



Article

MISSR: A Mentoring Interactive System for Stripe Rust

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Abstract: Wheat is one of the most important crops in the world and was considered the major grain crop grown in Egypt. Nowadays, Egypt is the largest wheat importer in the world and consumes an extensive amount of it. To decrease the gap between production and consumption and increase the yield, we need to control wheat diseases, especially stripe rust, due to its major damage to wheat. Further, we need to advise farmers as early as we can to control and treat them. The paper proposed an interactive intelligent system to monitor, predict and give the correct advice at the right time to farmers. This system is called MISSR (Mentoring Interactive System for Stripe Rust). The system is considered an important means to effectively prevent risks in agricultural production. It also plays an important role in guiding farmers and decision-makers to plan and implement suitable practices to increase yield and mitigate stripe-rust disease. On the other hand, it can acquire relevant and timely information in the areas where this information or data is unavailable. To build this model for the wheat crop in Egypt, we used wheat experts' knowledge and climate data API. MISSR is available as a mobile application to provide access for more farmers and increase its availability.

Keywords: wheat; rust; *Puccinia*; mobile app; interactive system



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1. Introduction

Wheat is the major winter grain crop in Egypt. It represents about 10% of the agriculture production in Egypt and about 20% of the total value of the agriculture imports. Wheat production in Egypt is not adequate for the urgent needs of people, thus more than 50% of the consumption is annually imported. The damage caused by rust diseases is considered one of the major obstacles facing the production of wheat crops. Stripe rust caused by *Puccinia striiformis* f.sp. *tritici* is a serious wheat disease that causes a severe economic loss in wheat production in many parts of the world including Egypt [1–4]. Stripe rust requires two distinct hosts.

Since 2010, it has been considered to be macrocyclic rust, after the identification of *Berberis* spp. as an alternative host and elucidation of the complete life history of this rust pathogen for the first time by Jin et al. [5]. Briefly, it spends its Telial/uredinial stages on the primary host(s), including *T. aestivum*, however, it spends its pycnial/aecial stages on an alternate host(s), which mainly include *Berberis* spp. Fortunately, alternate hosts of *P. striiformis* do not exist in Egypt and its urediniospores cannot persist or survive in Egypt during the summer; nevertheless, the source of a primary inoculum is typically brought in by northern winds from foreign sources annually [6,7].

In Egypt, wheat stripe rust was epidemic in 1967, 1995, 1997, and 2015, attacking bread wheat cultivars removed and discarded soon after their introduction and widespread usage in

agriculture due to their susceptibility to stripe-rust disease, i.e., Giza-144, Giza-150, Gemmeiza-1, Giza-163, Sakha-69, Sids-1, Sids-12, Sids-13, Gemmeiza-7, and Gemmeiza-11 [1,8–10].

In Egypt, grain yield losses due to stripe-rust infection in some susceptible wheat cultivars reached 56.3%, depending on several factors, including the degree of cultivar susceptibility, infection time, rate of disease development, and duration of disease [1,11,12]. These crop and disease factors are influenced by environmental factors, among which temperature and moisture are the most important in determining disease severity and yield loss [13,14]. As temperature and moisture conditions vary significantly from year to year in most wheat-producing regions, they are the major limiting factors for the development of stripe-rust epidemics and therefore have been used to develop descriptive and forecasting models for the disease. To control the spreading of the stripe rust as far as possible, some actions should be taken: (i) The use of resistant cultivars, (ii) Monitor crops and trap nurseries so that early decisions can be made on whether fungicide sprays would be beneficial, and (iii) The use of fungicide sprays [15].

Over time, agronomists and researchers have a great concern to implement a multitude of techniques for the early detection and prediction of diseases that acutely affect the crops and the quality of the grain. Early warning systems are commonly used methods in the current research to monitor and predict the symptoms of pests and diseases in agriculture. Currently, a concept name “smart agriculture” is widely used in agriculture to incorporate advanced technologies in agriculture practices as a strategy for crop management and decision-making [16]. An EWS developed in Ethiopia involves a complicated framework that integrates field and mobile phone collecting data, spore dispersal, and environmental disease suitability forecasting, as well as providing timely information to the policy-makers, advisors, and smallholder farmers. A short message service and reports to 10,000 development agents and about 275,000 smallholder farmers in Ethiopia were sent wheat rust alerts and advisories [17].

Several mobile applications have been developed in the agriculture sector which has many objectives, such as optimization of resource use, better agronomical practices, and task programming, among others [18–20]. Carmona et al. developed the AgroDecisor EFC application which can help farmers and crop consultants assess the risk of late-season soybean disease epidemics as well as yield and economic response from foliar fungicide applications based on the weather, disease pressure, and other factors [18]. Ramírez-Gil et al. [21] have designed a mobile application which is used as an early warning system for avocado wilt complex disease. They designed an electronic device for the collection and transmission of climatic variables from inside the soil including moisture and temperature. Moreover, a mobile application was designed with three functions: (i) Available information immediately, which may be used as an early warning system for the avocado wilt complex, (ii) Diagnosis of causal agents based on patterns associated with image processing, and (iii) Management of avocado wilt complex. Lida Sharafi et al. [22] designed a study that could aid policy-makers to design early alert systems to minimize the risk of drought and move from conventional to climate-smart agriculture. A questionnaire was used to gather data from 370 wheat farmers using randomization, and finally, this study used a quantitative methodology to assess farmers’ decisions to use a drought early warning system for monitoring drought to reduce its serious consequences. Khattab et al. [23] used the Internet of Things (IoT) to design an IoT-based monitoring system for epidemic disease control. IoT has been considered as state-of-the-art in implementing distributed and controlling systems in different application areas. Several studies imply that global warming and climate change harm food production and safety, especially with population growth worldwide [24–26]. This problem clearly shows the need for timely decisions in planting, pest and disease management, and harvesting.

To the best of our knowledge, no such system for predicting wheat stripe-rust disease risk has been developed for Egypt’s weather conditions. So, this work has two main objectives: (i) to design a model to collect and transmit the climatic change in Egypt, including rain, wind, humidity, and temperature, and (ii) to develop a model with two

functions: (1) an EWS for climate change that will affect the development of wheat stripe rust in Egypt, and (2) to recommend the appropriate agriculture practices directed towards correct farm management to wheat stripe rust.

2. Materials and Methods

The proposed method combines a knowledge-based module with a weather forecast module for early prediction of the wheat stripe-rust disease and how to control it.

2.1. Wheat Stripe Rust Knowledge Acquisition

Wheat yellow rust disease surveys are collected by expert pathologists and recorded using the traditional survey method [27]. Fourteen yellow rust races were identified in the yellow rust greenhouse in the Wheat Diseases Research Department at Sakha Agriculture Research Station, ARC, Egypt (Table 1). Some wheat-resistant varieties became susceptible where the “Warrior” race (PstS7) in the Pst populations in Egypt and the other countries were detected [4,28,29]. This “Warrior” race broke the resistance in the genes responsible for resistance to stripe rust such as Chinese 166 (*W*, *Yr1*), *Yr32/6*Avocet S*, *Yr27/6*Avocet S* and *Yr17/6*Avocet S* as shown in Figure 1.

Table 1. Virulence pattern of stripe-rust races detected at seedling stage under greenhouse conditions.

Race	Virulence Phenotype *																		
PstS1,v3,v27,v32	-	2	3	-	-	6	7	8	9	-	-	-	-	25	27	32	-	Avs,	-
PstS1,v3,v17,v27,v32	-	2	3	-	-	6	7	8	9	-	-	17	-	25	27	32	-	Avs,	-
PstS2	-	2	-	-	-	6	7	8	9	-	-	-	-	25	-	-	-	Avs,	-
PstS2,v27	-	2	-	-	-	6	7	8	9	-	-	-	-	25	27	-	-	Avs,	-
PstS2,v10, v27	-	2	-	-	-	6	7	8	9	10	-	-	24	25	27	-	-	Avs,	-
Other/Eg2015	1	2	-	-	-	6	7	-	9	-	-	17	-	-	27	-	-	Avs,	-
PstS3	-	-	-	-	-	6	7	8	-	-	-	-	-	-	-	-	-	Avs,	-
PstS1 and PstS2	-	2	-	-	-	6	7	8	9	10	-	-	24	25	27	-	-	Avs,	-
Warrior (PstS7)	1	2	3	4	-	6	7	-	9	-	-	17	-	25	-	32	Sp,	Avs,	Amb
Warrior (-) (PstS10)	1	2	3	4	-	6	7	-	9	-	-	17	-	25	-	32	Sp,	Avs,	-
PstS1,v3,v27,v32	-	2	3	-	-	6	7	8	9	-	-	-	-	25	27	32	-	Avs,	-
PstS2,v3,v17,v27,v32	-	2	3	-	-	6	7	8	9	-	-	-	-	25	27	32	-	Avs,	-
PstS13 (Triticale2015)	-	2	-	-	-	6	7	8	9	-	-	-	-	-	-	-	-	Avs,	-
PstS14	-	2	3	-	-	6	7	8	9	-	-	17	-	25	-	32	Sp,	Avs,	-

* Symbols designate virulence and avirulence (-) corresponding to yellow rust resistance genes: *Yr1*, *Yr2*, *Yr3*, *Yr4*, *Yr5*, *Yr6*, *Yr7*, *Yr8*, *Yr9*, *Yr10*, *Yr15*, *Yr17*, *Yr24*, *Yr25*, *Yr27*, *Yr32*, and the resistance specificity of Spalding Prolific (*Sp*), *Avocet S* (*AvS*), and *Ambition* (*Amb*), respectively.

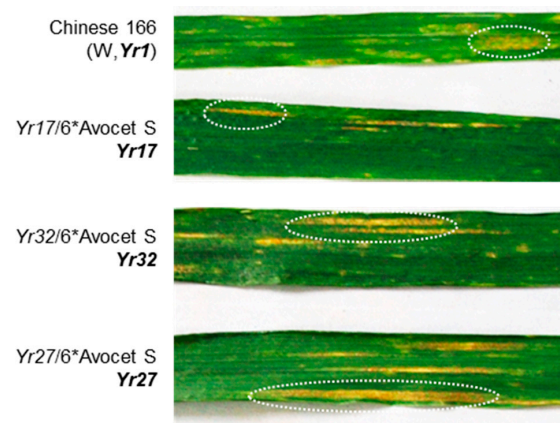


Figure 1. Symptoms of stripe rust on Chinese 166 (*W*, *Yr1*), *Yr17/6*Avocet S*, *Yr32/6*Avocet S*, and *Yr27/6*Avocet S*.

Due to the early appearance of stripe-rust infection on the wheat of the susceptible wheat cultivars—in addition to the early detection of both initial infection and time of the outbreak, the high amount of rainfall, combined with the lower degrees of average minimum and maximum temperatures, recorded during this season—all of these reasons significantly contributed to the establishment, spread, and subsequent epidemic outbreak of stripe rust.

Furthermore, Table 2 shows the knowledge about the most common wheat varieties in Egypt during three successive seasons (2020, 2021, and 2022) and their resistance status to stripe rust in six different Egypt governorates. Each variety is classified either as resistant (R), moderately resistant (MR), moderately susceptible (MS), or susceptible (S). It is worth mentioning that although most of the tested varieties were susceptible or moderately susceptible in Lower Egypt (Kafr El-Sheikh, Beheira, Menoufia, and Sharkiya governorates), the same varieties were resistant or moderately resistant when grown in Upper Egypt (Minia and Beni Swef governorates).

Table 2. Final rust severity of some Egyptian wheat varieties to yellow rust in the six governorates during the 2020–2022 growing seasons.

Wheat Variety	Governorate/Season/Rust Infection Type																	
	2020						2021						2022					
	Kafr El-Sheikh	Beheira	Menoufia	Sharkiya	Minia	Beni Swef	Kafr El-Sheikh	Beheira	Menoufia	Sharkiya	Minia	Beni Swef	Kafr El-Sheikh	Beheira	Menoufia	Sharkiya	Minia	Beni Swef
Sakha-93	20S	30S	20S	30S	0	5S	10S	5S	10S	10S	0	TrS	60S	40S	50S	60S	0	10S
Sakha-94	5MS	5MS	0	0	0	0	5MS	0	0	0	0	0	20S	10S	5S	5S	0	0
Sakha-95	0	0	0	0	0	0	0	0	0	0	0	0	5MR	0	0	0	0	0
Gemmeiza-7	20S	10S	20S	10S	0	5S	20S	5S	10S	10S	0	TrS	40S	30S	20S	30S	0	10S
Gemmeiza-9	5MS	0	0	0	0	0	0	0	0	0	0	0	10S	10S	5S	5S	0	0
Gemmeiza-10	10S	5S	5S	5S	0	0	0	0	0	0	0	0	20S	20S	10S	10S	0	0
Gemmeiza-11	60S	50S	50S	40S	0	10S	40S	20S	20S	20S	0	5S	90S	60S	70S	40S	0	20S
Gemmeiza-12	5MS	5MS	5MS	5MS	0	0	TrMS	0	0	0	0	0	20S	10S	10S	20S	0	5S
Sids-12	40S	30S	50S	40S	0	10S	30S	20S	30S	30S	0	5S	90S	80S	80S	80S	0	20S
Sids-13	5S	5S	5S	5S	0	0	5MS	0	0	0	0	0	30S	10S	10S	5S	0	5MS
Sids-14	20S	10S	10S	20S	0	5S	10S	5S	5S	10S	0	0	60S	40S	50S	40S	0	10S
Giza-168	20S	10S	10S	10S	0	5S	5MS	0	0	0	0	0	10S	10S	20S	10S	0	TrS
Giza-171	5MS	5MS	5MS	5MS	0	0	0	0	0	0	0	0	5MR	TrMR	5MS	5MS	0	0
Misir-1	40S	30S	20S	20S	0	10S	20S	10S	10S	10S	0	5S	70S	60S	50S	60S	0	20S
Misir-2	20S	20S	30S	10S	0	10S	20S	10S	10S	10S	0	5S	60S	50S	60S	50S	0	20S
Misir-3	5MR	0	0	0	0	0	0	0	0	0	0	0	5MR	5MR	0	0	0	0
Shandweel-1	5S	10S	5S	5S	0	0	5S	5MS	5MS	5S	0	0	40S	30S	20S	20S	0	5S

(R) = Resistant, (MR) = Moderately resistant, (MS) = Moderately susceptible, and (S) = Susceptible.

Additionally, the two-way hierarchical cluster analysis showed a clear separation between tested varieties, as well as tested locations. For instance, the most susceptible varieties (Sids-12 and Gemmeiza-11) were clustered together and separately from other varieties during the 2020 and 2021 seasons. However, during the 2022 season, both varieties were clustered in the middle of the dendrogram close to Misr-1, Misr-2, Sids-14, and Sakha-93. Interestingly, the final rust severity during the 2020 season ranged from 0 to 60%, but it reached no more than 40% during the 2021 season; however, stripe-rust disease was more epidemic during the 2022 season since it peaked up to 90% on the susceptible varieties in Lower Egypt governorates (Figure 2).

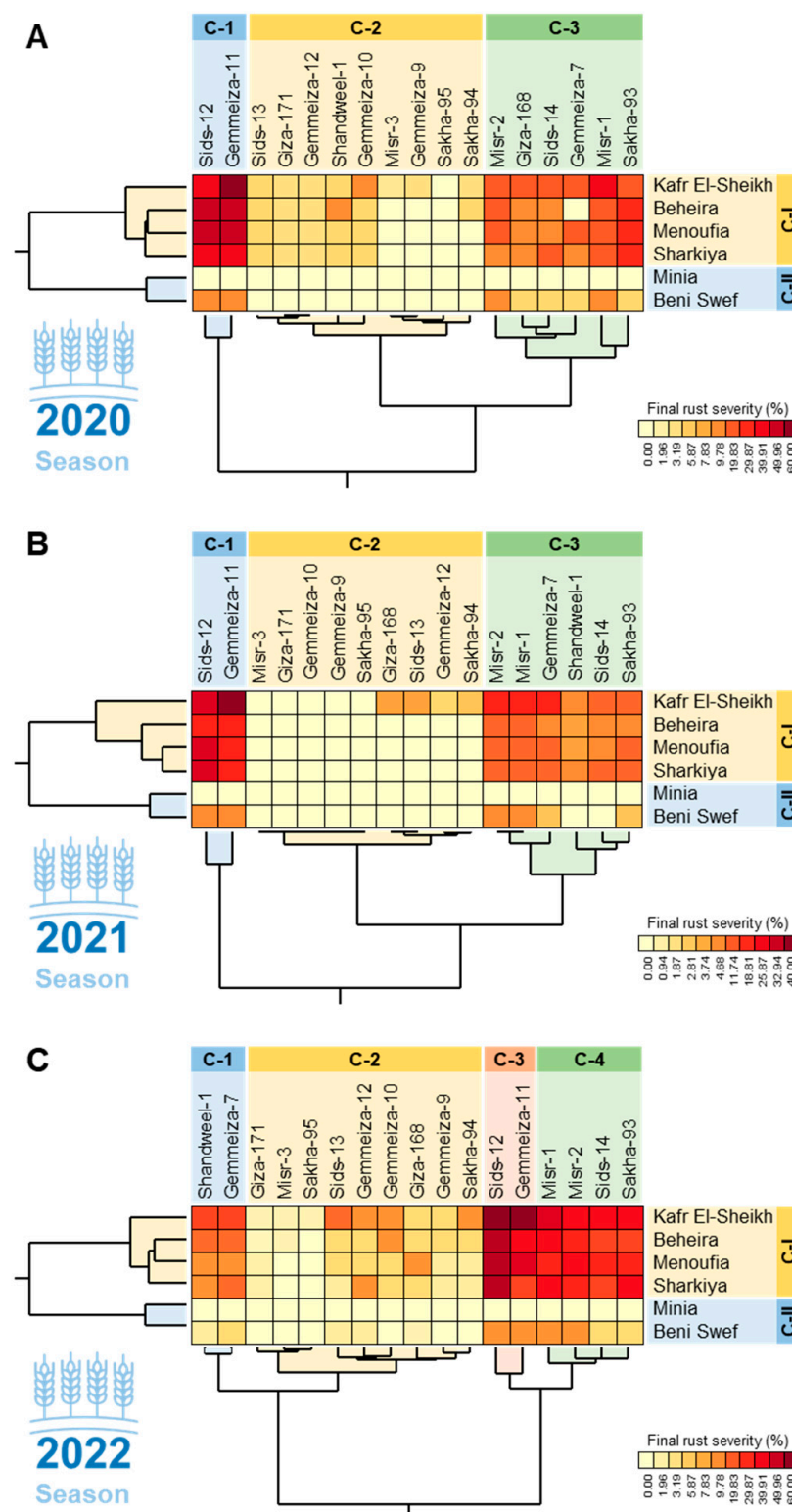


Figure 2. Two-way hierarchical cluster analysis (HCA) of final rust severity of *Puccinia striiformis* f. sp. tritici on 17 Egyptian varieties in six different governorates during three successive seasons, 2020, 2021, and 2022 ((A), (B) and (C), respectively). The final rust severity (%) of *P. striiformis* f. sp. tritici is visualized in the heatmap diagram where dark red signifies the highest severity whereas the light-yellow color signifies the lowest severity (see the scale at the bottom-right corner of the heatmap). Rows represent the individual locations, while columns represent the tested varieties.

2.2. Knowledge-Based Module

Any knowledge-based system consists of two main modules: a knowledge base and an inference engine. In this paper, the knowledge base of the wheat stripe-rust disease has been extracted from different domain experts from the Agricultural Research Center in Egypt. To build the knowledge base for the wheat stripe-rust disease, we used the knowledge acquisition tool (KAT) [30] to build it. We created a new project for wheat stripe-rust disease and used KAT to construct a knowledge base of variety selection and pest identification. To use KAT, we start by building a global ontology of all concepts related to wheat stripe-rust disease, and then we specified all concepts and properties which are related to it.

The main concepts are:

1. Disorder: it includes properties of diseases such as name and evolution stages.
2. Variety: it includes different properties including variety name, stripe rust-resistant status, and other properties to specify if it is recommended and if it is a new variety.
3. Region: it has a property to specify the governorate or region name.
4. Weather: it includes most of the weather variables such as rain, humidity, and minimum and maximum temperature to represent data that are related to stripe rust susceptibility.

The knowledge base is elastic and we can add and edit new concepts. After that, KAT generates a data entry form for entering knowledge. We used the data entry form to enter knowledge that is related to wheat stripe-rust disease and resistant wheat varieties. We used a rule-based mechanism. A rule-based mechanism is represented as “if-then” rules, in which, if condition(s) happen, then one makes a decision.

2.3. Weather Forecast Module

This module allows us to obtain weather forecasts in different geographical locations around Egypt. We used OpenWeatherMap API that is available from “api.openweathermap.org”. OpenWeatherMap is a commercial provider of meteorological data. It avails access to weather data for every part of the world. Anyone who needs to use minute forecasts, hourly predictions, historical data, and other weather data must register using an email address. Many pricing plans enable weather forecasting for 30 days; also, there is a free plan for forecasting for five days for three hours.

For this research, the OpenWeatherMap free plan option was used to obtain a weather forecast five days ahead. Hence, the five-day prediction and climate control are adequate to expect the occurrence of wheat stripe rust. Temperature and humidity forecasts are obtained to be used as inputs to the stripe-rust prediction module.

To use the endpoint, api.openweathermap.org for the API calls, we registered and then we called the API. “<https://openweathermap.org/api/one-call-3>” (accessed on 18 September 2022)”.

This web-based service requires basic parameters such as latitude, longitude, and number of hours for the forecast. The response format is either XML or JSON. In this paper, the used response format is JSON format. Figure 3 shows part of the returned JSON data. It displays the expected weather variables at “18 June 2022 18:00:00” according to the specified latitude and longitude that represent the coordinates of the selected region.

After calling the API, we parsed it and extracted weather variables such as minimum, maximum temperature, and humidity. Figure 4 shows a sample of the forecasted humidity and maximum temperature for the Kafr-El-Sheikh governorate. The horizontal access represents the sequence of measurement (three-hour prediction) per five days.

```
{
  "dt": 1655575200,
  "main": {
    "temp": 27.09,
    "feels_like": 27.26,
    "temp_min": 23.38,
    "temp_max": 27.09,
    "pressure": 1009,
    "sea_level": 1009,
    "grnd_level": 1009,
    "humidity": 46,
    "temp_kf": 3.71
  },
  "weather": [
    {
      "id": 800,
      "main": "Clear",
      "description": "clear sky",
      "icon": "01n"
    }
  ],
  "clouds": {
    "all": 0
  },
  "wind": {
    "speed": 4.66,
    "deg": 326,
    "gust": 8.68
  },
  "visibility": 10000,
  "pop": 0,
  "sys": {
    "pod": "n"
  },
  "dt_txt": "2022-06-18 18:00:00"
}
```

Figure 3. Part of the response format of OpenWeatherMap API in JSON.

We used the forecast data as an input to the disease prediction module to predict the wheat stripe rust five days ahead. The weather forecast module will be combined with the knowledge-based module to predict the occurrence of wheat stripe rust. The output of this module is a list of five days ahead with maximum and minimum temperatures for every day and an early warning to the wheat farmers.

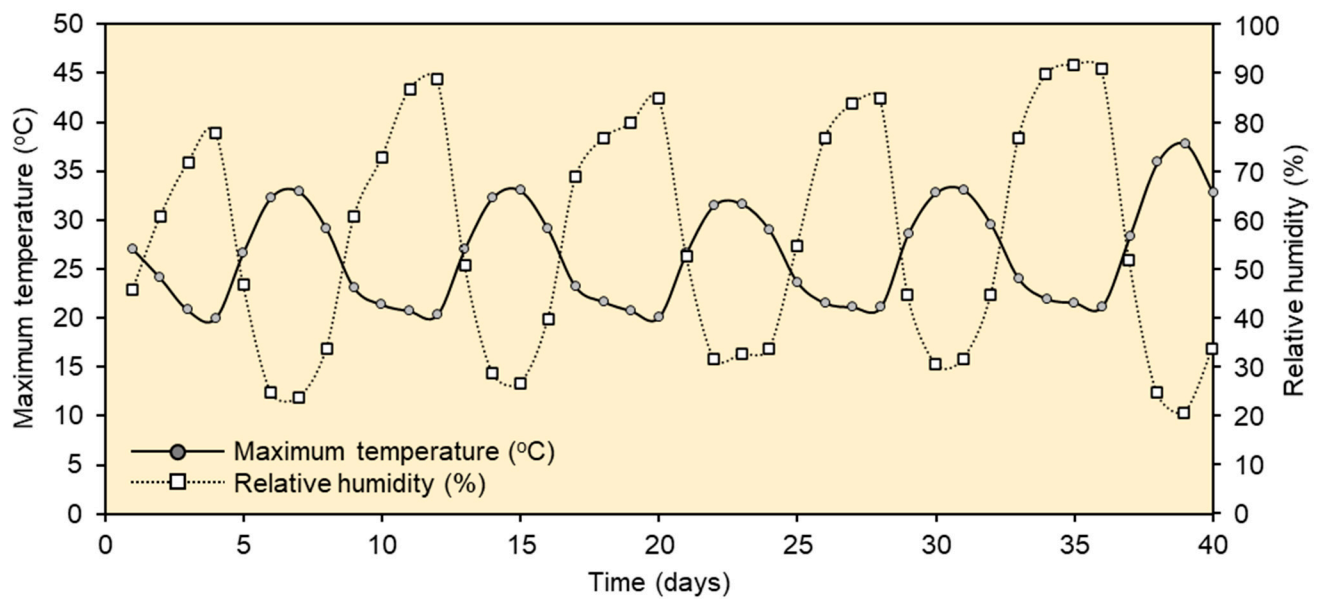


Figure 4. Sample of forecasted humidity and maximum temperature for Kafr El-Sheikh.

3. System Structure

The proposed system consists of selection and recommendation practices. Additionally, it has a component for the weather as shown in Figure 5.

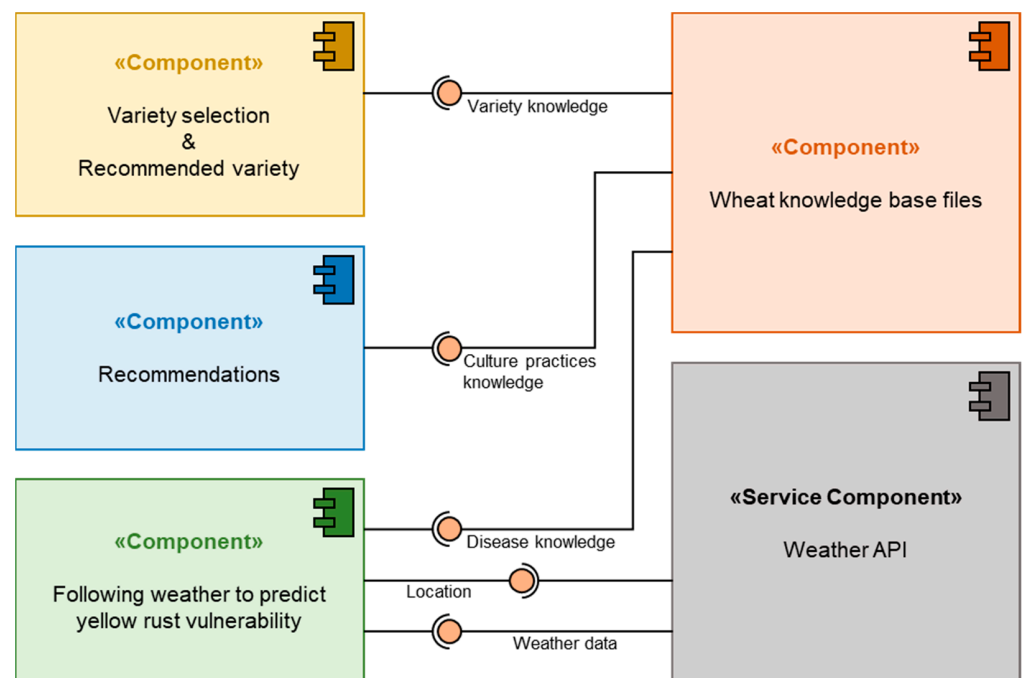


Figure 5. Shows the main components of the proposed system.

3.1. Variety Selection

MISSR enables farmers to find suitable wheat varieties to maximize yield and mitigate and resist stripe-rust disease. The farmer has to specify the farm's governorate then he will get the recommended varieties. Additionally, he can obtain information about the degree of resistant and susceptible varieties to stripe rust. Based on the farmer's input, the variety selection component will obtain the knowledge of the varieties from the wheat knowledge base files. It will use the variety knowledge file.

3.2. Recommendations

MISSR avails the best agriculture practices to prevent and reduce the effect of stripe rust. This component uses the wheat knowledge base files which are related to cultural practice.

3.3. Following the Weather to Predict Yellow Rust Vulnerability

MISSR is the most crucial component; it uses a weather API service to forecast weather data. Moreover, it uses the wheat knowledge base to obtain the knowledge that associates stripe rust growth stages with weather data. This component empowers farmers by availing weather data for five days and declaring the possibility of occurrence of stripe rust on specific days based on weather data. Hence farmers can take proactive procedures and be ready.

3.4. Wheat Knowledge Base Files

MISSR includes files of wheat knowledge: it includes files for variety knowledge, cultural practices, and disease identification of stripe rust and other diseases.

3.5. Weather API

MISSR uses weather API services to forecast weather data for five days. These weather data will be used by the “following weather” component. The input of this component is the latitude and the longitude in addition to other parameters such as language and units of temperature which are available in Fahrenheit, Celsius, and Kelvin.

4. Results and Evaluation

To evaluate the proposed system, we developed a mobile application to be a tool for farmers, extension agents, and researchers. The domain experts run different test cases to check if it displays the correct knowledge. Many iterations of the test have been applied until we reached the satisfaction of the domain experts.

The developed app is having a bilingual interface in English and Arabic. Figure 6 shows the main page of the app. The end-user can obtain information about stripe-rust disease, follow weather data, and select wheat varieties that are resistant to stripe rust.

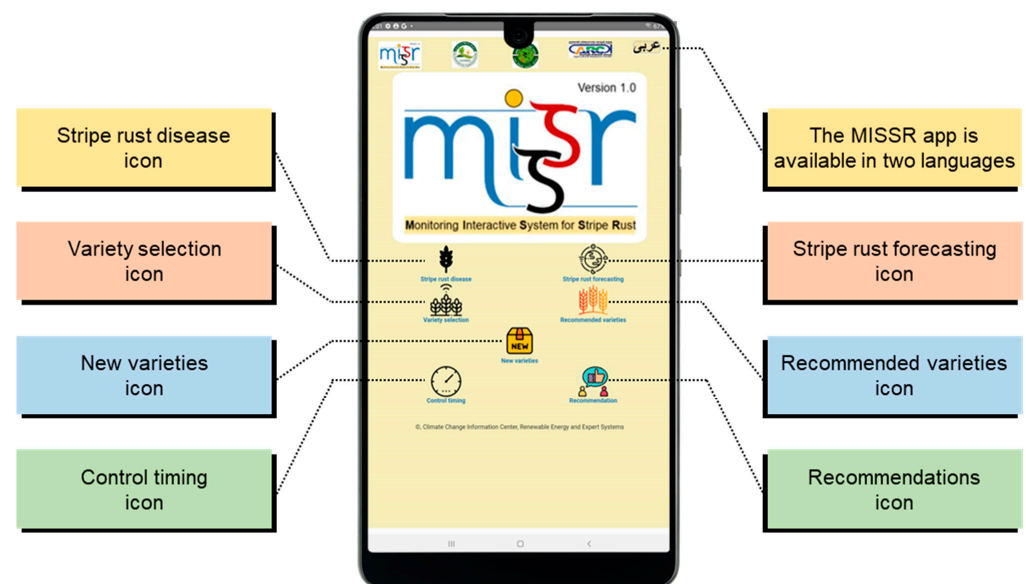


Figure 6. The main page of the “MISSR” mobile application.

The farmer can obtain information about symptoms and the time of the infection symptoms by clicking the stripe-rust button as shown in Figure 7. Furthermore, the farmer can select and search for varieties that are resistant to stripe rust and recommended for the selected governorate as shown in Figure 7.

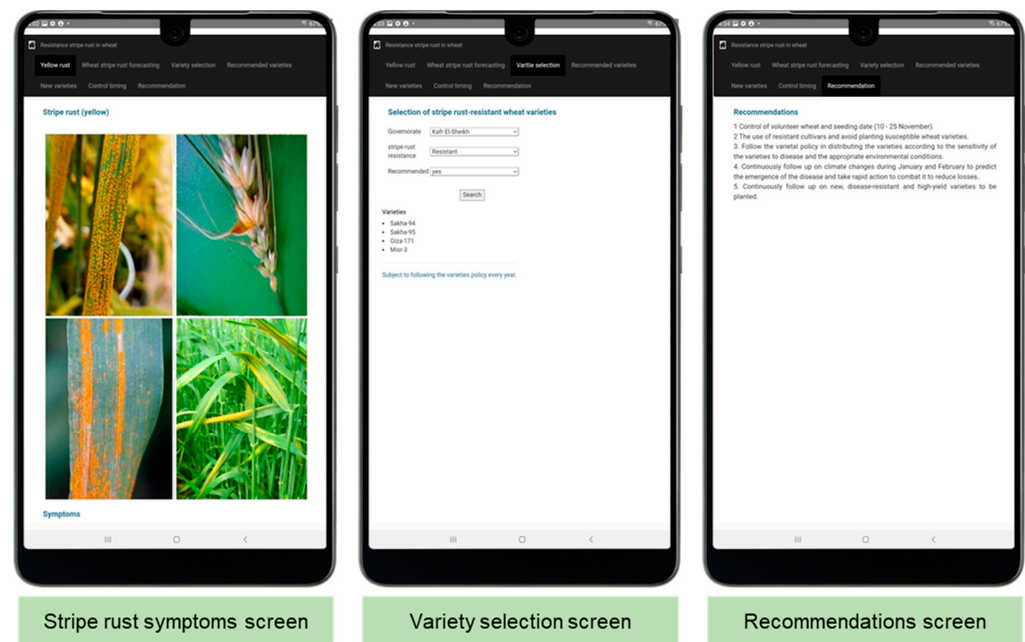


Figure 7. Screens of stripe-rust symptoms, variety selection, and recommendations.

Moreover, Figure 8 shows the result of the following weather data in the Kafr El-Sheikh governorate. Figure 8A: illustrates the case of wheat cultivation where conditions are not suitable for infection with stripe rust. While Figure 8B: illustrates another case when weather conditions are suitable for infection by stripe-rust disease. It displays the minimum and maximum temperature for the coming five days. Further, it displays susceptibility to stripe rust including growth stages of fungal and suitable temperatures and humidity for its growth.

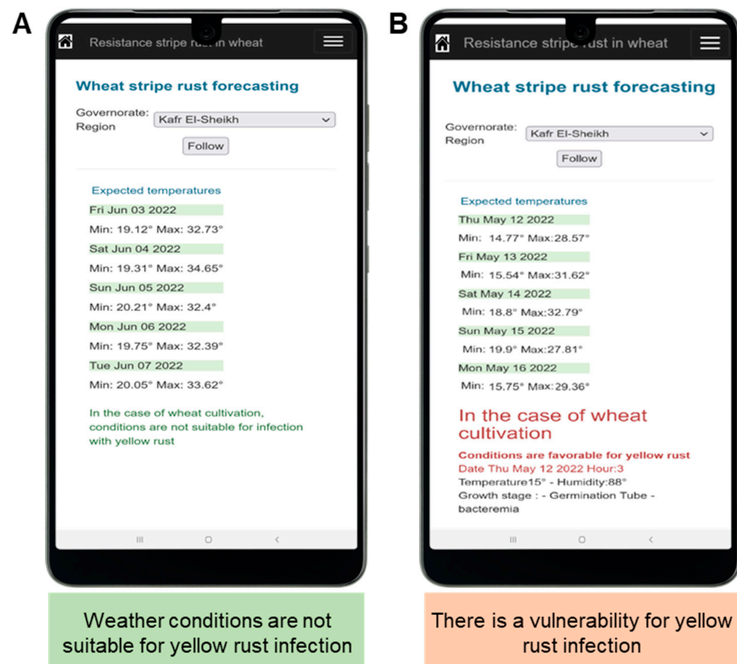


Figure 8. Following weather data and prediction of wheat stripe rust.

Usability Testing and Evaluation of MISSR Mobile System

To build a better product, usability testing was carried out to collect data before a MISSR app was launched. Briefly, the MISSR app was set up on the smartphones of 100 farmers from each of the six targeted governorates (Kafr El-Sheikh, Beheira, Menoufia, Sharkiya, Minia, and Beni Swef) during the 2022 growing season. In all Nile-Delta governorates (Kafr El-Sheikh, Beheira, Menoufia, and Sharkiya), more than 90% of the users were satisfied with the program and confirmed that the MISSR mobile system provides new information promptly. However, this percentage was reduced to 76 and 83%, respectively, in upper-Egypt governorates (Minia and Beni Swef) (Figure 9). Approximately, 93% of the Nile-Delta governorates (Kafr El-Sheikh, Beheira, Menoufia, and Sharkiya) confirmed that the MISSR program predicted yellow rust disease correctly, and more than 95% of the users agreed that the MISSR mobile system changed the behavior of farmers in the terms of choosing varieties, nevertheless, this percentage was reduced again in Minia and Beni Swef governorates (75% and 80%, respectively). As a result, more than 90% of the system users in Nile-Delta governorates (Kafr El-Sheikh, Beheira, Menoufia, and Sharkiya) reported that the program reduce losses resulting from yellow rust disease and increased wheat productivity in the next stage during the 2022 season. Additionally, they suggested that the provided information via the MISSR mobile system should cover all governorates, and also, they highly recommended to include all wheat diseases, particularly the other rust diseases (stem rust and leaf rust) with the app.

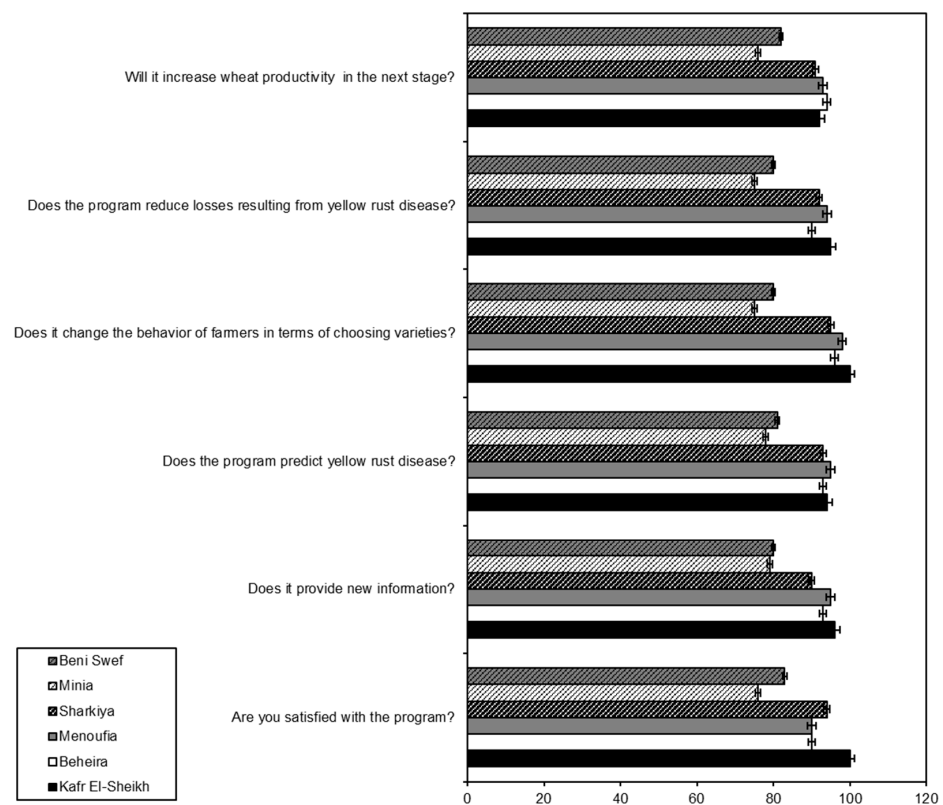


Figure 9. Usability testing and Evaluation of the MISSR mobile system.

5. Discussion

The world faces a multi-layered global food crisis that seriously threatens global food security in general, and wheat supply in particular [31]. The near-term food security risks include COVID-19, climate change, and recently, the Ukraine–Russia war [31]. Egypt is one of the most affected countries by wheat supply disruptions since it imports more than half of its consumption mainly from Russia (50%) and Ukraine (30%) [31]. Moreover, global food

security these days relies greatly on only a few crops, so a single plant disease potentially can cause a food crisis [32]. In context, wheat stability can be impaired by several abiotic and biotic stressors. For instance, most cultivated wheat varieties are susceptible to one or more wind-borne rust diseases [33].

It has been reported that stripe-rust disease caused by *P. striiformis* f. sp. *tritici* is one of the most destructive diseases of wheat worldwide. It caused yield losses of up to 40% in Azerbaijan, Egypt, Ethiopia, Iraq, Morocco, Syria, Tajikistan, and Uzbekistan [34]. Five years ago, newly emerged lineages of *P. striiformis* f. sp. *tritici* were introduced into Argentina, quickly spread into three million hectares, and caused a severe epidemic during the 2017 season [35]. Stripe rust can cause severe losses ranging from 10 to 70% [11]; these losses are mainly due to a reduction in the photosynthetic area leading to both reduced grain yield and quality [36]. Therefore, rapid emergency response(s) to wheat rust epidemics in general, and newly introduced lineages of the pathogen of stripe rust, *P. striiformis* f. sp. *tritici* particularly, are required to mitigate negative near-term food security effects.

Although it is well known that breeding for rust-resistant wheat cultivars is the most effective, long-term control strategy [37], chemical control using agrochemicals such as fungicides is heavily used to control rust diseases due to the absence of effective resistance [38]. Despite the effectiveness of commonly used fungicides, their extensive use is harmful to the environment, human and animal health, and other non-targeted microorganisms [38], and, as well, it might help the development of resistant races of the pathogen. Therefore, the need for control alternatives and a further improvement in the yield potential of wheat is essential [39]. Recently, Bentley and others reviewed the actions that might help in increasing the resilience of wheat supply from the local to global scale [31]. Interestingly, they mentioned the expanded technical support as one of the effective mid-term actions that could ensure sufficient wheat supply [31].

Provision of technical support to wheat producers includes the development and deployment of disease early warning systems (DEWS). DEWS might help smallholder wheat farmers to increase the yield of their cultivated area by providing near real-time recommendations for resistant cultivars and optimizing the efficient use of chemical fungicides [38]. In the current study, we introduced an easy-to-use mentoring interactive system for stripe rust (MISSR). MISSR is a mobile application system that helps farmers protect their crops against wheat stripe-rust disease. It is an early warning decision-making system that uses data which were collected by using automatic monitoring equipment and a prediction model for wheat stripe-rust disease based on deep learning technology.

The MISSR mobile application system helps farmers to mitigate the negative impact of stripe-rust disease that is caused due to weather and climate change. MISSR integrates field survey data and environmental disease suitability forecasting, as well as communication to makers of wheat cultivar policy, advisors, and smallholder farmers. The proposed system has a knowledge base component to acquire and store knowledge of weather data such as humidity, minimum and maximum temperatures, and vulnerability to plant diseases.

Temperature and relative humidity are the most critical meteorological variables to explain the development of stripe rust [40]. It has been reported previously that the causal agent of stripe-rust disease, *P. striiformis* f. sp. *tritici*, favors cold temperatures [41]. Moreover, based on the modeled global climate vulnerability for stem rust, upper Egypt was reported as a seasonally vulnerable area suitable for stem-rust infection, whereas the Nile delta was reported as a persistently vulnerable area where stem rust can establish and persist [33]. Collectively, these findings highlighted the importance of integration of weather data within the newly developed DEWS. In 2020, Rodríguez-Moreno and others proposed a weather-data-based model for forecasting leaf and stripe rust on winter wheat [42]. This model used classification and regression trees (CARTs) for data analysis, an hourly weather dataset, and a three-year field disease severity survey of winter wheat rust to forecast pathogens' presence/absence [42]. In the current study, we modeled the effects of meteorological parameters (particularly maximum temperature and relative humidity), virulence pattern of stripe-rust races, and three-year final stripe-rust severity of 17 Egyptian

wheat varieties to develop an easy-to-use, efficient, cost-effective DEWS based on the Internet of Things.

The developed system helps farmers and any agriculture specialist to enter farm locations and combines these data with the weather forecast data to predict the occurrence of the disease five days ahead which helps farmers and agriculture specialists make more informed decisions to keep them out of the danger of the occurrence of the wheat stripe-rust disease [43]. Furthermore, it enables farmers to find suitable wheat varieties to maximize yield and mitigate and resist stripe-rust disease. It is the first time in Egypt that we built such an application to predict the wheat stripe-rust disease by using a combination of knowledge-based components and an API service to provide the users with the early detection of the disease to make better control decisions to help them minimize losses of the crop. However, as this is considered a novel system in Egypt, there are still future improvements to be made. We can add knowledge about other wheat diseases, and we can apply the proposed system to other crops. In the near future, it will begin experiments in different locations and on different varieties to obtain more data, develop and verify the accuracy of the model, and study the fixed mechanism of disease occurrence to adapt to their long-term prevalence. It is hopeful that this concept can be extended to other crops, thereby accelerating the modernization of Egyptian agriculture.

6. Conclusions

In conclusion, our findings provide valuable baseline information to identify key weather–disease links. We suggest that the integration of meteorological parameters, virulence pattern of *P. striiformis* f. sp. *tritici* races, and accumulative stripe-rust severity to build real-time DEWS might offer helpful information to forecast the stripe-rust disease at both large and small scales. Herein, we tried to better understand how stripe-rust epidemics are correlated with weather variables using automatic monitoring equipment and a prediction model for stripe rust based on deep learning technology. The proposed system has a knowledge-based component to acquire and store knowledge of weather data such as humidity, minimum and maximum temperatures, and vulnerability to plant diseases. The developed system helps farmers and any agriculture specialist to enter farm locations and combines these data with the weather forecast data to predict the occurrence of the disease five days ahead. Furthermore, it enables farmers to find suitable wheat varieties to maximize yield and mitigate and resist stripe-rust disease. For future work, we can add knowledge about other wheat diseases and we can apply the proposed system to other crops.

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