

Article

Management of Rust in Wheat Using IPM Principles and Alternative Products

Lise Nistrup Jørgensen ^{1,*}, Niels Matzen ¹, Rebekka Leitzke ¹, Jane E. Thomas ², Aoife O'Driscoll ², Bettina Klocke ³, Claude Maumene ⁴, Ida Lindell ⁵, Kerstin Wahlquist ⁵, Līga Zemeca ⁶, Marcos Barberena Apesteguia ⁷, Biango Randazzo ⁸, Svetlana Slikova ⁹  and Sarah Holdgate ¹⁰

¹ Department of Agroecology, Aarhus University, Flakkebjerg, DK-4200 Slagelse, Denmark

² National Institute of Agricultural Botany, Cambridge CB3 0LE, UK

³ Julius Kühn Institute, 14532 Kleinmachnow, Germany

⁴ Arvalis Institut du Végétal, 91720 Boigneville, France

⁵ HIR Skåne, 237 91 Bjärred, Sweden

⁶ Institute for Plant Protection Research, Latvia University of Life Sciences and Technologies, LV-3001 Jelgava, Latvia

⁷ The Institute for Agrifood Technology and Infrastructures, 31610 Villava, Spain

⁸ Associazione Agricola Randazzo, 66100 Chieti, Italy

⁹ Narodne Pol'Nohospodarske a Potravinaskie Centrum, 951 41 Lužianky, Slovakia

¹⁰ Syngenta, Cambridge CB21 5XE, UK

* Correspondence: lisen.jorgensen@agro.au.dk

Abstract: Overall, there is a major wish that European farmers implement integrated pest management (IPM), particularly to reduce dependence on pesticides. In the European Rustwatch project, partners conducted nineteen trials across nine different countries during 2020 and 2021 to investigate different IPM strategies, focusing on controlling rust diseases in winter wheat. The trials included the use of varieties with contrasting levels of resistance, variety mixtures, reduced fungicide rates, thresholds, and Decision Support Systems (DSSs), and testing alternative products to fungicides. Sixteen trials developed yellow rust (*Puccinia striiformis* f. sp. *tritici*) infections, and six trials developed brown rust (*Puccinia triticina*) infections. Resistant varieties proved highly effective in keeping down yellow rust infection, and variety mixtures also effectively reduced infection levels and stabilized yields. Rust was fully controlled using 25% of standard fungicide rates, even under high disease pressure. Using DSSs provided sufficient control of rust diseases and resulted in competitive net economic returns due to fewer fungicide applications. The alternative products tested included two biological control agents and four alternative chemistries, which all gave inferior and insufficient control against rust compared with chemical fungicides. The trial work demonstrated that there are good and reliable options for including IPM into disease control in wheat.

Keywords: *Puccinia striiformis*; *Puccinia triticina*; decision support systems; variety mixtures; fungicides; biological control agents



Citation: Jørgensen, L.N.; Matzen, N.; Leitzke, R.; Thomas, J.E.; O'Driscoll, A.; Klocke, B.; Maumene, C.; Lindell, I.; Wahlquist, K.; Zemeca, L.; et al. Management of Rust in Wheat Using IPM Principles and Alternative Products. *Agriculture* **2024**, *14*, 821. <https://doi.org/10.3390/agriculture14060821>

Academic Editors: Anna Andolfi, Thomas Thomidis and Changjun Chen

Received: 16 December 2023

Revised: 21 February 2024

Accepted: 18 May 2024

Published: 24 May 2024



Copyright: © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

Wheat is a dominant cereal crop worldwide and very important as a staple food resource. Multiple diseases can develop in the crop and are a major threat to wheat production, including rust diseases (yellow rust caused by *Puccinia striiformis* f. sp. *tritici*, brown rust caused by *Puccinia triticina* and stem rust caused by *Puccinia graminearum*). All three rust diseases can cause yield reductions between 5% and 50%, depending on the year, region and developmental stage of wheat at the time the epidemic starts [1]. Following significant epidemics of yellow rust, major economic losses have been measured in Europe, Australia and the US [2,3]. No specific data exist that reflect the current economic importance of brown rust and stem rust.

Yellow rust is a major focus area for research and breeding programs due to the ability of the fungus to overcome race-specific resistance genes just within a few seasons, causing major changes in patterns of epidemics and subsequent yield losses [4]. Compared with, e.g., *Septoria tritici* blotch (*Zymoseptoria tritici*) in Northwestern Europe, yellow rust has been less of a problem in many countries due to the availability of sufficient genetic resistance in commonly grown varieties. However, *P. striiformis* capacity to generate new virulent races capable of overcoming varietal resistance has resulted in sudden epidemics in varieties previously regarded as resistant. Particularly, since 2010, new races are spreading widely and rapidly, causing severe yield losses [4]. This seismic change in the race structure of *P. striiformis* has increased the pressure on breeders to produce new wheat varieties that are resistant to these new races, but it has also put pressure on in-field crop management practices and the use of fungicides. At the outset of a potential yellow rust epidemic in the field, fungicide treatments are usually recommended as soon as the disease is observed to prevent a yield-reducing epidemic [5]. Several fungicides belonging to the chemical groups of azoles, strobilurins and SDHIs (succinate dehydrogenase inhibitors) are known to be effective against rust diseases. If treatments are applied at the very early stages of infection, reduced dose rates can be used and provide good control of yellow rust, whereas a delayed treatment has proved to be less cost-effective [6]. Yield losses and benefits from the use of fungicides strongly depend on the level of varietal resistance [7–9].

There is an overall aim and wish from policy makers to reduce the use of chemical pesticides and promote more sustainable cropping practices, stimulated by different directives and stricter legislation for authorisation of pesticides. In the EU, these aims are included in the Sustainable Use of Pesticides Directive (Directive 2009/128/EC of 21 October 2009), which is now part of legislation in EU Member States. A crucial element is the use of integrated pest management (IPM), as defined in the eight IPM principles [10]. This involves more focus on growing resistant varieties, inclusion of monitoring and decision support systems before application of pesticides and use of alternative disease control measures, including biological control agents (BCA). Despite intensification and promotion of IPM from national organisations, fungicides are still the main disease control strategy; typically, one to four treatments are applied per season depending on year, region and general practice [5,11].

Variety resistance is an important IPM tool against pest and diseases and is considered a cost-effective and environmentally friendly approach to control fungal diseases. Qualitative (major) resistance genes can confer full protection [12]. However, the deployment of varieties carrying the same genes across large areas creates strong selective pressure on pathogen populations. This pressure favours the emergence of virulent isolates capable of infecting plants that were hitherto resistant and increases the frequency of such isolates [13]. Along with the frequency of virulent isolates increasing, varietal resistance is eroded and will typically be considered to have broken down in a relationship commonly known as the boom-and-bust cycle [14]. The current challenge is, therefore, to identify and/or optimise agricultural practices to extend the lifetime of varieties' resistance to diseases. Cropping with variety mixtures has recently been noted as one method of reducing the selection pressure for new more virulent pathogen isolates [15].

BCAs and alternative chemistries are often considered to be less harmful than conventional fungicides due to fewer adverse health effects and negative impacts on the environment [16]. BCAs and alternative chemistries are also thought to have a lower risk of pathogens developing resistance due to their complex mode of actions. Only limited research has been carried out searching for BCAs and other alternative chemistries for the control of rust diseases under field conditions. Few field studies have shown that the use of *Bacillus subtilis* (now called *Bacillus amyloliquefaciens*) against different pathogens like yellow rust and powdery mildew (*Blumeria graminis*) gives low to moderate levels of disease control and higher variability on control compared with synthetic fungicides [17,18].

Currently, only a few specific decision support systems (DSSs) addressing the control of rust diseases in wheat have been adopted within farming practices, where decisions

on rust control during the season rely on scouting or national monitoring systems. Crop Protection Online is an example of a DSS combining control thresholds for all major diseases in wheat into one system [19]. Yellow rust is considered a high priority disease, as such the control threshold is very low, and control measures are recommended when 1–10% of the plants are infected (disease incidence).

The current study presents results from the Horizon 2020 project Rustwatch, which, among other elements, aimed at searching for a better IPM-based control of rust diseases in wheat. In this part of the project, we investigated options for replacing conventional fungicides with BCAs or alternative substances. Secondly, we designed specific IPM trials placed across Europe, testing the efficacy of different IPM elements. These included different varieties with contrasting levels of resistance, the effects of growing variety mixtures, the potential for reducing fungicide rates or using alternative chemistries and BCAs and using DSSs as a basis for when to apply fungicides.

2. Methods and Materials

2.1. Search for Alternative Control Products to Fungicides

Four field trials were conducted in 2019 in four countries (UK, DE, DK and FR), which tested the same eight products listed in Table 1. Two treatments (2 and 3) included fungicides with known efficacy on rust diseases, but these were applied at very reduced rates. The efficacy on rust of the other test products were unknown but picked based on seen efficacy on other pathogens. The dose applied using chitosan was variable depending on the water volume applied, as 1 g of product was used per litre.

All four trials were conducted in moderately susceptible to susceptible varieties. Details on treatments, varieties and disease severity is provided in Table 2. The trials used randomised block design with either two, three or four replicates. In all four trials, the plots were treated four times with the same products. To increase disease pressure in the German and the Danish trials, they were artificially inoculated using spreader plants with virulent yellow rust strains at the beginning of April.

Table 1. Active ingredients used in the field trials for control of yellow rust. Treatment nos. 1–9 cover the substances used in the search for alternative substances in 2019. Products were applied at four timings with ca. 10 day intervals. A: growth stage (GS) (BBCH) 31–32; B: GS 33–37; C: GS 45–51; D: GS 61–65. The products annotated IPM were used in the IPM trials carried out in 2020 and 2021, as given in Table 3. Specific products were provided from France (FR) or Denmark (DK) or by local providers from the international chemical companies.

Treatment No.	Product Name and Dose/ha	Active Content	Provider of Products
1	Untreated (Control)		
2	0.25 L Folicur EW 250	Tebuconazole (250 g/L)	Bayer Crop Science
3	0.1 L Comet Pro	Pyraclostrobin (200 g/L)	BASF AG
4	3.0 kg Phosphate	DSPF 016 (K ₂ HPO ₃)	DE Sangosse, FR
5	3.0 kg Phosphate + 3.5 L Sulphur	DSPF 016 (K ₂ HPO ₃) + DSPF 011 (Sulphur)	DE Sangosse, FR
6	4.0 L Serenade ASO + 0.1% Silwet	<i>Bacillus amyloliquefaciens</i>	Bayer Crop Science
7	0.1–0.2 kg Chitosan (1 g/L water)	D-glucosamine + N-acetyl-D-glucosamin	Santos Carballal, FR
8	3.0 kg Trium P	<i>Trichoderma harzianum</i> T-22	Bioplant, DK
9	7.0 L Sulphur	DSPF011 (Sulphur)	DE Sangosse, FR
IPM-trial	0.75 L Balaya	Mefenitruconazole + pyraclostrobin (100 + 100 g/L)	BASF AG
IPM-trial	0.5 L Elatus Era	Prothioconazole + benzovindiflupyr (150 + 75 g/L)	Syngenta
IPM-trial	0.6 L Comet Pro	Pyraclostrobin (200 g/L)	BASF AG
IPM-trial	0.5 L Folicur EW 250	Tebuconazole (250 g/L)	Bayer Crop Science
IPM-trial	2.0 L Prev-gold	Orange oil 60 g/L	ORO Agri International, FR

Table 2. Trial information from the four trials carried out in 2019 testing different BCAs and alternative chemistries. Data include country, variety, timing of fungicide applications, severity of yellow rust disease and information on harvest.

Country	Variety	Fungicide Timings	Level of Yellow Rust on Flag Leaf/2nd Leaf by Late Season	Harvest
France	Grapeli	9/4; 16/4; 29/4; 7/5	63%/93%	Major yield responses
UK	Reflection	23/4;10/5; 20/5; 29/5	29%/100%	Major yield responses
Germany	Rumor	30/4; 14/5; 24/5; 7/6	0.1%/0.1%	No clear yield response
Denmark	Kalmar	25/4/6/5; 20/5: 3/6	20%/5%	No harvest

The French trial was carried out in Boigneville, south of Paris. The plot size was 11.3 m², with three replicates. The crop was sown on the 25th of October 2018 and harvested on the 31st of July. The UK trial was conducted near Cambridge in the east of England. Plot size was 24 m² in each of the four replicates. The crop was sown on the 24th of October 2018 and harvested on 21st August 2019. The German trial was carried out in Dahnsdorf (Brandenburg). Plot sizes were 13 m² and four replicates were laid out. The trial was sown at the end of September 2018. The trial was harvested on the 18th of July. The Danish trial was carried out near Slagelse, using small plots of 6.3 m² and two replicates. The trial was sown on the 28th of September 2018 and this trial was not taken through to harvest.

2.2. IPM Split-Plot Trials

Different IPM strategies were evaluated using different control strategies to quantify the yield and economic impacts of rust infection and assess options for minimising disease outbreaks and associated yield losses. Winter wheat crops were planted in the autumn months 2019 and 2020, respectively, and were monitored through the 2020 and 2021 summer seasons. Nineteen trials were carried out in the following nine countries: AU (Denmark), HIR (Sweden), LLU (Latvia), INTIA (Spain), AS.A.R. (Italy), NIAB (UK), NPPC (Slovakia), JKI (Germany) and ARVALIS (France).

The locations of the trials are visualised in Figure 1. All countries involved are known to regularly or occasionally have problems with rust infections in wheat. With the exception of the Italian wheat, which used durum wheat, trials were carried out in soft wheat. All partners used a split-plot design, with varieties as the main factor and fungicide treatments as the secondary factor. Depending on the locality, three or four replicates were included. Each trial included a rust-susceptible variety, a variety with a lower risk of severe disease development (a moderately susceptible variety (slow rust)), a rust-resistant variety and a mixture of these three varieties. For each of the varieties, the following strategies were applied: (1) untreated control, (2) full fungicide program using four times 50% of the standard dose rates of different fungicides (treatment frequency (TF) = 2), (3) similar to treatment two but using reduced dose rates, four times of 25% standard rates (TF = 1), (4) treatment using alternative chemistries and BCAs and (5) strategy where DSSs were used as the basis for when application should take place. The calculation of treatment frequency (TF) was calculated using the total input of fungicides per hectare, based on standard dose rates of active ingredients, as given by Kudsk et al. [20].

All partners followed a similar trial protocol (Table 3), with the choice of varieties adjusted to fit local practices. First application took place at GS 31–32 and the following three applications with ca. 10 day intervals. The DSS applied was also adjusted to local conditions. This strategy proved slightly difficult to summarise, as, in some countries, only rust was included in the decision making, while others also included the control of *Septoria tritici* blotch (STB) (*Zymoseptoria tritici*). To ensure infection of yellow rust, 9 of the 19 trials were artificially inoculated with yellow rust using spreader plants once or twice in spring. All trial details are shown in Tables 4, S1 and S2.



Figure 1. Locations of IPM rust trials in 2020 and 2021.

Table 3. Treatments in the IPM Rustwatch trial with five treatments in the three varieties and the variety mixture carried out in 2020 and 2021. The active components of the products are listed in Table 1. GS—growth stage (BBCH).

Treatments	GS 31–32	GS 33–37 +10 Days	GS 45–51 +10 Days	GS 65 +10 Days
1. Untreated control				
2. High input	0.6 L Comet Pro	0.75 L Balaya	0.5 L Elatus ERA	0.5 L Folicur
3. Low input	0.3 L Comet Pro	0.375 L Balaya	0.25 L Elatus ERA	0.25 L Folicur
4. Alternative products *	7.0 L Sulphur	4.0 L Serenade ASO	7.0 L Sulphur	4.0 L Serenade ASO
5. Sprayed following DSS				

* In 2021, 2.0 L Prev-gold was used as the alternative chemistry in all four applications.

Table 4. Information on individual varieties included in the IPM trials in 2020 and 2021.

Country	Resistant Varieties	Moderately Susceptible Varieties (Slow Ruster)	Susceptible Varieties	Year
DK	Informer	Sheriff	Benchmark	2020/2021
SW	Informer	Julius	Memory	2020/2021
FR	KWS Extase	LG Absalon	Amboise	2021
UK	Crusoe	KWS Zyatt	JB Diego/Skyfall	2020/2021
DE	Informer	Sheriff	Rumor	2020/2021
SK	PS Jeldka	PS Puqua	PS Sunanka	2020/2021
LA	Informer	Kalmar	Julius	2020/2021
ES	Nudel	Filon	Camargo	2020
ES	Mufasa	Marco polo	Camargo	2021
IT	467175	Aureo	Monastir	2020/2021 (SR)
IT	Iride	Monastir	Tirex	2020/2021 (YR)

Disease assessments were carried out following the EPPO guideline 1/26 (4) [21]. Individual leaf layers were assessed as % of symptomatic leaf area approximately every ten days starting at first application. However, mainly assessments carried out at growth stage (GS) 65 and 75 were included in the analysis. Disease severity scores in individual trials are shown in Table S1.

Trials were harvested and grain yields were measured for each plot, which were adjusted to 85% dry matter. Additionally, grain quality parameters like specific weight, thousand grain weight (TGW), % protein and % gluten content were measured in some trials (15 trials with TGW, 14 trials with % protein, 16 trials with specific weight and 8 trials with gluten). Protein and gluten content, as well as specific weight, were measured using near infrared spectroscopy (NIRS) (e.g., Infratec 1241 Grain Analyzer from Foss, Hillerød, Denmark), while TGW was measured using a seed counter (e.g., Contador, Pfeuffer GmbH, Kitzingen, Germany), followed by weighing. The overall effects of varieties and mixtures on grain quality were summarised across all trials. In this analysis, data from untreated control and alternative chemistry were merged (Group 1), as they did not differ significantly with respect to disease severity and yields. Similarly, the high and reduced dose rates with fungicides were grouped (Group 2) because of even performances, while the treatments based on DSSs were kept out of this analysis.

To determine whether any economic benefits were gained from increases in yield, the cost of treatments was calculated. As the costs vary across Europe, a standard cost was estimated based on the following: grain price of 20 EUR/dt; cost of high fungicide dose per treatment plus cost of application reached 41.60 EUR/ha (2.08 dt/ha), which gave a cost equivalent to 8.32 dt/ha for four applications; cost of low dose fungicide per treatment equalled 1.26 dt/ha per application, leading to a cost of 5 dt/ha using four treatments; alternative product cost per treatment was estimated equal to the cost of the full chemical treatment, being equal to 8.32 dt/ha using four applications. The cost of the DSS treatments varied widely across the trials, but across all trials, the cost was fixed to 4.16 dt/ha in total, equivalent to two applications in susceptible varieties, one application in the mixtures and slow rusters equivalent to 2.1 dt/ha and only 0.5 application in the resistant variety equivalent to 1.05 dt/ha.

2.3. Statistical Analysis

The rust disease severity and yield performance were analysed for all combinations using the Student–Newmann–Keuls method ($p = 0.05$) with Agricultural Research Management (ARM 2021) software (Gylling Data Management, Inc., Brookings, SD, USA).

The effects on grain quality parameters were analysed across all trials using R for the statistical analyses. This was performed using RStudio version 1.2.5019 [22], with $\alpha = 0.05$ for all tests.

3. Results

3.1. Search for Alternative Control Products to Fungicides

In 2019, only three of the four trials used for screening the efficacy of alternative products developed yellow rust. The French trial developed a severe yellow rust attack, starting mid-April. The final assessment, conducted 20 days after the final application, conveyed that the disease control from the alternative solutions was not significantly different from untreated, while both conventional fungicides significantly reduced disease levels (Table 5). Four applications with Folicur (tebuconazole) increased yields by 44 dt/ha and with Comet Pro (pyraclostobin) by 19 dt/ha; the rest of the treatments did not alter yields compared with the untreated control. Yellow rust infection developed in the UK trial by the start of the first treatment applications in mid-May. Efficacy from these treatments was observed from the 25th of June, ca. one month after the last application (Table 5). Again, no clear effects were seen from the alternative products at any of the assessment dates. Yields in the trial were relatively low, with untreated controls only yielding 28.6 dt/ha. While none of the alternative treatments provided significant yield increases, the best treatment using four times 25% rate of tebuconazole provided ca. 40 dt/ha in yield increases (Table 5). The Danish trial developed moderate levels of yellow rust infection (20% on the flag leaf at GS 73). The alternative products tested gave between 20% and 50% control as an average of the two replicates (Table 5). In the German trial, no significant

infection of yellow rust developed despite inoculation of the trial site, the main reason being extreme drought conditions.

Table 5. Screening the efficacy of alternative products for yellow rust control in winter wheat. Data from three trials carried out in the UK, France and Denmark in 2019. Yellow rust data are presented as the average disease on the 2 upper leaves at GS 73–75 (flag leaf and 2nd leaf), assessed 20–30 days after last application. Figures followed by different letters indicate significant differences at 95% level.

	% Yellow Rust on Upper Two Leaves			Yield dt/ha	
	Denmark	France	UK	France	UK
Untreated control	20.0 a	78.0 a	56.4 a	37.98	28.58
0.25 L Folicur EW	0.05 d	0.1 c	4.0 c	83.39	68.36
0.1 L Comet Pro	2.5 c	26.0 b	47.7 b	57.09	40.57
3.0 Phosphonate	15.0 ab	75.5 a	57.0 b	38.56	29.68
7 L Sulphur	16.0 ab	78.0 a	58.0 b	36.75	31.79
4 L Serenade ASO	12.5 b	74.3 a	57.5 b	38.62	29.47
3 kg Trianum P	10.0 b	78.0 a	60.0 b	36.75	29.67
3 kg Phosphonate + 3.5 L Sulphur	11.5 b	74.0 a	58.0 b	38.51	29.41
0.1–0.2 kg Chitosan	13.5 ab	78.0 a	62.5 b	35.52	27.62
LSD ₉₅ values				3.6	4.0

Different letters indicate significant differences between means ($p < 0.05$).

The results from the three trials with significant levels of yellow rust infection were similar. The tested alternatives showed low and/or inferior control even in comparison with very reduced dose rates of tebuconazole or pyraclostrobin (Figure 2). Two of the trials also showed significantly positive yield responses to conventional fungicides, while only minor yield increases were observed in any of the tested alternatives.

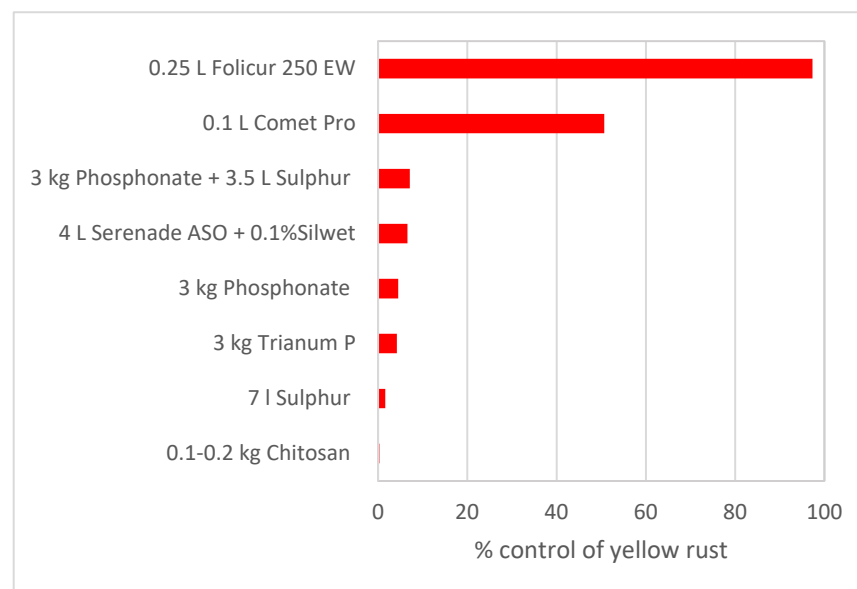


Figure 2. Cont.

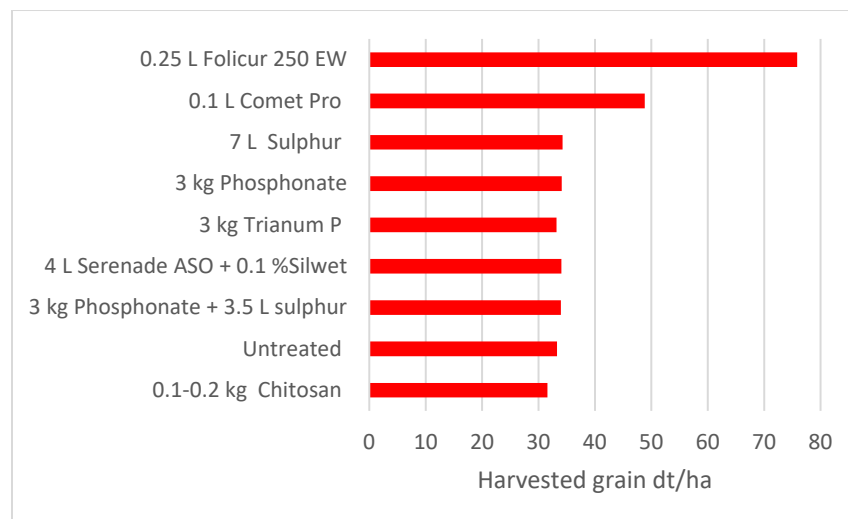


Figure 2. (Top): Control of yellow rust (%) using different fungicides and alternatives to fungicides applied at four timings. The disease was assessed on the two upper leaves. Average of three trials carried out in France, UK and Denmark in 2019. **(Bottom):** average Yields (dt/ha) from two trials in France and UK following four applications with different treatments. $LSD_{95} = 3.2$.

3.2. IPM Trials: Disease Data

The Rustwatch partners conducted 19 trials in nine different countries during 2020 and 2021 following a similar trial protocol. Yellow rust and brown rust developed differently: 16 trials had significant yellow rust infection, 6 trials developed a low to moderate infection of brown rust, and 1 trial experienced very minor levels of stem rust, which was too minor to be addressed specifically. Overall disease developments of rust varied more by site and cultivar than by year, which statistically gave no reason to separate data by year. As expected, the varieties categorised as susceptible had the highest level of yellow rust. The moderately susceptible varieties low to moderate disease, in line with the mixture, and no or very little rust was seen in the resistant cultivar (Figure 3).

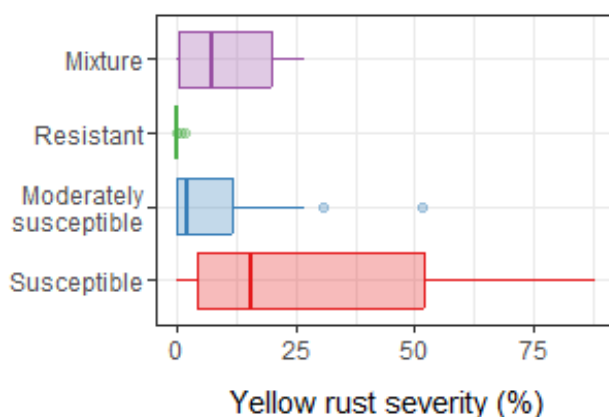


Figure 3. Distribution of yellow rust severity in untreated control plots in 16 winter wheat trials conducted during 2020 and 2021. Data represent the three variety groups and the mixture of the three. Assessments are scored between GS 73 and 77 on the two upper leaves.

Variable levels of control were achieved from the four different control strategies (Table 6). The high input treatments ($TF = 2$), involving four applications, provided good control of yellow rust in all trials. The strategies using reduced rates ($TF = 1$), also provided good control, even in the most susceptible varieties. The strategy using alternative products, with Serenade ASO and Sulphur in 2020, or Orange-oil in 2021, provided insufficient control of rust. The strategy using DSSs as guidance for treatment applications provided

good control and reduced the number of applications, in some cases to no applications, depending on the variety's susceptibility and the trial location (Table S2). The average level of infection over the three solo varieties was greater than that seen in the variety mixture (Table 6). In untreated plots, the % of yellow rust infection in the mixtures was reduced by 62% and 29%, respectively, at the two timings presented, compared with the average of the individual components in the mixtures.

Table 6. Average yellow rust severity (%) assessed at growth stage GS 65 on leaf 2 in 11 trials (top) and at GS 75 on leaf 1 in 16 trials (bottom) from 2020 and 2021.

Yellow Rust, GS 65, Varieties	Untr. Control	4 × ½ Rates Fungicides	4 × ¼ Rates of Fungicides	4 × Alternative Products	Treatments according to DSS
Mixtures	1.7	0	0	1.2	0.9
Susceptible	9.5	0.01	0.06	6.7	1.6
Moderately susceptible	3.9	0	0	3.5	0.6
Resistant	0.01	0	0	0.03	0.1
Avg. single varieties	4.5	0.0	0.02	3.4	0.9
LSD ₉₅ 1.3; standard deviation: 2.9					
Yellow Rust, GS 75 Varieties	Untr. Control	4 × ½ Rates Fungicides	4 × ¼ Rates of Fungicides	4 × Alternative Products	Treatments according to DSS
Mixtures	10.0	0.1	0.4	9.1	3.6
Susceptible	31.8	0.7	0.7	25.6	6.4
Moderately susceptible	10.2	0.1	0.5	7.9	2.5
Resistant	0.2	0.1	0.1	0.2	0.4
Av. single varieties	14.1	0.3	0.4	11.2	3.1
LSD ₉₅ 1.9; standard deviation: 5.0					

The six trials that developed brown rust infections (Table 7) had on average 3.5% of disease in the untreated, with the maximum disease severity in an individual trial reaching 15% on flag leaves. All tested varieties developed low to moderate brown rust disease. Both the treatments with high and reduced input of fungicides provided full control of brown rust in all trials. The strategy using alternative products provided insufficient control of brown rust. The strategy using a DSS as guidance for treatments achieved only moderate control. This might be a result of recommendations mainly having focused on yellow rust control and not on brown rust. The severity of brown rust in the variety mixtures compared with the average of the three components was either similar or slightly lower. On average, brown rust infection levels in the mixtures' untreated plots had an 11% disease reduction compared with the average of the individual varieties.

Table 7. Average brown rust severity (%) assessed on flag leaf at GS 75 in six trials from 2020 and 2021.

Brown Rust, GS 75 Varieties	Untr. Control	4 × ½ Rates Fungicides	4 × ¼ Rates of Fungicides	4 × Alternative Products	Treatments according to DSS
Mixtures	3.1	0.0	0.0	2.4	1.0
Susceptible	3.5	0.0	0.1	2.3	1.3
Moderately susceptible	3.8	0.0	0.0	2.8	0.5
Resistant	3.3	0.1	0.0	1.7	1.5
Av. single varieties	3.5	0.05	0.0	2.3	1.1
LSD ₉₅ : 0.7; standard deviation: 0.7					

Six trials also developed septoria tritici blotch (STB), with ca. 16% infection on leaf 2 (leaf 1 from the top) and 8% on the flag leaf (Table 8). All treatments provided some control of this disease, showing similar control patterns as for rust diseases. For STB, infection levels in the variety mixtures were not reduced compared with the average infection levels observed in the three varietal components of the mixture. One trial also developed significant infection of tan spot, with 15% severity on leaf 2 (data not included).

Table 8. Average Septoria tritici blotch severity (%) assessed on flag leaf at GS 75 in six trials from 2020 and 2021.

Septoria, GS 75	Untr. Control	4 × ½ Rates Fungicides	4 × ¼ Rates of Fungicides	4 × Alternative Products	Treatments according to DSS
Varieties					
Mixtures	8.1	0.9	1.6	7.3	5.8
Susceptible	5.7	1.7	2.5	5.3	2.8
Moderately susceptible	1.5	0.7	1.2	1.6	0.9
Resistant	5.4	1.1	1.5	2.6	2.9
Avg. single varieties	4.2	1.2	1.7	3.2	2.2

LSD₉₅: 1.6; standard deviation: 2.5

3.3. Yield Effects

All 19 trials were harvested, and average yield data are shown in Table 9. The yield variation of the untreated varieties is shown in Figure 4, showing an overall lower yield in the most susceptible varieties. Depending on the susceptibility of the variety, yield increases from the better treatments varied between 5 and 15 dt/ha. Yield increases from the most effective treatments in the most susceptible variety, the moderately susceptible variety and the resistant variety were 14 dt/ha, 8 dt/ha and 5 dt/ha, respectively. Slight differences were measured between high and low fungicide input, although the overall output did increase slightly, but not significantly, using a higher input. Treatments using alternative products did not yield significantly differently from untreated. Treatments following DSSs gave statistically significant increases, but these increases were below the standard treatments using either high or low input. In 8 of the 19 trials, where severity of yellow rust was higher than 20%, the corresponding yield responses were also higher (Table 9). The yield increases in these trials with the most susceptible varieties, the moderately susceptible varieties and the resistant varieties were 27 dt/ha, 15 dt/ha and 10 dt/ha, respectively.

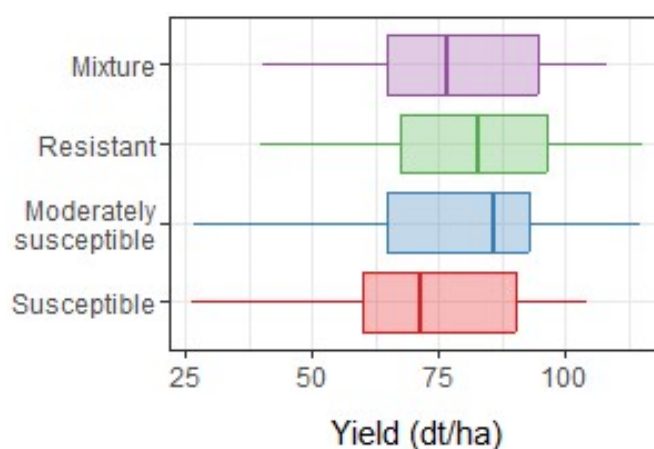


Figure 4. Variation of yield in untreated control in the 19 trials in 2020 and 2021. Data represent the three variety groups and the mixture of the three.

Table 9. Yields (dt/ha) in 19 trials across two seasons in 2020 and 2021 with average data from all trials (upper portion). Lower portion are data from eight trials with more than 20% of yellow rust. Numbers in bracket show relative yields (%) within the same variety group.

Yield dt/ha, 19 Trials	Untr. Control	4 × ½ Rates Fungicides	4 × ¼ Rates of Fungicides	4 × Alternative Products	Treatments according to DSS
Varieties					
Mixtures	78.7 (100)	87.9 (112)	86.7 (110)	78.4 (100)	83.8 (106)
Susceptible	72.1 (100)	86.8 (120)	86.3 (120)	73.9 (102)	82.9 (115)
Moderately susceptible	78.1 (100)	86.7 (111)	85.3 (109)	78.2 (100)	83.0 (106)
Resistant	81.3 (100)	86.9 (107)	86.5 (106)	82.8 (102)	83.1 (102)
Avg. single varieties	77.2 (100)	86.8 (112)	86.0 (111)	78.3 (101)	83.0 (108)
LSD ₉₅ = 1.9; standard deviation: 4.9					
Yield dt/ha, 8 Trials	Untr. Control	4 × ½ Rates Fungicides	4 × ¼ Rates of Fungicides	4 × Alternative Products	Treatments according to DSS
Varieties					
Mixtures	84.5 (100)	100.8 (119)	99.7 (118)	85.9 (102)	94.1 (111)
Susceptible	73.2 (100)	100.9 (138)	99.3 (136)	75.0 (102)	92.4 (126)
Moderately susceptible	85.7 (100)	100.8 (118)	97.8 (114)	86.1 (100)	96.7 (113)
Resistant	91.7 (100)	101.6 (111)	100.8 (110)	93.7 (102)	93.8 (102)
Avg. single varieties	83.5 (100)	101.1 (121)	99.3 (119)	84.9 (102)	94.3 (113)
LSD ₉₅ = 2.7; standard deviation: 5.1					

The average yield benefit gained from the variety mixture compared with the average of the single varieties was 1.5 dt/ha (1.9%) in untreated plots across all 19 trials, while yield benefits were lower (ca. 1%) in the treated plots. In the eight trials with most severe disease, the yield benefit in untreated was 1 dt/ha (1.2%), while no yield benefit was seen in the treated plots.

3.4. Net Yield: Economical Return

Based on the calculated cost of treatments and net yields measured as dt/ha, the economic benefit (EUR) was calculated for the different treatment programs (Table 10). Both fungicide treatment programs (on average) provided a positive economic benefit, although the high input program did not provide an economic benefit in the resistant variety. The reduced rate program (TFI = 1) provided overall a better economic return than the high input program. The use of alternative products gave a negative economic return due to the lack of yield increases. Treatments according to DSS also gave good yield responses in line with the low input fungicide strategy. The eight trials with more severe levels of yellow rust showed generally better net economic returns from the low fungicide input strategy, although differences between the DSS strategy and the higher and lower input were limited.

Table 10. Average yield (untreated) and net yield increases (benefit) (dt/ha) in 19 trials across two seasons in 2020 and 2021 (top), and 8 trials with significant levels of yellow rust (below) (the cost of application and chemistry has been deducted).

Yield dt/ha, 19 Trials	Untr. Control	4 × ½ Rates Fungicides	4 × ¼ Rates of Fungicides	4 × Alternative Products	Treatments according to DSS
Varieties					
Mixtures	78.7	1.0	3.0	−8.5	3.0
Susceptible	72.1	6.5	9.2	−6.4	6.6
Moderately susceptible	78.1	0.4	2.2	−8.1	2.8
Resistant	81.3	−2.6	0.2	−6.7	0.8
Average benefit		1.3	3.6	−7.4	3.3
Yield dt/ha, 8 Trials	Untr. Control	4 × ½ Rates Fungicides	4 × ¼ Rates of Fungicides	4 × Alternative Products	Treatments according to DSS
Varieties					
Mixtures	84.5	8.1	10.2	−6.8	7.5
Susceptible	73.2	19.5	21.1	−6.4	15.0
Moderately susceptible	85.7	6.9	7.1	−7.8	8.9
Resistant	91.7	1.7	4.0	−6.2	1.1
Average benefit		9.1	10.6	−6.8	8.1

The economic benefit from treating a very rust-susceptible variety with a fungicide program was ca. 20 dt/ha (=400 EUR/ha), highlighting the necessity for an urgent response during a rust outbreak. In the resistant varieties where no yellow rust infection was observed, fungicide treatment using high rates resulted in a negative net yield of 2.6 dt/ha (=52 EUR/ha) when investigated across all trials.

3.5. Impact on Yield Grain Parameters

The impact of varietal resistance and treatment programs on grain quality parameters was investigated separately, with the analysis summarised in two groups. In the untreated group, both untreated controls and alternative treatments were included, as yield data did not differ significantly for these two. The second group used fungicide treated data, summarising data from both high and low input programs, as these two data sets also did not differ significantly. Data from Group 1 showed clear and significant differences for yield, specific weight and TGW, where the results from susceptible varieties were lower in yield and grain qualities than both mixtures and more resistant varieties (Table 11). The results from mixtures and moderately susceptible varieties were similar and did not differ significantly. Results from Group 2 with the fungicide treated data showed overall higher values for yield, specific weight and TGW than data from Group 1. No significant differences were seen between the varieties for yield and specific weight, but some overall differences for TGW were observed. There were no significant differences in either group for % protein and % gluten content, although the latter was only measured in 8 of the 19 trials.

Table 11. Yield (dt/ha) and grain quality parameters in 19 trials across two seasons (2020, 2021). Group 1 covers both untreated and treatments from alternative substances, while Group 2 includes data from treatments with both high and low fungicide input. Different letters indicate significant differences at 95% level.

Group 1, Varieties	Yield dt/ha	Gluten Content %	Protein Content %	Specific Weight kg/100 L	TGW g
Mixtures	81.0 b	22.3 a	12.5 a	77.2 a	40.9 b
Susceptible	73.1 c	22.0 a	12.3 a	75.6 b	37.8 c
Moderately susceptible	82.5 b	21.8 a	12.5 a	76.4 a	40.4 b
Resistant	85.9 a	21.6 a	12.5 a	76.9 a	42.7 a
No of trials	(19)	(8)	(14)	(16)	(15)
Group 2, Varieties	Yield dt/ha	Gluten Content %	Protein Content %	Specific Weight kg/100 L	TGW g
Mixtures	89.2 a	22.1 a	12.5 a	77.9 a	42.3 b
Susceptible	89.3 a	21.7 a	12.3 a	78.0 a	39.4 d
Moderately susceptible	89.4 a	21.4 a	12.4 a	77.7 a	40.7 c
Resistant	88.6 a	22.1 a	12.7 a	77.4 a	43.7 a
No. of trials	(19)	(8)	(14)	(16)	(15)

4. Discussion

The results from this project indicate that good IPM options exist for the management of rust diseases, reducing disease risk, severity of rust diseases and helping to minimise the reliance on fungicides. The options assessed can readily be adopted by farmers and, for some elements, this is already taking place. The optimal strategy for avoiding an epidemic of rust in wheat should be based on combined IPM elements, including both varieties with good disease resistance, use of fungicides at appropriate rates, inclusion of alternative chemistries, monitoring and use of DSS all in line with EU-IPM strategies [10].

In the IPM trials, full control was achieved from a conventional fungicide four-spray program using both high and low input (Table 6). In comparison, the control from the

strategy with alternative products using four treatments gave only poor and generally insufficient control, verifying that there is still a major need to find relevant alternatives to conventional fungicides, as clarified in the more detailed study also presented in this paper (Figure 2). The use of decision support systems (DSS) provided reliable and good control of yellow rust and showed good opportunities for using a reduced number of applications.

4.1. Variety Resistance

Genetic resistance is the most efficient and cost-effective way to control rust diseases. As expected, the varieties categorised as susceptible developed the most severe infections of yellow rust. Moderately susceptible varieties developed intermediate levels of infection, in line with the variety mixture. No or very little rust was seen in the resistant varieties. The disease development was not secured in all the trials. Despite artificial inoculation with yellow rust in 9 of the 19 trials using infected spreader plants, only 4 of those developed moderate to severe attack, indicating that the weather conditions following inoculation are important for the success of these methods.

Brown rust infection was more even across all variety groups, as varieties were not specifically chosen based on their brown rust resistance characters. Two trials in Sicily focused on stem rust management, but the disease level stayed too low for any conclusions to be made.

Overall, the trials showed a benefit from growing varieties with strong yellow rust resistance and that choosing a rust susceptible variety had a major risk for yield losses. In line with data presented in this paper, yield losses and benefits from use of fungicides are strongly dependent on the level of varietal resistance [7–9]. So far, more than 80 resistance genes for both yellow and brown rust have been identified separately [23,24], but the frequent emergence of new virulent races necessitates a continuous search for new sources of resistance, underpinned by qualitative (major gene resistance) or quantitative trait loci (QTL).

Although many commercially available winter wheat varieties have effective genetic resistance to yellow rust and brown rust [25–27], it is often not known which resistance genes are present in individual varieties. Without doubt, the long-term success of IPM strategies against rust diseases in wheat relies on the provision of varieties that can resist against ever-evolving virulence in rust pathogens. Most recently, this was highlighted by Bouvet et al., [28], who presented new sources of resistance based on next-generation breeding techniques and the use of molecular markers. In addition to the provision of resistant varieties, sustainable use of these varieties, e.g., by regional diversification, should also be considered to prevent pathogen adaptation for as long as possible by reducing selection pressure.

4.2. Variety Mixture Effects

The tested variety mixtures, which included a mix of the three solo varieties, helped to reduce infection severity of both yellow rust and brown rust when measured against the average infection in individual varieties. In untreated plots, yellow rust severity at GS 75 was reduced by 29% and brown rust by 11% with the use of variety mixtures. Similar benefits from variety mixtures have been seen in other projects for yellow rust [29–31] and brown rust [32,33].

In this study, the decrease in rust provided by variety mixtures was in line with the moderately resistant variety but inferior to the resistant varieties (Table 6 and Figure 3). The trials also showed a relatively limited yield benefit from the mixtures mainly in untreated control plots. Data in other studies have shown that variety mixtures can effectively suppress diseases in crops, resulting in yield increases typically in the range of a few percent [34–36]. Using a variety mixture to suppress or reduce disease has been found to work successfully for both powdery mildew and rust diseases of wheat [37], while reductions in STB have been lower, usually in the range of 10–15% [36,38,39]. Borg et al. [40] summarised the major mechanisms of disease reduction in mixtures as

a cause of (i) dilution, (ii) barrier, (iii) premunition (induced resistance), (iv) disruptive selection and (v) compensation.

Variety mixtures are a means of stabilising cropping situations and reducing the risk of yield loss in high disease pressure years where there is a sudden incursion or epidemic of foliar pathogens. For organic farmers, variety mixtures are an additional tool to help maintain robustness and resilience in their cropping situations. Among conventional farmers, variety mixtures can typically reduce the number of necessary fungicide treatments by one [41]. In breeding programs, which must stay ahead of emerging virulent pathogens, variety mixtures could potentially bolster or substitute the need for laborious crossing and selection that is required for the genetic pyramiding of resistance genes [42]. It could be expected that the long-term viability of disease resistance provided by a variety mixture potentially allows the mixture to have longer commercial viability than any sole variety. A commonly expressed concern of farmers with respect to choosing variety mixtures is the reduced uniformity in terms of maturity, height and resistance to multiple disease, which can challenge management of the crops [43]; however, these factors can be managed by choosing mixture partners with similar agronomic traits based on data from local and regional variety trials.

4.3. Fungicides with Use of Appropriate Rates

When protecting wheat crops from losses due to yellow rust and other leaf diseases, it is particularly important to ensure that the two upper leaves are kept free from infection as they generate ca. 45% of the final grain yield [44]. In years where a rust epidemic develops in early spring, it is important that new leaves are protected during stem elongation. This might lead to repetitive applications every 10–14 days. The need for continuous protection is also the reason behind the standard treatments in the IPM trials presented here, where four timings with ca. 10 day intervals were used to ensure continuous control, leaving no gap for outbreaks of rust (Tables 6 and 7).

Preventive fungicide applications with reduced dose rates proved to be a good option to reduce inputs while achieving full control and thus a better net yield. The good control from reduced rates confirms previous findings similarly proving that rust in most cases can be also controlled with reduced rates [6,8]. The most crucial element when it comes to optimal rust control is ensuring correct timing.

The governing principle of resistance evolution suggests that diverse choices of mode of actions combined with reduced and optimised dosages lead to slower evolution of resistance than the use of full recommended doses [45], unless the reduction in dose leads to an increase in the number of applications. This was also the principle behind the choice of the four fungicides applied in the IPM trials. In treatments applied based on the DSS output, the number of applications was reduced and varied depending on site and variety from zero to three applications, using 25% to 50% standard dose rates successfully. In the DSS-treated plots, the benefit to fungicide resistance management is expected to have been maximised, although, at some sites, benefits related to variety resistance were not fully addressed when diversifying the input.

Despite some seasons with intensive use of fungicides for control of particularly yellow rust and warnings about potential resistance development [46], no case of field failure of fungicides in a cereal rust disease has yet been recorded. From a historical perspective, rust diseases in cereals have not been observed to be at substantial risk of developing fungicide resistance to the applied fungicides. However, recently, a high proportion of yellow rust isolates from China and New Zealand were found to carry a DMI resistance-associated substitution (Y134-F) in the Cyp51 gene, and some resistance to SDHIs have also been reported (SdhC -I85V), [47]. Both cases had no clear impact on field performance, but it does highlight that a diverse choice of fungicides is important to ensure a low risk for selection.

4.4. Alternative Products to Fungicides

Currently, limited information is available about alternatives that can fully or partly replace conventional fungicides for control of rust diseases in practical wheat production. The trials conducted in the Rustwatch project confirmed that it is currently difficult to find alternative solutions that provide sufficient or reliable control of yellow rust. Two alternative solutions were evaluated in the 19 IPM trials in 2020 and 2021; neither proved effective, which confirmed the results from the 2019 trials, where a range of products were evaluated (Table 5 and Figure 2). The tested solutions included both biological control agents (BCAs) and older substances like sulphur and phosphonate, but neither gave substantial control. Even in comparison with very reduced rates of conventional fungicides (tebuconazole and pyraclostrobin), the alternatives did not prove to be a realistic option. Specifically for BCAs, it has been seen that control under field conditions [18] can be a challenge if there is high rust pressure, as the persistence of the alternatives even following four application timings is inferior to conventional chemistries. Significant control of rust diseases has been observed for some BCAs in *in vitro* tests on uredospore germination in seedling assays with *Bacillus subtilis* and *Bacillus megaterium* [17,48]. Different formulations using bacterial cell suspensions (BCS) and fermentation liquid with and without bacterial cells have been tested, with an efficacy of around 80%. Studies have generally proved that protective treatments provide better control than curative treatments [17,18,48].

The findings in this study on the use of alternative products for rust control are somewhat in contrast to achievements seen against other diseases, e.g., sulphur has proven to give ca. 50% control of STB in recent trials [49], BCAs based on strains of *Clonostachys rosea* have provided low to moderate control of both STB and fusarium head blight in wheat [50] and *Bacillus velezensis* was observed to postpone the development of STB [51]. The search for alternative products with efficacy against rust diseases will thus likely continue.

4.5. Thresholds and DSSs

The use of decision support systems (DSS) in the trials provided moderate but still reliable disease control, good yield responses and competitive economic benefits compared with other solutions using appropriate rates of fungicides (Table 10). Despite development of weather-driven risk models for yellow rust based on temperatures and relative humidity [52], DSS for control of rust in this project relied mainly on visual scouting in the field [53]. To predict the risk for yellow rust in the season, it has, however, proven important to include information on winter temperatures, with the pathogen's probability of survival decreasing in cold winters where temperatures drop below -5°C [54–56]. To have a robust and good DSS for farmers to adopt, the system must include all relevant diseases, as farmers need a holistic approach to their control strategies. Crop Protection Online is an example of such a DSS combining control thresholds for all major diseases in one system [19]. Several tools developed during the Rustwatch project summarise the findings of rust across Europe, which can help obtain a better knowledge of the risk and spread of rust diseases across years and regions [57].

4.6. Impact on Grain Yield and Grain Qualities

Yield and grain quality were highly impacted by the specific control strategies evaluated in the IPM trials (Tables 9 and 11). In the untreated section (Group 1), the most susceptible variety yielded significantly lower, the average yields in the moderately susceptible varieties and the variety mixtures did not vary significantly, while the best yields in untreated plots were observed in the most resistant varieties.

Across the fungicide treatments (Group 2), no significant differences in yields were measured between the varieties, indicating that the four applications completely controlled the diseases and stabilised yields (Table 11). On average, yields in fungicide-treated plots were 8.5 dt/ha higher than the untreated plots, with positive yield responses in susceptible and resistant varieties of 16.2 and 2.7 dt/ha, respectively. No impact on gluten

and protein was observed in either Group 1 or Group 2. Overall, TGW and specific weights were improved following fungicide treatments compared with the untreated, which is in accordance with other studies [58]. Matzen et al. [58] also showed a significant reduction in grain protein content in fungicide-treated crops compared with the untreated control as a dilution effect following higher yields. This effect could not be confirmed in this study, where protein percentage was constant across all treatments and varieties.

In this study, the variety mixture showed no negative effects on any of the grain qualities measured. With respect to growing variety mixtures, grain quality is often considered a challenge for bread-making wheat. Few studies have investigated the effects of variety mixtures on grain quality [59,60]. Some investigations have shown that mixtures can either improve grain quality or provide a quality equivalent to the mean of the components [60,61], while Clarke et al. [62] found that the Hagberg falling number (HFN) was reduced in variety mixtures compared with the mean of the component varieties. More studies are needed to investigate impact on milling and breadmaking qualities using variety mixtures.

5. Conclusions

Similar IPM trials were conducted across nine different countries in Europe across two seasons to investigate different IPM solutions for the control of rust diseases in wheat. Resistant varieties proved highly effective in escaping or avoiding rust infection, with variety mixtures also reducing infection risk significantly and stabilising yields. Rust did not prove difficult to control using reduced rates of fungicides, even under high disease pressure. In trials with severe infection of yellow rust, yields losses above 35% were measured. The use of DSS provided sufficient control of rust diseases and gave competitive yields and economic returns due to fewer applications of fungicides. Different alternatives to conventional fungicides including BCAs were investigated for their ability to control yellow rust; however, none of the tested alternatives proved sufficiently effective to provide reliable control.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/agriculture14060821/s1>, Table S1: Overview on individual trials, trial no., country, GPS coordinates, varieties, yields in untreated plots and levels of yellow rust (YR) and brown rust (BR); Table S2: Information on treatments in the trials. H—high input (TF = 2), L—low input (TF = 1), A—alternative solutions, D—decision support system.

Author Contributions: Conceptualisation, L.N.J., C.M., J.E.T. and B.K.; methodology, L.N.J., B.K., C.M. and J.E.T.; validation, L.N.J., N.M., B.K., A.O. and J.E.T.; formal analysis, L.N.J., R.L. and N.M.; investigation, L.N.J., N.M., R.L., J.E.T., A.O., B.K., C.M., I.L., K.W., L.Z., M.B.A., B.R., S.S. and S.H.; data curation, L.N.J., N.M., J.E.T., B.K., C.M., I.L., K.W., L.Z., M.B.A., B.R., S.S. and S.H.; writing—original draft preparation, L.N.J., N.M. and A.O.; writing—review and editing, all authors. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by EU as part of Horizon 2020 grant agreement No. 773311 (named Rustwatch), and the APC was funded by Aarhus University.

Institutional Review Board Statement: Not applicable.

Data Availability Statement: Data are presented in deliverables D3.8 in the Rustwatch project. <https://agro.au.dk/forskning/projekter/rustwatch/dissemination-activities-incl-publications/deliverables-reports> (accessed on 30 November 2023). The IPM field data presented in this study are openly available in Zenodo: <https://zenodo.org/search?q=RustWatch&l=list&p=1&s=10&sort=bestmatch>.

Acknowledgments: The authors of this study are very thankful to the technicians at all trial sites, who ensured that high-quality trial work was conducted, collected disease assessments and ensured that harvest data were collected.

Conflicts of Interest: Author Ida Lindell and Kerstin Wahlquist were employed by the company HIR Skåne. Sarah Holdgate was employed by NIAB during the project but is now employed by Syngenta. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results. Several authors (L.N.J., N.M., J.T., A.O. and S.H.) have over the last 5 years received grants/contracts work (paid to their institutions) from chemical companies like BASF, Bayer CropScience, Syngenta, Corteva Agriscience, etc.

References

1. Singh, R.; Singh, R.; Rutkoski, J.; Hodson, D.; Jørgensen, L.N.; Hovmøller, M.S.; Huerta-Espino, J. Disease impact on wheat yield potential and prospects of genetic control. *Annu. Rev. Phytopathol.* **2016**, *54*, 303–322. [\[CrossRef\]](#) [\[PubMed\]](#)
2. Beddow, J.M.; Pardey, P.G.; Chai, Y.; Hurley, T.M.; Kriticos, D.J.; Braun, H.J.; Park, R.F.; Cuddy, W.S.; Yonow, T. Research investment implications of shifts in the global geography of wheat stripe rust. *Nat. Plants* **2015**, *1*, 15132. [\[CrossRef\]](#)
3. Murray, G.M.; Brennan, J.P. Estimating disease losses to the Australian wheat industry. *Australas. Plant Pathol.* **2009**, *38*, 558. [\[CrossRef\]](#)
4. Hovmøller, M.S.; Walter, S.; Bayles, R.; Hubbard, A.; Flath, K. Replacement of the European wheat yellow rust population by new races from the centre of diversity in the near-Himalayan region. *Plant Pathol.* **2015**, *65*, 402.e1. [\[CrossRef\]](#)
5. Jørgensen, L.N.; Hovmøller, M.S.; Hansen, J.G.; Lassen, P.; Clark, B.; Bayles, R.; Rodemann, B.; Flath, K.; Jahn, M.; Goral, T.; et al. IPM strategies and their dilemmas including an introduction to www.eurowheat.org. *J. Integr. Agric.* **2014**, *13*, 265–281. [\[CrossRef\]](#)
6. Jørgensen, L.N.; Nielsen, B.J. Control of Yellow rust (*Puccinia striiformis*) by ergosterol inhibitors at full and reduced dosages. *Crop Prot.* **1994**, *13*, 323–330. [\[CrossRef\]](#)
7. Carmona, M.; Sautua, F.; Pérez-Hernández, O.; Reis, E.M. Role of Fungicide Applications on the Integrated Management of Wheat Stripe Rust. *Front. Plant Sci.* **2020**, *11*, 733. [\[CrossRef\]](#) [\[PubMed\]](#)
8. Mercer, P.C.; Ruddock, A. Disease management of winter wheat with reduced doses of fungicides in Northern Ireland. *Crop Prot.* **2005**, *24*, 221–228. [\[CrossRef\]](#)
9. Zhang, X.Y.; Loyce, C.; Meynard, J.M.; Monod, H. Modeling the effect of cultivar resistance on yield losses of winter wheat in natural multiple disease conditions. *Eur. J. Agron.* **2007**, *26*, 384–393. [\[CrossRef\]](#)
10. Bazman, M.; Bàrberi, P.; Birch, A.N.E.; Boonekamp, P.; Dachbrodt-Saaydeh, S.; Graf, B.; Hommel, B.; Jensen, J.E.; Kiss, J.; Kudsk, P.; et al. Eight principles of integrated pest management. *Agron. Sustain. Dev.* **2015**, *35*, 1199–1215. [\[CrossRef\]](#)
11. Turner, J.A.; Chantry, T.; Taylar, M.C.; Kennedy, M.C. Changes in agronomic practices and incidence and severity of diseases in winter wheat in England and Wales between 1999 and 2019. *Plant Pathol.* **2021**, *70*, 1759–1778. [\[CrossRef\]](#)
12. Dodds, P.N.; Rathjen, J.P. Plant immunity: Towards an integrated view of plant-pathogen interactions. *Nat. Rev. Genet.* **2010**, *11*, 539–548. [\[CrossRef\]](#) [\[PubMed\]](#)
13. McDonald, B.A.; Linde, C. Pathogen population genetics. evolutionary potential. and durable resistance. *Annu. Rev. Phytopathol.* **2002**, *40*, 349–379. [\[CrossRef\]](#) [\[PubMed\]](#)
14. Brown, J.K.M.; Tellier, A. Plant-parasite coevolution: Bridging the gap between genetics and ecology. *Annu. Rev. Phytopathol.* **2011**, *29*, 345–367. [\[CrossRef\]](#) [\[PubMed\]](#)
15. Orellana-Torrejón, C.; Vidal, T.; Boixel, A.; Géllisse, S.; Saint-Jean, S.; Suffert, F. Annual dynamics of *Zymoseptoria tritici* populations in wheat variety mixtures: A compromise between the efficacy and durability of a recently broken-down resistance gene. *Plant Pathol.* **2022**, *71*, 289–303. [\[CrossRef\]](#)
16. Sundh IDel Giudice, T.; Cembalo, L. Reaping the Benefits of Microorganisms in Cropping Systems: Is the Regulatory Policy Adequate? *Microorganisms* **2021**, *9*, 1437. [\[CrossRef\]](#)
17. Li, H.; Zhao, J.; Feng, H.; Huang, L.; Kang, Z. Biological control of wheat stripe rust by an endophytic *Bacillus subtilis* strain E1R-j in greenhouse and field trials. *Crop Prot.* **2013**, *43*, 201–206. [\[CrossRef\]](#)
18. Reiss, A.; Jørgensen, L.N. Biological control of yellow rust *Puccinia striiformis* on wheat by *Bacillus subtilis* strain QST713. *Crop Prot.* **2017**, *93*, 1–8. [\[CrossRef\]](#)
19. Hagelskjær, L.; Jørgensen, L.N. A web-based decision support system for integrated management of diseases and pests in cereals. *EPPO Bull.* **2003**, *33*, 467–471. [\[CrossRef\]](#)
20. Kudsk, P.; Jørgensen, L.N.; Ørum, J.E. Pesticide Load—A new Danish pesticide risk indicator with multiple applications. *Land Use Policy* **2018**, *70*, 384–393. [\[CrossRef\]](#)
21. EPPO/OEPP. Foliar and ear diseases on cereals; european and mediterranean plant protection organization. *Bull. OEPP/EPPO* **2012**, *42*, 419–425. [\[CrossRef\]](#)
22. R Core Team. R: A Language and Environment for Statistical Computing. 2016. Available online: <http://www.r-project.org/> (accessed on 23 June 2023).
23. Jamil, S.; Shahzad, R.; Ahmad, S.; Fatima, R.; Zahid, R.; Anwar, M.; Iqbal, M.Z.; Wang, X. Role of genetics, genomics and breeding approaches to combat stripe rust of wheat. *Front. Nutr.* **2020**, *7*, 580715. [\[CrossRef\]](#) [\[PubMed\]](#)

24. Sapkota, S.; Hao, Y.; Johnson, J.; Buck, J.; Aoun, M.; Mergoum, M. Genome-Wide Association Study of a Worldwide Collection of Wheat Genotypes Reveals Novel Quantitative Trait Loci for Leaf Rust Resistance. *Plant Genome* **2019**, *12*, 190033. [CrossRef] [PubMed]
25. Bundessortenamt. 2023. Available online: <https://www.bundessortenamt.de/bsa/sorten/beschreibende-sortenlisten> (accessed on 30 November 2023).
26. ADHB-Recommended List. 2023. Available online: <https://ahdb.org.uk/knowledge-library/recommended-lists-for-cereals-and-oilseeds-rl#h21> (accessed on 30 November 2023).
27. Sortinfo. 2023. Available online: <https://sortinfo.dk/#/overview/88011220/latestYear/LF> (accessed on 30 November 2023).
28. Bouvet, L.; Percival-Alwyn, L.; Berry, S.; Fenwick, P.; Mantello, C.C.; Sharma, R.; Holdgate, S.; Mackay, I.J.; Cockram, J. Wheat genetic loci conferring resistance to stripe rust in the face of genetically diverse races of the fungus *Puccinia striiformis* f. sp. tritici. *Theor. Appl. Genet.* **2022**, *135*, 301–319. [CrossRef] [PubMed]
29. Chaulagain, B.; Chhetri, G.B.K.; Shrestha, S.M.; Sharma, S.; Sharma-Poudyal, D.; Lamichhane, J.R. Effect of two-component cultivar mixtures on development of wheat yellow rust disease in the field and greenhouse in the Nepal Himalayas. *J. Gen. Plant Pathol.* **2017**, *83*, 131–139. [CrossRef]
30. Akanda, S.I.; Mundt, C.C. Effect of two-component cultivar mixtures and yellow rust on yield and yield components of wheat. *Plant Pathol.* **1997**, *46*, 566–580. [CrossRef]
31. Huang, C.; Sun, Z.; Wang, H.; Luo, Y.; Ma, Z. Effects of wheat cultivar mixtures on stripe rust: A meta-analysis on field trials. *Crop Prot.* **2012**, *33*, 52–58. [CrossRef]
32. Al-Maaroof, E.; Yahyaoui, A. Response of some wheat genotypes to strip and leaf rust diseases. *Iraqi J. Agric. Sci.* **2004**, *5*, 15–20.
33. Cox, C.M.; Garrett, K.A.; Bowden, R.L.; Fritz, A.K.; Dendy, S.P.; Heer, W.F. Cultivar mixtures for the simultaneous management of multiple diseases: Tan spot and leaf rust of wheat. *Phytopathology* **2004**, *94*, 961–969. [CrossRef]
34. Finckh, M.R.; Gacek, E.S.; Goyeau, H.; Lannou, C.; Merz, U.; Mundt, C.C.; Munk, L.; Nadziak, J.; Newton, A.C.; De Vallavieille-Pope, C.; et al. Cereal variety and species mixtures in practice. with emphasis on disease resistance. *Agronomie* **2000**, *20*, 813–837. [CrossRef]
35. Newton, A.C.; Begg, G.S.; Swanston, J.S. Deployment of diversity for enhanced crop function. *Ann. Appl. Biol.* **2009**, *154*, 309–322. [CrossRef]
36. Kristoffersen, R.; Jørgensen, L.; Eriksen, L.; Nielsen, G.; Kiær, L. Control of Septoria tritici blotch by winter wheat cultivar mixtures: Meta-analysis of 19 years of cultivar trials. *Field Crop Res.* **2020**, *249*, 107696. [CrossRef]
37. Finckh, M.R.; Mundt, C.C. Stripe rust, yield, and plant competition in wheat cultivar mixtures. *Phytopathology* **1992**, *82*, 905–913. [CrossRef]
38. Mille, B.; Fraj, M.B.; Monod, H.; De Vallavieille-Pope, C. Assessing Four-Way Mixtures of Winter Wheat Cultivars from the Performances of their Two-Way and Individual Components. *Eur. J. Plant Pathol.* **2006**, *114*, 163–173. [CrossRef]
39. Vidal, T.; Lusley, P.; Leconte, M.; De Vallavieille-Pope, C.; Huber, L.; Saint-Jean, S. Cultivar architecture modulates spore dispersal by rain splash: A new perspective to reduce disease progression in cultivar mixtures. *PLoS ONE* **2017**, *12*, e0187788. [CrossRef] [PubMed]
40. Borg, J.; Kiær, L.P.; Lecarpentier, C.; Goldringer, I.; Gauffreteau, A.; Saint-Jean, S.; Barot, S.; Enjalbert, J. Unfolding the potential of wheat cultivar mixtures: A meta-analysis perspective and identification of knowledge gaps. *Field Crops Res.* **2018**, *221*, 298–313. [CrossRef]
41. Kristoffersen, R.; Heick, T.M.; Møller, G.; Eriksen, L.B.; Nielsen, G.C.; Jørgensen, L.N. The potential of cultivar mixtures to reduce fungicide input and mitigate fungicide resistance development. *Agron. Sustain. Dev.* **2020**, *40*, 36. [CrossRef]
42. Wuest, S.E.; Peter, R.; Niklaus, P.A. Ecological and evolutionary approaches to improving crop variety mixtures. *Nat. Ecol. Evol.* **2021**, *5*, 1068–1077. [CrossRef]
43. Barot, S.; Allard, V.; Cantarel, A.; Enjalbert, J.; Gauffreteau, A.; Goldringer, I.; Lata, J.-C.; Le Roux, X.; Niboyet, A.; Porcher, E. Designing mixtures of varieties for multifunctional agriculture with the help of ecology. A review. *Agron. Sustain. Dev.* **2017**, *37*, 13. [CrossRef]
44. Lupton, F.G.H. Further experiments on photosynthesis and translocation of carbon in wheat. *Ann. Appl. Biol.* **1972**, *71*, 69–79. [CrossRef]
45. Van den Bosch, F.; Oliver, R.; Van den Berg, F.; Paveley, N. Governing principles can guide fungicide-resistance management tactics. *Annu. Rev. Phytopathol.* **2014**, *52*, 175–195. [CrossRef] [PubMed]
46. Oliver, R.P. A reassessment of the risk of rust fungi developing resistance to fungicides. *Pest Manag. Sci.* **2014**, *70*, 1641–1645. [CrossRef] [PubMed]
47. Cook, N.M.; Chng, S.; Woodman, T.L.; Warren, R.; Oliver, R.P.; Saunders, D.G. High frequency of fungicide resistance-associated mutations in the wheat yellow rust pathogen *Puccinia striiformis* f. sp. tritici. *Pest Manag. Sci.* **2021**, *77*, 3358–3371. [CrossRef]
48. Kiani, T.; Mehboob, F.; Hyder, M.Z.; Zainy, Z.; Xu, L.; Huang, L.; Farrakh, S. Control of stripe rust of wheat using indigenous endophytic bacteria at seedling and adult plant stage. *Sci. Rep.* **2021**, *11*, 14473. [CrossRef]
49. Jørgensen, L.N.; Heick, T.M.; Matzen, N.; Madsen, H.P.; Kristjansen, H.S.; Kirkegaard, S.S.; Nielsen, C.A.S.; Nørholm, S.R.; Almskou-Dahlgaard, A. *Disease Control in Wheat. Applied Crop Protection*, 2022nd ed.; Lise Nistrup Jørgensen; DCA Report. 216; DCA—Nationalt Center for Fødevarer og Jordbrug: Foulum, Denmark, 2023; Volume 216, pp. 15–43. ISBN 978-87-94420-11-2.

50. Jensen, B.; Jensen, D.F.; Heick, T.M.; Dubey, M.; Karlsson, M.; Compagni, W.; Jørgensen, H.J.J.; Collinge, D.V.; Jørgensen, L.N. *Combination of Clonostachus rosea and an azole fungicide to Control Diseases in Wheat and Reducing the Risk of Fungicide Resistance*; Report Pesticide research; The Danish Environmental Protection Agency: Odense C, Denmark, 2022; ISBN 978-87-7038-460-5.
51. Kildea, S.; Ransbotyn, V.; Khan, M.R.; Fagan, B.; Leonard, G.; Mullins, E.; Doohan, F.M. *Bacillus megaterium* shows potential for the biocontrol of septoria tritici blotch of wheat. *Biol. Control* **2008**, *47*, 37–45. [\[CrossRef\]](#)
52. El Jarroudi, M.; Kouadio, L.; Bock, C.H.; El Jarroudi, M.; Junk, J.; Pasquali, M.; Maraite HDelfosse, P. A threshold-based weather model for predicting stripe rust infection in winter wheat. *Plant Dis.* **2017**, *101*, 693–703. [\[CrossRef\]](#)
53. Secher BJ, M.; Jørgensen, L.N.; Murali, N.S.; Boll, P.S. Field validation of a Decision Support System for the control of pests and diseases in cereals in Denmark. *Pestic. Sci.* **1995**, *45*, 195–199. [\[CrossRef\]](#)
54. Chen, X.M. Epidemiology and control of stripe rust [*Puccinia striiformis* f. sp. tritici] on wheat. *Can. J. Plant Pathol.* **2005**, *27*, 314–337. [\[CrossRef\]](#)
55. Gladders, P.; Langton, S.D.; Barrie, I.A.; Taylor, M.C.; Paveley, N.D. The importance of weather and agronomic factors for the overwinter survival of yellow rust (*Puccinia striiformis*) and subsequent disease risk in commercial wheat crops in England. *Ann. Appl. Biol.* **2007**, *150*, 371–382. [\[CrossRef\]](#)
56. Aslanov, R.; El Jarroudi, M.; Gollier, M.; Pallez-Barthel, M.; Beyer, M. Yellow rust does not like cold winters. But how to find out which temperature and time frames could be decisive in vivo? *J. Plant Pathol.* **2019**, *101*, 539–546. [\[CrossRef\]](#)
57. Rustwatch. Disease Severity Map. 2023. Available online: <https://agro.au.dk/forskning/projekter/rustwatch/wheat-rust-early-warning/vcu-surveillance/disease-severity-map> (accessed on 30 November 2023).
58. Matzen, N.; Jørgensen, J.R.; Holst, N.; Jørgensen, L.N. Grain quality in wheat—Impact of disease management. *Eur. J. Agron.* **2019**, *103*, 152–164. [\[CrossRef\]](#)
59. Swanston, J.S.; Newton, A.C.; Brosnan, J.M.; Fotheringham, A.; Glasgow, E. Determining the spirit yield of wheat varieties and variety mixtures. *J. Cereal Sci.* **2005**, *42*, 127–134. [\[CrossRef\]](#)
60. Hoang, T.N.; Kopecký, M.; Konvalina, P. Winter wheat mixtures influence grain rheological and mixinglab quality. *J. Appl. Life Sci. Environ.* **2022**, *54*, 417–428. [\[CrossRef\]](#)
61. Osman, A. The effect of growing cultivar mixtures on baking quality of organic spring wheat. In *Cereal Crop Diversity: Implications for Production and Products, Proceedings of the COST SUSVAR Workshop, La Besse, France, 13–14 June 2006*; ITAB Press: Paris, France, 2006.
62. Clarke, S.; Hinchliffe, K.; Jones, H.; Martin, S.; Wolfe, M.; Thomas, J.; Gibbon, D.; Harris, F.; Lyon, F. A Participatory Approach to Variety and Mixture Trials: Methods. Results and Farmer Opinions. In *Cereal Crop Diversity: Implications for Production and Products, Proceedings of the COST SUSVAR Workshop, La Besse, France, 12–15 June 2006*; ITAB Press: Paris, France, 2006.

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.