust epidemiology due to intercropping with maize. Phytopathol. 10: 1051-1060.

Emeran, A.A., Sillero, J.C., Fernández-Aparicio, M., Rubiales, D., 2011. Chemical control of faba bean rust (*Uromyces viciae-fabae*). Crop Prot. 30: 907-912

Eshesu, G., Bimrew, Y., Shifa, H., 2018. Association of Chocolate Spot and Faba Bean Rust Epidemics with Climate Change Resilient Cultural Practices in Bale Highlands, Ethiopia. Hindawi Advances in Agriculture 2018: 6042495. https://doi.org/10.1155/2018/6042495

Fernández-Aparicio, M., Rubiales, D., Flores, F., Hauggard-Nielsen, H., 2006. Effects of sowing density, nitrogen availability and crop mixtures on faba bean rust (*Uromyces viciae-fabae*) infection. Pp. 143-147. In: C.M. Avila, J.I. Cubero, M.T. Moreno, M.J. Suso & A.M. Torres (Eds.). International Workshop on faba bean breeding and agronomy. Edit. Junta de Andalucía, Sevilla, ISBN: 84-8474-195-8.

Fernández-Aparicio, M., Sillero, J.C., Rubiales D., 2007. Intercropping with cereals reduces infection by *Orobanche crenata* in legumes. Crop Prot. 26: 1166-1172.

Fernández-Aparicio, M., Shtaya, M.J.Y., Emeran, A.A., Allagu, M.B, Kharrat, M., Rubiales D., 2011. Effects of crop mixtures on chocolate spot development on faba bean grown in Mediterranean climates. Crop Prot. 30: 1015-1023

Finckh, M.R., Gacek, E.S., Goyeau, H., Lannou, C., Merzd, U., Mundt, C.C., Munk, L., Nadziak, J., Newton, A.C., De Vallavieille-Pope C., 2000. Cereal variety and species mixtures in practice, with emphasis on disease resistance. Agronomie 20: 813-837.

Guo, Z., Dong, Y., Dong, K., Zhu, J., Ma L., 2020. Effects of nitrogen management and intercropping on faba bean chocolate spot disease development. Crop Prot. 127: 104972

Hauggard-Nielsen, H., Andersen, M.K., Jørnsgaard, B., Jensen, E.S., 2006. Density and relative frequency effects on competitive interactions and resource use in pea-barley intercrops. Field Crops Res. 95: 256-267.

Ijaz, U., Adhikari, K.N., Stoddard, F.N., Trethowan, R.N., 2017. Rust resistance in faba bean (*Vicia faba* L.): status and strategies for improvement. Australas. Plant Pathol. 47: 71-81

Jensen, E.S., Carlsson, G., Hauggaard-Nielsen H., 2020. Intercropping of grain legumes and cereals improves the use of soil N resources and reduces the requirement for synthetic fertilizer N: A global-scale analysis. Agron. Sustain. Dev. 40: 5.

Karkanis, A., Ntatsi, G., Lepse, L., Fernández, J.A., Vågen, I.M., Rewald, B., Alsina, I., Kronberga, A., Balliu, A., Olle, M., Bodner, G., Dubova, L., Rosa, E., Savvas, D., 2018. Faba Bean Cultivation – Revealing Novel Managing Practices for More Sustainable and Competitive European Cropping Systems. Front. Plant Sci. 9: 1115. doi: 10.3389/fpls.2018.01115.

Luo, C., Ma, L., Zhu, J., Guo, Z., Dong, K., Dong, Y., 2021. Effects of nitrogen and intercropping on the occurrence of wheat powdery mildew and stripe rust and the relationship with crop yield. Front. Plant Sci. 12: 637393. doi: 10.3389/fpls.2021.637393

Malezieux, E., Crozat, Y., Dupraz, C., Laurans, M., Makowski, D., Ozier-Lafontaine, H., Rapidel, B., de Tourdonnet, S., Valantin-Morison, M., 2009. Mixing plant species in cropping systems: concepts, tools and models. A review. Agron. Sustain. Dev. 29: 43–62. https://doi.org/10.1051/agro:2007057

Mikić, A., Ćupina, B., Rubiales, D., Mihailović, V., Šarūnaitė, L., Fustec, J., Antanasović, S., Krstić, D., Bedoussac, L., Zorić, L., Đorđević, V., Perić, V., Srebrić, M., 2015. Models, developments and perspectives of mutual legume intercropping. Adv. Agron. 130: 337-419.

Mínguez, I., Rubiales, D., 2020. Faba bean. Chapter 15, pages 453-482 in: Sadras V.O. & Calderini D.F. (eds.), Crop Physiology: Case Histories for Major Crops, Academic Press, ISBN 978-0-12-819194-1. https://doi.org/10.1016/B978-0-12-819194-1.00015-3

Sahile, S., Fininsa, C., Sakhuja, P.K., Ahmed S., 2008a. Effect of mixed cropping and fungicides on chocolate spot (*Botrytis fabae*) of faba bean (*Vicia faba*) in Ethiopia. Crop Prot. 27: 275-282.

Sahile, S., Ahmed, S., Fininsa, C., Abang, M.M., Sakhuja P.K., 2008b. Survey of chocolate spot (*Botrytis fabae*) disease of faba bean (*Vicia faba* L.) and assessment of factors influencing disease epidemics in northern Ethiopia. Crop Prot. 27: 1457-1463.

Sapoukhina, N., Tyutyunov, Y., Sache, I., Arditi, R., 2010. Spatially mixed crops to control the stratified dispersal of airborne fungal diseases. Ecol. Model. 221(23): 2793-2800. https://doi.org/10.1016/j.ecolmodel.2010.08.020.

SAS Institute, 2002. User's Guide. Statistics. Ver.9.0. Cary, N.C.

Schoeny, A., Jumel, S., Rouault, F., Lemarchand, E., Tivoli, B., 2010. Effect and underlying mechanisms of pea-cereal intercropping on the epidemic development of ascochyta blight. Eur. J. Plant Pathol. 126: 317-331.

Sharaiha, R., Haddad, N., Abu Blan, H., 1989. Potential of row intercropping of faba bean, potato, and corn on the incidence and severity of Alternaria leaf spot, late blight and rust under the Jordan Valley conditions. Phytopathol. Mediterr. 28: 105-112.

Sillero, J.C., Moreno, M.T., Rubiales, D., 2000. Characterization of new sources of resistance to *Uromyces viciae-fabae* in a germplasm collection of *Vicia faba*. Plant Pathol. 49(3): 389-395.

Sillero, J.C., Rojas-Molina, M.M., Emeran, A.A., Kharrat, M., Winkler, J., Khan, H.R., Flores, F., Rubiales, D., 2017. Identification and multi-environment validation of resistance to rust (*Uromyces viciae-fabae*) in *Vicia faba*. Crop Pasture Sci. 68: 1013-1023

Stoddard, F.L., Nicholas, A., Rubiales, D., Thomas, J., Villegas, A.M., 2010. Integrated pest management in faba bean. Field Crops Res. 115: 308-318.

Terefe, H., Fininsa, C., Sahile, S., Tesfaye, K., 2016. Effect of Integrated Climate Change Resilient Cultural Practices on Faba Bean Rust (*Uromyces viciae-fabae*) Epidemics in Hararghe Highlands, Ethiopia. J. Plant Path. Micro. 7: 8. doi: 10.4172/2157-7471.1000373

Villegas-Fernández, A.M., Amarna, A., Moral, J., Rubiales, D., 2017. Faba bean rust and pea powdery mildew management by intercropping with cereals and by cultivar mixture. In: Proceedings International Conference Advances in grain legume breeding, cultivations and uses for a more competitive value-chain, Novi Sad, Serbia, pg. 104.

Villegas-Fernández, A.M., Amarna, A., Moral, J., Rubiales, D., 2021. Crop diversification to control powdery mildew in pea. Agronomy 11: 690. https://doi.org/10.3390/agronomy11040690

Willey, R.W., 1979. Intercropping –Its importance and research needs. Part 2. Agronomy and research approaches. Field Crop Abs. 32: 73-85.

Yang, Z.X., Tang, L., Zheng, Y., Dong, Y., Dong, K., 2014. Effects of different wheat cultivars intercropped with faba bean on faba bean Fusarium wilt, root exudates and rhizosphere microbial community functional diversity. J. Plant Nutr. Fertilizer. 20: 570-579.

Zhang, C., Dong, Y., Tang, L., Zheng, Y., Makowski, D., Yu, Y., Zhang, F., van der Werf, W., 2019. Intercropping cereals with faba bean reduces plant disease incidence regardless of fertilizer input; a meta-analysis. Eur. J. Plant Pathol. 154: 931–942. doi: 10.1007/s10658-019- 01711-4.