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Assessment and Integrated Management of Yellow Rust (Puccinia Striiformis F. Sp. Tritici) Disease of Bread Wheat (Triticum Aestivum L.) in Debre Elias District, East Gojjam Adminstrative Zone, Northwestern Ethiopia

Amare, Yekedem

BAHIR DAR UNIVERSITY

COLLEGE OF AGRICULTURE AND ENVIRONMENTAL SCIENCES

DEPARTMENT OF PLANT SCIENCES

M. Sc. IN PLANT PROTECTION

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M. Sc. Thesis

By

Yekedem Amare Abesha

March 2025

Bahir Dar, Ethiopia

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Yekedem Amare Abesha

A Thesis Submitted in Partial Fulfillment of the Requirements for the Degree of Master of Science (M. Sc.) in Plant Protection

Major Advisor: Abaynew Jemal (PhD)

Co-Advisor: Esmelealem Mihretu (PhD)

March 2025

Bahir Dar, Ethiopia

DECLARATION

This is to certify that the thesis entitled "Assessment and Integrated Management of Yellow Rust (*Puccinia striiformis* f. sp. *tritici*) Disease of Bread Wheat (*Triticum aestivum* L.) in *Debre Elias District*, East Gojjam Administrative Zone, North-western Ethiopia", submitted in partial fulfilment of the requirements for the degree of Master of Sciences in Plant Protection of Department of Plant Sciences, Bahir Dar University, is a record of original work carried out by me and has never been submitted to this or any other institution to get any other degree or certificates. The assistance and help I received during the course of this investigation have been duly acknowledged.

Yekedem Amare Abesha		30/03/2025 G.C.	Bahir Dar
Name of the candidate	Signature	Date	Place

ADVISOR APPROVAL FORM

BAHIR DAR UNIVERSITY

COLLEGE OF AGRICULTURE AND ENVIRONMENTAL SCIENCES

DEPARTMENT OF PLANT SCIENCES

M. Sc. IN PLANT PROTECTION

Approval of Thesis for Defense

I hereby certify that I have supervised, read, and evaluated this thesis titled "Assessment and Integrated Management of Yellow Rust (*Puccinia striiformis* f. sp. *tritici*) Disease of Bread Wheat (*Triticum aestivum* L.) in *Debre Elias District*, East Gojjam Administrative Zone, North-western Ethiopia", by Yekedem Amare Abesha prepared under my guidance. I recommend the thesis to be submitted for oral defense.

Abaynew Jemal	[signature]	30/3/2025
Advisor's name	Signature	Date
Esmelealem Mihretu (PhD)	[signature]	30/03/2025 G. C.
Co-Advisor's name	Signature	Date
Abaynew Jemal Jenber (PhD Head, Department of Plant Sciences	[signature]	02/4/2025
Department Head	Signature	Date

College of Agricultural & Environmental Sciences Department of Plant Sciences

EXAMINERS' APPROVAL FORM

BAHIR DAR UNIVERSITY

COLLEGE OF AGRICULTURE AND ENVIRONMENTAL SCIENCES

DEPARTMENT OF PLANT SCIENCES

M. Sc. IN PLANT PROTECTION

Approval of Thesis for Defense Result

As member of the board of Examiners of the Master of Sciences (M.Sc.) thesis open defense examination, we have read and examined these thesis entitled "Assessment and Integrated Management of Yellow Rust (*Puccinia striiformis* f. sp.*tritici*) Disease of Bread Wheat (*Triticum aestivum* L.) in *Debre Elias District*, East Gojjam Administrative Zone, North-western Ethiopia", prepared by Miss Yekedem Amare Abesha. We hereby certify that the thesis is accepted for fulfilling the requirements for the award of the degree of Master of Science (M.Sc.) in plant protection.

Board of Examiners

External examiner name: Yehizbalem Ameraw (Ph.D)	Signature	Date: 30/03/2025
Internal examiner name: Merkuz Abera	Signature	Date: 2nd April, 2025
Chair person's name: Tesfaye M.T.	Signature	Date: 2/04/2025

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Assessment and Integrated Management of Yellow Rust (*Puccinia striiformis* f. sp. *tritici*) Disease of Bread Wheat (*Triticum aestivum* L.) in Debre Elias District, East Gojjam Administrative Zone, Northwestern Ethiopia

By: Yekedem Amare Abesha

Major Advisor: Abaynew Jemal (PhD) and Co-Advisor: Esmelealem Mihretu (PhD)

ABSTRACT

In Ethiopia, bread wheat is a significant cereal crop in terms of production volume and area coverage. However, its yield is influenced by yellow rust disease. Hence, this study was carried out to assess the status of yellow rust disease and to develop bread wheat yellow rust disease integrated management options using varieties and fungicides in Debre Elias district during 2023 main cropping season. A total of 100 wheat farmer fields were assessed from four kebele administrations in the district for yellow rust disease prevalence, incidence, and severity and the collected data were analyzed using SPSS version 25 software. The field experiment was conducted at Guay Kebele administration on a farmer's field. A total of 9 treatment combinations, including three bread wheat varieties (Danda'a, Ogolcho, and Kakaba) and two fungicides (Nativo SC 300 and Kanzole 25% EC, including unsprayed check) with three replications were laid out in a factorial arrangement using RCBD design. Both disease and yield-related data were collected, and SAS 9.4 software was used to analyze them. Survey results revealed that 88%, 42.41%, and 28.67% of yellow rust mean prevalence, incidence, and severity were observed in the district respectively. Survey result also revealed that the highest mean severity was recorded on fields covered by Ogolcho variety (50.91%), which were at heading growth stage (31.48%), had high plant density (40.79%), previously covered by wheat crop (36.97%) with an altitude range $\geq$2167 m.a.s.l. (31.77%) and unsprayed ones (36.61%). The field study result showed that the highest FYRS of 89.08%, 80.48%, and 43.33% were recorded on unsprayed Ogolcho, Kakaba, and Danda'a varieties, respectively. And also the minimum (363.02% days^{-1}) AUDPC value was registered on the Danda'a variety treated with Nativo SC 300 fungicide. Varieties of unsprayed plots resulted in maximum RYL of 74.55%, 52.31%, and 48.13% on Ogolcho, Kakaba, and Danda varieties, respectively. Variety Danda treated with Nativo SC 300 fungicide gave the maximum (4.55 t ha^{-1}) of grain yield and NB (302,150 birr ha^{-1}). As a result, the combined use of Danda variety with Nativo SC 300 fungicide could be suggested for efficient yellow rust management and optimization of production in Debre Elias. The study should be repeated in similar and differe nt agro-ecologies and years to set a solid recommendation.

Keywords: *AUDPC, Fungicide, Prevalence, Severity, Incidence, Wheat varieties, Yield loss*

TABLE OF CONTENTS

Contents **Page**

TABLE OF CONTENTS (Continued)

TABLE OF CONTENTS (Continued)

TABLE OF CONTENTS (Continued)

LIST OF TABLES

Tables **Page**

LIST OF TABLES (Continued)

LIST OF FIGURES

LIST OF APPENDIX TABLES

Appendix Tables **Page**

LIST OF APPENDIX FIGURES

Appendix Figures **Page**

LIST OF ABBREVIATIONS AND ACRONYMS

AGY	Adjusted Grain Yield
AGBY	Above Ground Biomass Yield
ANRS	Amhara National Regional State
ASE	Amhara Seed Enterprise
ASY	Adjusted Straw Yield
AUDPC	Area Under Disease Progress Curve
CSA	Central Statistical Agency
CIMMYT	Centro Internacional de Mejoramiento de Maíz y Trigo
DEDAO	*Debre Elias District* Agricultural Office
DFDSA	Days to First Disease Symptom Appearance
EGAZAO	East Gojjam Administrative Zone Agricultural Office
FSLC	Fungicide Spraying Labor Cost
FYRS	Final Yellow Rust Severity
GYSP	Grain Yield Selling Price
GRDC	Grain Research and Development Corporation
KARC	Kulumsa Agricultural Research Center
PDC	Percent Disease Control
PYI	Percent Yield Increment
USDA	United State Department of Agriculture

CHAPTER 1: INTRODUCTION

1.1. Background and Justification

Wheat (*Triticum spp.)* is one of the world's most significant and important cereal crop in terms of volume production and nutritional content (Worku Abebe, 2020). Wheat is a tall, annual plant that can grow up to a height ranging from two to six feet in early varieties. According to McKevith (2004), the wheat plant is composed of leaves that round a thin stem and ends in spikes, or ears, of grain at the top. Bread wheat (*Triticum aestivum* L.) is a self-pollinating plant in a member of the Triticeae tribe and genus Triticum within the family Poaceae (Kochito G/Mariam, 2019). The two most widely grown and economically important wheat species in Ethiopia are durum wheat (*Triticum turgidum var. durum* L.) and bread wheat (*Triticum aestivum* L.) (Gedifew Gebrie *et al*., 2020).

Bread wheat is the major staple food for 40% of the world's population with an annual global production of 789.17 million metric tons during 2022/2023 production year. Currently, China and the European Union are the largest wheat-producing countries in the world (Statista, 2024). Over 90% of Ethiopia's and 95% of the world's total wheat production area are covered by bread wheat (Wuletaw Tadesse *et al*., 2022). Ethiopia is the second largest wheat producer in Africa with area coverage of 2.1 million hectares annually with a total production of 6.7 million tons of grain at average productivity of 3.0 and 4.0 t/ha under rain-fed and irrigated conditions, respectively during 2021/22 production year (CSA, 2022; Wuletaw Tadesse *et al*., 2022).

Debre Elias district is one of the most productive *districts* in the East Gojjam Administrative Zone and is the main wheat-producing *district* in Amhara National Regional State (ANRS). That is why it is known as *"the breadbasket of the West Gojjam Zone"* (Mengistu Yismaw, 2021). It contributes more than 17% of the total wheat production in east Gojjam zone with annual production 101,050 tons of yields during 2019/2020 production year (EGAZAO, 2021)

In Sub-Saharan Africa, including Ethiopia, complex and interactive effects of biotic and abiotic factors and socio-economic challenges, notably in the smallholder farming systems, affect wheat production and productivity (Yared Semahegn *et al*., 2021). Wheat rust is one of the major biotic production constraints reported by most farmers (Mulu Nigus *et al*., 2022). Yellow rust (*Puccinia striiformis* f.sp. *tritici*) is one of an economically significant airborne wheat disease worldwide, caused by the basidiomycete fungus *Puccinia striiformis*. Historically, yellow rust has caused and is presently causing significant and severe losses on susceptible wheat cultivars in the world (Worku Abebe, 2020). Previous literature reported that yellow rust disease could destroy entire wheat crops under favorable conditions. In comparison with the leaf rust (*P. triticina* f.sp. *tritici)* pathogen of wheat, the global distribution of yellow rust is more restricted to midland and highland altitudes including Ethiopia. It can cause up to 100% yield loss, at high altitudes, when susceptible cultivars are grown and the environmental condition is conducive (Getachew Gudero, 2020). To prevent yield loss due to yellow rust disease of wheat, farmers use different fungicides released for either wheat rusts or other crop diseases alone or in combination of fungicides with each other due to disease aggressiveness under field conditions (Kabna Asefa *et al*., 2024).

The repeated application of the same fungicide for several years under extensive wheat production may encourage the pathogen to become resistant (Massi *et al*., 2021). Thus, the major approach for the management of yellow rust diseases would remain focused on the development of resistant varieties. In Ethiopia, quite a lot of achievements were made towards the development of resistant varieties, and several varieties with varying degrees of rust resistance were released for production. However, most of them attacked by yellow rust soon after their release due to either climate change or the evolution of new pathogen races (Wubishet Alemu and Chemeda Fininsa, 2016). This might also probably be due the ongoing cultivation of wheat year after year (Getachew Gudero, 2020).

As a result, we have to use other management options to control yellow rust disease effectively and efficiently. A combination of environmentally safe and sustainable disease management practices of disease resistance with fungicide applications are the most effective means for yellow rust control (Ashagre Asnakew, 2021). Accordingly, there is a limitation on evaluating these alternative management options for yellow rust disease of wheat in the study area. In addition, there is a lack of sufficient and documented information related to the disease and still few studies have been done to manage yellow rust disease of bread wheat through integrated use of host resistance with fungicides in the study area. With this background, this research aims in determining the effects of variety and fungicide application on yellow rust under natural field conditions of bread wheat.

1.2. Statement of the Problem

In terms of both volume produced and area covered, wheat is one of Ethiopia's most significant cereal crops. Despite the large area under wheat production, the national average yield of wheat in Ethiopia is 3.1 t/ha (CSA, 2022), which is lower than the world's average yield of 3.5 t/ha (FAOSTAT, 2022). This is due to the diseases like stem rust, yellow rust, and septoria leaf spot, as well as inadequate or suboptimal use of production inputs (such as improved seeds and fertilizers) and the decline in resistance capacity of the released cultivars after a few years of production (Mengistu Meskele *et al*., 2022). Among these constraints, yellow (stripe) rust is the most prevalent and devastating disease of wheat in Ethiopia and other east African highlands. It has caused significant yield losses reaching up to 100% in the Ethiopian highlands (Wuletaw Tadesse *et al*., 2022).

Yellow rust is a widespread disease across major wheat growing regions and results in significant yield losses to wheat production that have been estimated to be at least 5.5 million tons per year at worldwide level (Worku Abebe, 2020). In 2010, yellow rust epidemic has occurred and resulted in a significant yield loss of 34% in Amhara region. In East Gojjam Administrative Zone, about 32% of grain yield loss was recorded due to yellow rust disease with the mean incidence of 100% and severity ranged from 50 – 80%. Yellow rust disease, was also prevalent in *Debre Elias district*, with a 95% disease incidence and 50% severity (Landuber Wendale *et al.,* 2016). Even though, yellow rust disease is more prevalent and resulted a higher yield losses on bread wheat production in Amhara region as well as *Debre Elias district,* there is a study gap on the distribution, status, and economic impacts of bread wheat yellow rust disease in the area.

According to Getachew Gudero and Biruk Kedir (2018), farmers use various fungicides to minimize yield losses caused by yellow rust disease. Various observations made in the research locations reported that, using a single fungicide repeatedly over a period of years resulted in the requirement for additional fungicides. These and other factors, such as farmers' lack of awareness on the effect of combination of varieties with fungicide application, made it necessary to mount a management option (Getachew Gudero, 2020).

Debre Elias district has a full potential for crop production, especially wheat. However, the production data from 2017/18 to 2020/2021 production year shows a decrease in production yield from 117,453.6 to 82,900.8 tons per year respectively due to yellow rust disease (EGZBOA, 2021). In this area, the production and productivity of bread wheat during the 2021/ 2022 cropping season was very low due to yellow rust disease. The grain yield obtained from farmer's fields at that time was accounted for about 0.8-2 t/ha (Farmer's, personal communication).

In addition, most of farmer's lack awareness about yellow rust disease; they mostly grow commonly used local varieties repeatedly and they apply fungicides only to manage the disease. However, use of chemicals only as a management option is not enough to control the disease effectively. To overcome this problem and to improve production and productivity of bread wheat in *Debre Elias district,* it is important to conduct a study on integrated disease management option for yellow rust through host resistance and fungicide application.

1.3. Objectives of the Study

1.3.1. General objective

- ✓ To assess the status of bread wheat yellow rust and develop integrated disease management option for yellow rust disease of bread wheat through host resistance and fungicide application at *Debre Elias District*, Ethiopia.

1.3.2. Specific objectives

- ✓ To determine the distribution and damage level of yellow rust disease of bread wheat at *Debre Elias District*.
- ✓ To manage yellow rust disease of bread wheat through integrated use of fungicide and host resistance.
- ✓ To suggest the cost effective combination of varieties and fungicides for yellow rust disease management on bread wheat.

CHAPTER 2: LITERATURE REVIEW

2.1. Origin and Distribution of Wheat

An essential portion of the history of agriculture is the history of wheat, which dates back to around 10,000 B.C. It is believed that wheat was first grown in the Fertile Crescent, a region of the Middle East that stretches from Jordan, Palestine, and Lebanon to Syria, Turkey, Iraq, `and Iran. The earliest cultivated species are hulled (glumed) wheat's and comprise all three polyploidy levels known in Triticum spp., diploid, tetraploid, and hexaploid (Arzani and Ashraf, 2017). These species are einkorn (*Triticum monococcum* L.), emmer (*Triticum Dicoccum*), and spelt (*Triticum spelta*), and their corresponding wild ancestors are still found in these territories (De Sousa *et al*., 2021).

According to reports, wheat was first cultivated in the Mesopotamian Fertile Crescent about 6000 years ago, and it apparently spread to the Middle East, North Africa, Asia and ultimately Europe. Around 1500 AD, wheat was distributed to the Americas and Southern Africa, and introduced into Australia in 1790. Currently, wheat is the most commonly and diversely cultivated food crop in the world. Due to its cultivability and adaptability nature, wheat is grown at elevations ranging from sea level to 4500 meters and under a variety of agro-ecological circumstances (Tiwari and Shoran, 2007).

2.2. Taxonomy and Botanical Description of Wheat

Wheat belongs to the Poaceae family, which includes the Triticeae tribe, the division with the most economically important cereals. The Triticeae tribe comprises 14 genera, grouped into the sub tribes Triticinae and Hordeinae, and the production of amphiploids and interspecific hybrids indicates there is genetic or cytoplasmic compatibility between the different genera. Many modifications in the taxonomic description of *Triticum* and its associated genera have happened since the original naming by Linnaeus in 1753. There is now general agreement that the genus *Aegilops*, which is closely related to wheat, gets merged with *Triticum* as done by Bowden (1959). The hexaploid wheat *Triticum aestivum* L. (AuAuBBDD; $2n = 6x = 42$), tetraploid *Triticum turgidum* L. (AuAuBB; $2n = 4x = 28$), and diploid einkorn *Triticum* *monococcum* L. (AmAm; 2n = 2x = 14) are most representative wheat species of Triticeae tribe (Peng *et al*., 2011).

Currently, the most economically important species are tetraploid durum wheat (*Triticum* turgidum subsp. durum (AuAuBB; 2n = 4x = 28) and hexaploid bread wheat. The origin of the latter two wheat species was the result of two polyploidization events. The first of these occurred with the association of the genomes of two diploid species: the A genome was derived from a species that is related to the wild species *Triticum urartu* (AuAu; 2n = 2x = 14), and the B genome was derived from unknown species from the Sitopsis. This produced the allotetraploid wild emmer wheat (*Triticum Dicoccum*; AuAuBB; 2n = 4x = 28) (Consortium *et al*., 2014). With the genetic resources of both ancestral diploids, this cultivated allotetraploid wheat is generally more vigorous, giving higher yields and adapting to a wider range of environmental conditions compared to its parents. The second event occurred between *T. turgidum* and *Aegilops tauschii* (DD), a wild diploid species, which produced the allohexaploid early spelt (*Triticum aestivum* subsp. *spelta*; AuAuBBDD; 2n = 6x = 42). Initially, *T. aestivum* L. and *T. turgidum* produced sterile hybrids; however, a duplication of chromosomes in gametes or progeny gave rise to fertile species (De Sousa *et al*., 2021).

Wheat is a tall, annual plant which can grow from two to six feet height in early varieties. The plant is made up of leaves around a slender stalk that ends in spikes, or ears, of grain at the top of wheat (International Starch Institute). Each spike, ear, of grain is made up of spikelet’s, which encloses the wheat grain in between the lemma and the palea. The wheat grain has an oval shape and gives its nutritional value. The grain may also vary in its length of brush hairs, either long or short (McKevith, 2004).

The wheat plant has two types of roots, the seminal (seed) roots and roots that initiate after germination, the nodal (crown or adventitious) roots. The seminal roots develop from the root primordial contained within the grain. Nodal roots are associated with tiller development. The grain or caryopsis of the wheat plant is made up of the bran coat and the endosperm surrounding the embryo. The bran coat consists of three layers, the pericarp, testa and aleurone. The endosperm makes up 83% of the wheat grain (Kirby, 2002). Cultivated wheat is most commonly grown with physical characteristics of fusiform spikes, are awned (bearded) and are easily threshed (McKevith, 2004). With the exception of spelt form of bread wheat, the cultivated forms of diploid, tetraploid, and hexaploid wheat have a hard rachis. Similarly, modern tetraploid and hexaploid wheat varieties are free-threshing, but the early domesticated varieties of einkorn, emmer, and spelt wheat species are all hulled (Shewry, 2009). Bread wheat is a naked, free threshing soft wheat that has a higher grain yield and shorter plant height than the hulled einkorn, emmer, and spelt wheat species (Longin *et al*., 2016).

2.3. Production and Economic Importance of Wheat

Wheat is the most widely grown crop in the world, with global area coverage of 220 million hectare and in terms of production, the global production of wheat amounted to over 765 million metric tonnes and 3.5 t/ha average productivity in 2020 production year. In Africa, about 26.95 million tons of wheat is produced annually on 9.86 million hectares of land with an average yield of 2.7 t/ha (FAOSTAT, 2022). In Ethiopia, wheat is grown on 1.9 million hectares of land, yielding 5.8 million tons per year at an average productivity of 3.1 t/ha during the 2021–2022 production year (CSA, 2022).

Wheat is mainly grown in Oromia, Amhara, SNNP, and Tigray regions of Ethiopia. Amhara region is the second largest producer next to Oromia region. According to the CSA report, Amhara region wheat production covered 689,614.06 ha of land and produced 1,922,028.97 tons of yield with productivity 2.8 t/ha of yield. From Amhara region administrative Zones, East Gojjam Zone ranks first in area coverage, 166,577.99 ha, production 530,330.17 tons and 3.18 t/ha of productivity (CSA, 2022).

Wheat is a crucial cereal crop, used as a staple food worldwide. It contributes significantly to food production and provides essential calories and proteins in human diets. Particularly in many developing countries, it is the primary means of caloric intake, making it vital for ensuring food security for their growing populations. Over 21% of food calories and 20% of protein for more than 4.5 billion individuals come from wheat, underscoring its fundamental role in food security. Wheat was one of the miracle crop in the 20th century, significantly contributes to alleviate poverty and hunger and saves millions of lives worldwide (Worku Abebe, 2020).

In Ethiopia, wheat is a key staple crop, consumed in various forms, from industrially processed to traditionally prepared forms. It plays a role for the preparation of numerous products, including the traditional fermented thin bread ("injera"), regular bread ("dabo"), local beer ("tella"), and several other local food items (USDA, 2022). Wheat serves as a vital source of food and income for millions of smallholder farmers in the world. The authors said, wheat-based foods are essential for food security and nutritional stability worldwide (CIMMYT, 2018).

2.4. Ecological Requirement of Wheat

Wheat can able to thrive in various environmental settings primarily due to the complex nature of its genome, which allows the plant significant adaptability. In Ethiopia, wheat can grow in highlands, which are located between 6°, 16°N latitude and 35°, 42°E longitude and at altitudes ranging from 1500 to 3000 meter above sea level. The ideal elevations for cultivating wheat are found between 1900 and 2700 meters above sea level (Mengistu Meskele *et al*., 2022). Wheat crops can be grown in most locations where annual rainfall ranges from 250-1750mm. Wheat is produced across a wide range of soil conditions, although it is best adapted to fertile, well-drained silt loam and clay loam soils (Zenebu Belay *et al*., 2018).

Wheat is a C3 plant that is well suitable to cool environments and adapted to a broad range of climates from wet temperate to dry and high rainfall areas, and from warm- humid to dry-cold environment (Acevedo *et al*., 2006). The ideal temperatures for wheat growth lies between 18 °C and 24 °C, while the minimum and maximum temperatures suitable for its growth are from 3 °C to 4 °C and 30 °C to 32 °C, respectively (Banchgize Getie, 2015). Wheat will grow optimally in a deep, fertile, well-drained and well aerated soil at a pH range between 6.0 and 7.5 (slightly acidic and neutral soils). Conditions such as poor soil fertility and high salinity negatively affect wheat cultivation, and irrigated fields are more prone to salinity problems (Geremu Negera, 2020).

2.5. Wheat Production Constraints in Ethiopia

Although there is significant potential to enhance Ethiopia's wheat production, it remains limited due to issues like the prevalence of biotic (yellow rust, stem rust, septoria, fusarium) and abiotic (acidity, heat, drought) factors. Furthermore, yield gaps resulting from low adoption of new technologies, high costs and limited availability of inputs, minimal public and private investments, as well as inadequate infrastructure and marketing systems also hinder wheat production in Ethiopia (Wuletaw Tadesse *et al*., 2022). According to the study, drought stress, disease (especially rust) and the high cost of fertilizers were noted as a significant constraints of wheat production identified by the farmers (Yared Semahegn *et al*., 2021).

2.5.1. Biotic wheat production constraints

The most significant biotic constraints influencing wheat production in Ethiopia comprise diseases, insects, and weeds. Wheat diseases, including stem rust (*Puccinia graminis* f. sp. *tritici*), stripe or yellow rust (*P. striiformis* f. sp. *tritici*), and leaf rust (*P. triticina),* along with insect pests such as the Russian wheat aphid (*Diuraphis noxia*), represent key biotic factors affecting wheat production in Ethiopia (Yared Semahegn *et al*., 2021). Rusts (*Puccinia* spp.), Helminthosporium, septoria (*Septoria tritici),* tan spot (*Pyrenophora tritici repentis*), fusarium (*Fusarium* spp.), as well as smuts, take-all, and root rots are significant wheat diseases prevalent in the highlands of Ethiopia. Yellow (stripe) rust caused by *Puccinia striiformis* f. sp. *tritici* is the most common and devastating disease in Ethiopia and other east African highlands. It has resulted in substantial yield losses reaching up to 100% in the Ethiopian highlands (Wuletaw Tadesse *et al*., 2022).

2.5.2. Abiotic wheat production constraints

In the rain fed environments, the most crucial abiotic stresses include drought (particularly in the lowlands), soil acidity, erosion, poor soil fertility, water-logging, and pre-harvest sprouting. Such constraints are predominantly found in the highlands of Ethiopia. Soil acidity is one of the most important factor affecting around 6.3 million ha or (43%) of the arable land area in Ethiopia. Measures have been taken to alleviate soil acidity through the use of liming.

Heat, salinity and inefficient use of irrigation water are the main abiotic constraints in the irrigated environments. Moreover, limited availability and high prices of inputs, yield gaps due to the low adoption of new technologies, and inadequate infrastructure and production policies also hinder wheat production in Ethiopia (Wuletaw Tadesse *et al*., 2022). Additionally, the average production and productivity of wheat in Ethiopia is below the global average, which is due to the influence of low adoption of improved varieties (Yared Semahegn *et al*., 2021).

2.6. Yellow Rust Disease

Yellow (stripe) rust, caused by a fungal pathogen *Puccinia striiformis* f. sp. *tritici*, is a serious threat to wheat occurring in most of wheat-producing areas with cool and moist weather conditions during the growing season. *Puccinia striiformis* is a macro cyclic, heteroecious fungus that requires both primary (wheat or grasses) and alternate (*Berberis* or *Mahonia spp*.) host plants to fulfill its life cycle (Chen *et al*., 2014). It is an obligate bio trophic parasite that relies entirely on the host plant for its growth and reproduction (Chen, 2020).

2.6.1. Taxonomy of the pathogen

Puccinia striiformis Westend is commonly known as glume rust, yellow rust, and stripe rust. *Puccinia striiformis* f. sp. *tritici*, is the pathogen that causes yellow (stripe) rust, belongs to the kingdom Fungi, phylum Basidiomycota, class Urediniomycetes, order Uredinales, family Pucciniaceae, and genus Puccinia. *Puccinia* is a prominent genera within Pucciniaceae family that includes more than 4,000 distinct species (Feodorova-Fedotova and Bankina, 2018). *Puccinia striiformis* is distinguished below the species level through its specialization on various genera of grasses, consisting up to nine formae speciales, among which *Puccinia striiformis* f. sp. *tritici* causes stripe (or yellow) rust on wheat (Chen *et al.*, 2014).

2.6.2. Life cycle of the pathogen

According to Khanfri *et al*. (2018), *Puccinia striiformis* f. sp. *tritici* is an obligate bio trophic parasite that needs a living host to finish its life cycle. It is a macro cyclic, heteroecious fungus that requires both main (wheat or grasses) and alternate (*Berberis* or *Mahonia spp*.) host plants to complete its life cycle (Chen *et al.*, 2014). Like many rust fungi, *Puccinia* *striiformis* (Pst) alternates between hosts throughout its life cycle and has separate hosts for asexual and sexual phases. Pst comprises five types of spores in the life cycle on two taxonomically unrelated hosts; it alternates between a graminaceous host for asexual reproduction and a barberry for sexual reproduction (Jin *et al.*, 2010). Urediniospores and teliospores of the fungus are dikaryotic, however teliospores generate haploid basidiospores (Chen, 2005).

Pycnial and aecial spore stages of the fungus were recently verified. The dikaryotic phase of the life cycle, which produces urediniospores, teliospores, and basidiospores, is limited to the principal host, wheat. The telia stage begins when the nutrition supply from the diseased tissues diminishes. Pycniospores and aeciospores are formed on the top and lower leaf surfaces, respectively, after teliospores overwinter on residual senesced tissues and germinate the next spring to produce four haploid basidiospores that infect the alternate host (*Berberis spp.)* (Jin *et al.*, 2010). Additionally, late in the growing season, teliospores are produced from wheat leaves infected with *Puccinia striiformis* f.sp. *tritici*. These spores that can withstand abiotic stresses can survive on infected straw. At the beginning of a growing season, diploid teliospores germinate on the host plant or even dead tissues. The teliospores undergo meiosis to produce four or more haploid basidiospores, which are later dispersed into the air (Leonard and Szabo, 2005).

The basidiospores infect the alternative host through the stomatal cell walls to produce haploid spores, pycnia which are of various mating types. A single cell with an aecium and aeciospores is formed as a result of fertilization or plasmogamy that takes place when the pycniospores spread through rain, dew, or infection of other plants. The dikaryotic aeciospores are deposited on the host plant from which successful infection and colonization leads to formation of uredinium containing uredospore. The sexual cycle has been suggested to play an important role in off-season survival of many uredinales, while for yellow rust clonal survival has been assumed on volunteer plants and wheat seedlings (Worku Abebe, 2020).

2.7. Epidemiology of Yellow Rust

2.7.1. Source of inoculum

Puccinia striiformis f. sp. *tritici* belongs to the Pucciniaceae family, order Uredinales, phylum Basidiomycota and class Basidiomycete (Chen *et al*., 2014). It was commonly believed that urediniospores were the only source of inoculum, but a recent investigation by Jin *et al.* stated that *Berberis* spp. serves as an alternate host for the wheat stripe rust pathogen (Jin *et al.*, 2010). Teliospores can survive the winter on residual senesced tissues and sprout in the subsequent spring to generate four haploid basidiospores that infect the alternate host (*Berberis* spp.). These spores, which are tolerant to abiotic stress, can survive the winter on infected straw (Hovmøller *et al*., 2011). For this reason, infected wheat straw can act as a source of inoculum for yellow rust disease in wheat.

2.7.2. Disease development and dispersal mechanism

Puccinia striiformis infects the host using urediniospores, which gain entry through stomata following germination. Urediniospores are mainly responsible for the initiation and spread of the disease (Chen, 2005). Urediniospores after landing up on the surface of a wheat leaf adhere to it. Under optimum temperature and humidity conditions, urediniospores produce a germ tube, which grows towards stoma initiating primary infection in the stomatal cavity. After the germ tube produces an appressorium, the plant is invaded through the stomata and the fungus produces a series of infection structures, such as the sub stomatal vesicle, primary infection hyphae, haustorial mother cell, and finally a haustorium (Khushboo *et al*., 2021).

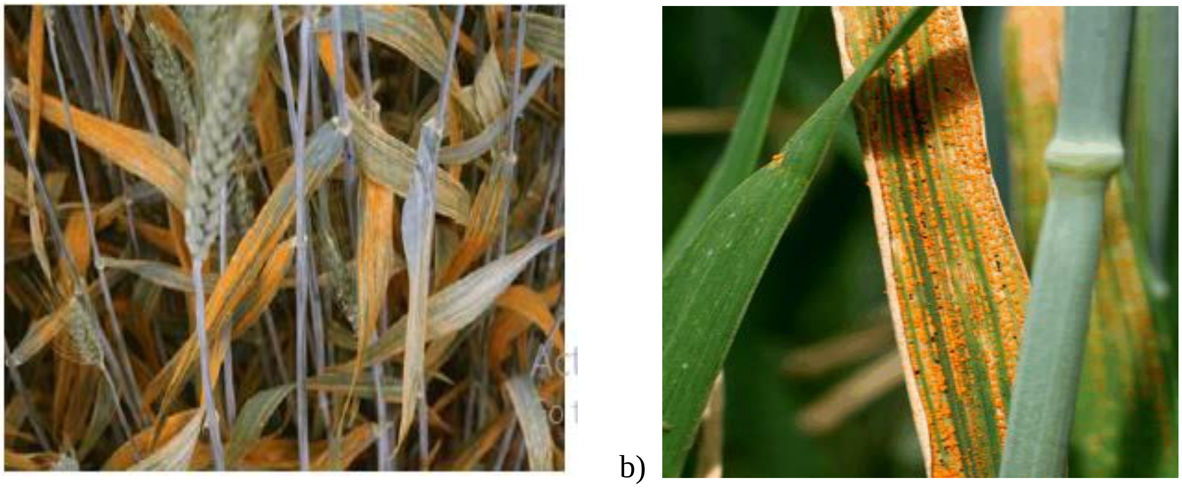
The secondary infection occurs, during which hyphae begin to develop from the primary infection hyphae, resulting in the creation of a vast hyphal network in the mesophyll layer. Approximately one week after the infection, the host response may appear, resulting in visible chlorotic spots appearing at the leaf surface. One week after, sporulation starts and the distinctive yellow spores will appear on the leaf (Chen, 2005). The optimum temperature for germination of the spores is 10-12 °C. High temperature inhibits sporulation or forces the fungus to enter dormancy. Under optimum conditions, the time between inoculation and sporulation is 12-13 days (Khanfri *et al*., 2018).

Wind serves as the primary method of spread or dispersal for stripe rust. The spores are generated in large quantities in pustules located on the upper surface of the leaves. After the spores are lifted into the air, their distribution becomes a matter of randomness. The majority will settle on soil or different plants, while a few remain airborne until sunlight destroys them within a few days. Spores of stripe rust and other rusts can also stick to clothing, enabling travelers to unintentionally transport them and disseminate them to another location (Fikrte Yirga, 2021).

2.7.3. Symptoms of the disease

Stripe rust infects the green parts of cereal crop and grass plants. Infection can take place at any time from the one-leaf stage until the plant reaches maturity, as long as the plants remain green. Symptoms begin to appear approximately one week after infection, with sporulation commencing around two weeks post-infection, provided the temperature conditions are optimal. The fungus produces small, yellow to orange-colored rust pustules, known as uredia. Each uredium is filled with thousands of urediniospores. A single urediniospore is too minute to be detected by the naked eye, but a mass of spores appears yellow to orange and powdery. No stripes of uredia or necrosis develop on the leaves of seedlings, but as the plants grow older, typically after stem elongation, the signs become more prominent (Chen, 2005).

The initial indication of stripe rust is the emergence of yellow streaks (pre-pustules), followed by small, bright yellow, and elongated uredial pustules organized in noticeable rows on the leaves, leaf sheaths, glumes and awns. Mature pustules will burst open and release yellow-orange clusters of urediniospores. In certain varieties, long and narrow yellow stripes may form on the leaves (Buck, 2014). In contrast to leaf and stem rusts, stripe rust consistently spreads beyond the initial infection site (Fikrte Yirga, 2021). As the plant enters the senescence stage during the stress period, the infected tissues turn brown and eventually dry out. The pathogen depletes the plant’s nutrients and water, thereby diminishing its vigor and causing leaf desiccation. Severe early infections can even lead to stunted plant growth (Khushboo *et al*., 2021). The symptom of yellow rust disease is shown below (Figure 2.1).



a) b)

Figure 2.1: Symptoms of yellow rust (Buck, 2014)

Individual uredinial pustules appear yellow to orange, are oblong in shape, and measure 0. 4 – 0.7 mm in length and 0.1 mm in width. Urediniospores can quickly germinate when there is free moisture (rain or dew) present on leaf surfaces and when temperatures lie between 7 and 12 °C. At higher temperatures or during the later growth phases of the host, black telia are commonly produced (Chen *et al*., 2014). The basidiospores, produced by the germination of teliospores, infect the leaves of barberry (*Berberis* spp.) and generate pycnia on the top side and aecia on the underside. Symptoms are also appear on Oregon grape (*Mahonia aquifolium*), serves as another alternate host of *Pst*. Likewise, pycnia and aecia develop on the upper and lower sides of the leaves respectively (Khushboo *et al*., 2021)..

2.7.4. Host range

Although rust fungi are generally regarded as being highly specific to their plant hosts, some species can exhibit a broad host range. For a cereal rust species, the main cereal crop is termed as a primary host due to its economic significance; wild grasses as auxiliary hosts because they share the same spore stages with the primary host; and non-grass hosts are categorized as alternate hosts because they are infected by a different spore stage (Chen and Kang, 2017). The host range of stripe rust fungus includes 320 grass species, which belong to nearly 50 genera within the subfamilies of Festucoideae and Eragosteae. The primary genera affected by stripe rust include *Aegilops, Agropyron, Bromus, Elymus, Hordeum, and Triticum.* Wheat and barley are the primary hosts of *Puccinia striiformis* (Khanfri *et al*., 2018). The alternative hosts of strip rust includes *Barberry* Spp *(Berberis chinensis, B. holstii, B. vulgaris, B. shensiana, B. potaninii, B. dolichobotrys, B. heteropoda,* etc.) and Oregon grape (*Mahonia aquifolium*) (Chen *et al*., 2014).

2.7.5. Conditions favoring the disease

Puccinia striiformis f. sp. *tritici* can survive as dormant mycelium on wheat. Urediniospores can sustain the disease on living host tissue, like volunteer wheat or susceptible wheat growing in other fields. Colder climates and higher elevations are the main habitats for yellow rust. Temperatures below 60ºF (15°C) at night are ideal for the pathogen's survival. Unlike other rusts, stripe rust can develop on wheat at lower temperatures. The ideal temperature range for urediniospore germination is 44–59°F (7–15°C). Infection and disease development is most rapid between 50-60ºF (10-16ºC). Wind currents carry urediniospores to healthy plants, where they might cause new infections. Intermittent rainfall or heavy dew might hasten the disease's spread. When temperatures regularly rise over 71-73ºF (21-23ºC), infection usually stops (Buck, 2014).

The outbreak of yellow rust is mostly dependent on the existing environmental conditions, including temperature, wind, and moisture, when there is a susceptible host and *P. striiformis* inoculum presents (Chen, 2005). Moisture, as a significant abiotic factor, directly affects spore germination, infection, dispersal, and the survival of the pathogen. For the germination of urediniospores and the subsequent infection of the host, continuous moisture for three hours is necessary. Rainfall, particularly light rains, creates favorable conditions for infection (Khushboo *et al*., 2021).

Various findings showed that all environmental factors had substantial relationship with disease severity. An increase of one unit in both minimum and maximum temperatures, relative humidity, rainfall, and wind speed resulted in an increase in disease severity. The germplasm that is susceptible, along with disease-promoting environmental factors such as temperature, relative humidity, rainfall, and wind speed, plays a crucial role in the development of yellow rust disease in wheat. The highest severity of yellow rust was recorded at minimum and maximum temperatures ranging from 13.7-16.7 and 23.5-27.65 °C, respectively. The increase in relative humidity from 52-64%, rainfall from 5.7-21.99 mm, and wind speed from 6.88-11.73 km/h, respectively, proved to be favorable for the development of yellow rust in Sargodha (Ali *et al*., 2017).

2.8. Status and Economic Importance of Yellow Rust Disease

Yellow rust is a widespread disease affecting major wheat producing regions across the globe and causes significant yield reductions in wheat yields that are estimated to be at least 5.5 million tons annually at a global scale (Worku Abebe, 2020). It diminishes both the yield and quality of grain and forage. Seeds produced from crops affected by yellow rust have reduced vigor and consequently poor emergence post-germination. Yellow rust can result in complete yield losses if infection happens very early and the disease continues throughout the growing season (Chen, 2005). The first report of stripe rust occurrence in Ethiopia dates back to the early 1940's and has been noted since the early 1980's. The extent of damage from stripe rust is influenced by the susceptibility of the wheat variety, the timing of epidemics, the level of stripe rust that manifests, and the prevailing low temperatures during the grain filling period (Chen, 2017). Yield losses can be considerable (60%) due to shriveled grain and damaged tillers, and in severe cases, it can result in total losses, especially when spikes are re-infected at higher elevations (Ayele Badebo *et al*., 2008).

In 2010, Ethiopia faced severe stripe rust outbreaks that affected more than 600,000 ha of wheat and resulted in an expenditure exceeding US$ 3.2 million on fungicides, while still experiencing significant, widespread losses (Fikrte Yirga, 2021). Wheat rusts have resulted in considerable income reduction, which we estimate on average to be of the order of 10s of millions US-D per year during the period of 2010–2019, with notable differences across the type of rusts and considerable inter-annual fluctuations. Among rusts, total loss estimates for stripe rust in the time interval from 2010-2019 vary between approximately 65 million US-D (peak in 2016) and 20 million US-D in years with smaller outbreaks (minimum in 2013) (Meyer *et al*., 2021). Yellow (stripe) rust caused by *Puccinia striiformis* f. sp. *tritici* is the predominant and most destructive disease in Ethiopia and other highlands of east Africa. It has led to substantial yield losses of up to 100% in the Ethiopian highlands (Wuletaw Tadesse *et al*., 2022). The disease adversely affects yield, quality and size of the harvested grains (Alemu Ayele *et al*., 2019).

According to Landuber Wendale *et al.* (2016), yellow rust epidemic during 2010, resulted in a significant grain yield loss of 34% in Amhara region. About 47%, 32%, and 28% of yield loss was recorded in north Shewa, east Gojjam, and south Gondar administrative zone of amhara region. Yellow rust disease is also prevalent in *Debre Elias district* with a 95% of mean incidence and 50% severity and resulted in a 25% of grain yield loss (Landuber Wendale *et al.*, 2016).

2.9. Management of Yellow Rust Disease

Yellow rust disease can be managed through the cultivation of disease-resistant cultivars, appropriate use of fungicides, and suitable cultural practices and by an integrated approach of combining them. However, greater effort are needed to develop more cultivars with durable, high level resistance, develop accurate forecast models, and monitor the disease and pathogen virulence for more effective, profitable, and sustainable control of yellow rust (Chen, 2020).

2.9.1. Cultural practices

Cultural techniques offer an alternative approach partially control wheat stripe rust. Implementing a variety of cultural techniques greatly improves the current sources of resistance. Consequently, crop management in terms of a combination of crop choice, timing of planting and removing volunteer cereals may provide effective control of stripe rust. Eliminating volunteer plants (the Green Bridge) that facilitate stripe rust survival serves as an effective management strategy for outbreaks caused by endogenous inoculum. Planting a mixture of wheat varieties with different resistance backgrounds may also significantly reduce disease (Khanfri *et al*., 2018). Furthermore, yellow rust disease can also managed by avoiding mono cropping system, planting early maturing variety and regular field monitoring. Cultural practices are mostly used to supplement the other disease control methods. Nevertheless, cultural methods, like delayed planting, decreased irrigation, avoidance of excessive nitrogen usage, and the removal of volunteer and grass plants, when utilized independently, may not be profitable (Fikrte Yirga, 2021). Overall, managing wheat rust through cultural techniques aids in reducing damage levels, but could be more effective if combined with other management strategies (EIAR, 2016).

2.9.2. Resistance varieties

Variety resistance serves as a crucial integrated pest management (IPM) strategy against pests and diseases, and it is regarded as a cost-efficient and eco-friendly means to manage fungal diseases. Using resistant varieties can be the simplest, practical, effective and affordable method for controlling plant diseases. The use of resistant varieties cannot only ensure protection against diseases but also save the time, energy and money used on alternative control measures. Management of stripe rust through resistance is an economical and environmentally secure method (Fikrte Yirga, 2021).

However, the disease can surpass the resistance of wheat varieties. The pathogen's significant pathogenicity variation enables its population to expand rapidly and disseminate under favorable weather conditions, resulting in devastating pandemics during growing seasons (Khan *et al*., 2023). Still, wheat breeding methods are inadequate for managing the newly emerged *Pst* strains and creating wheat varieties that possess high yields and resistance to yellow rust disease. Nonetheless, relying solely on resistant types may not be enough to completely prevent yellow rust; additional management strategies may be necessary (Zakaria *et al*., 2023).

Wild relatives of wheat may be a rich resource for new resistance genes for stripe rust. Thus widening the genetic base is a priority and primary target to improve the resistance of wheat varieties to cope with changing races of Pst is the preferred strategy for achieving global wheat demand (Khanfri *et al*., 2018). Most resistance genes to stripe rust originated from common wheat (*Triticum aestivum*), although a portion was sourced from various wild species, including *Triticum spelta album, Triticum dicoccoides, Triticum spelta, Secale cereale*, *Aegilops comosa*, *Aegilops ventricosa*, *Triticum tauschii and Haynaldia villosa* (Aktar-Uz-Zaman *et al*., 2017).

2.9.3. Biological control

Biological control agents are considered as less dangerous, because they have fewer detrimental effects on the environment and human health than traditional fungicides. Although microbial control is not a novel technique, the use of microbial control agents (MCAs) for the biological control of plant pests is referred to as an "alternative" strategy to chemical pesticides. In addition to controlling insect pests through entomopathogens, various antagonistic and mycoparasitic microorganisms have been extensively used in the management of plant pathogens (Sundh *et al*., 2021). One possible strategy for managing yellow rust is the use of bio agents or endophytic bacteria (Khan *et al*., 2023). By generating antifungal chemicals or competing with the pathogen for nutrition, these naturally occurring microorganisms can aid in protecting the plant from fungal infections. This strategy can be especially helpful in encouraging more sustainable agriculture and lessening the need for chemical pesticides. Beyond lowering the use of chemical pesticides, using bio agents or endophytic bacteria as environmentally friendly management strategies for disease control can have a number of advantages. For example, this strategy can also support biodiversity and soil health by preserving a healthy microbial community in the soil (Hermans *et al*., 2020).

According to Zakaria *et al*. (2023), the great efficiency of endophytic bacteria, *Bacillus subtilis* and *Pseudomonas putida* was shown, in reducing wheat stripe rust infection across three wheat varieties, namely Misr1, Gimmeiza11, and Sids12. After inoculation, *Bacillus subtilis* performed better than *Pseudomonas putida*, resulting infection types of 1 and 2.66, respectively. He further clarified that using bio agents can serve as a cost-effective and sustainable method for managing yellow rust, particularly for small-scale farmers who might not have access to costly chemical pesticides. Biological control agents are also believed to have a lower chance of pathogens becoming resistant, due to their intricate mode of actions. Only limited research has been carried out searching for biological control for the control of rust diseases under field conditions. Few field studies have demonstrated that, in comparison to synthetic fungicides, the use of *Bacillus subtilis* against various pathogens, such as powdery mildew (*Blumeria graminis*) and yellow rust, results in low to moderate levels of disease control and higher variability on control (Jørgensen *et al*., 2024).

2.9.4. Chemical control

Chemical fungicides are prioritized when the failures of resistant wheat varieties become apparent, as they offer a quick and easy way of controlling the disease. Foliar fungicides have been extensively utilized to combat yellow rust, which has helped prevent multimillion dollar losses and significantly minimized crop damage. Various studies reported that a relatively higher yield is achieved from treated plots compared to untreated ones under experimental conditions, and the timing of sprays has been identified as a crucial factor in lessening disease severity and the rate of epidemic development (Kabna Asefa *et al*., 2024). Similarly, Tesfaye Abdissa *et al*. (2024) noted that tested fungicides substantially decreased the yellow rust intensity as compared with untreated (control) plots.

However, the application of fungicides must be considered cautiously, as their effectiveness and economical use often relies on the resistance level of the variety, the crop's growth stage at the onset of the disease, disease severity and inoculum buildup, and current weather conditions, since these factors typically affect the frequency and rate of applications. Environmental considerations should always be taken whenever one decides on the use of chemicals for the control of diseases. Moreover, the timing of fungicide application is crucial for the effective and cost-efficient control of stripe rust (Fikrte Yirga, 2021).

Fungicide application is an essential strategy to combat stripe rust disease. To control this disease, a variety of synthetic chemicals were used. Globally, various commercial fungicide products were in use include Tilt, Evito, Quadri, Prosaro, Stratego and Quilt (Chen, 2007). Currently, the following active ingredients (including propiconazole, azoxystrobin, and propiconazole combined with trifloxystrobin, strobilurin, and azoxystrobin paired with propiconazole) are registered for the control of stripe rust in Morocco (Khanfri *et al*., 2018). However, the use of fungicides raises the cost of wheat production significantly, which burdens many growers, particularly in developing nations. The application of fungicides might also lead to health issues for users, negatively impact the environment, and contribute to the emergence of fungicide-resistant strains of the pathogen (Zewdie Bishaw *et al*., 2010).

2.9.5. Integrated disease management

The integrated management strategies rely on a combination of approaches which, depending on variety to be grown and the diseases. It includes variety selection, crop rotation, control of volunteers, Stubbs removal, and the uses of clean seed, seed and/or fertilizer treatments and foliar fungicide applications (GRDC, 2014). Policymakers have a general goal and desire minimize the use of chemical pesticides and encourage more sustainable cropping practices, driven by various directives and stricter regulations regarding pesticide authorization. The application of integrated pest management (IPM) is a key component, involves more focus on growing resistant varieties, inclusion of monitoring and decision support systems prior to pesticide application, and utilizing biological control agents (BCA) and other alternative disease management strategies (Jørgensen *et al*., 2024).

Because of the pathogen's complexity, comprehensive management strategies are necessary to effectively combat wheat rust infections. Single control measures are insufficient for long-term prevention; instead, integrated strategies and practices are required. The main strategy for disease prevention is the use of resistant varieties, but contingency plans must also be devised to manage potential outbreaks through the careful application of fungicides. Other agronomic practices such as eliminating green bridges between crop cycles, variety deployment, and precise irrigation and fertilization must also be taken into account (Fikrte Yirga, 2021).

For example, the combined impact of variety and fungicide application, alongside environmental variability, has shown significant effects on the management of epidemic development of yellow rust disease (Getachew Gudero, 2020). Additionally, a number of studies show that host resistance and fungicides may be useful in controlling wheat stripe rust disease (Alemu Ayele *et al*., 2019). Various research results have shown that the use of fungicides and resistant wheat types results in an increase in wheat yield. A study by Melka Kecha and Amin Mohammed (2023) found that fungicide-treated bread wheat varieties improved bread wheat rust control as compared to unsprayed varieties.

CHAPTER 3: MATERIALS AND METHODS

The research had two components; those are assessment to assess the extent of yellow rust of bread wheat and field experiment to evaluate the effects of bread wheat varieties and fungicides spraying on the management of yellow rust of wheat.

3.1. Assessment of Yellow Rust Disease of Bread Wheat

3.1.1. Description of the survey area

A field survey for yellow rust of bread wheat was conducted in *Debre Elias district*, which is found in East Gojjam, Amhara National Regional State of Ethiopia during the 2023 cropping season. Debre Elias is located around 340 km Northwest of Addis Ababa, 247 km southeast of Bahir Dar, and about 42 km Northwest of Debre Markos town. The local community’s primary source of income is small-scale mixed agriculture. Maize, Wheat, Barley, *Teff*, Niger seed, and Potatoes are the principal crops produced, and from the livestock Cattle, Sheep and Goats are the dominant animals in the area (Mengistu Yismaw, 2021).

Debre Elias is located at 10°0′0″- 10°25′0″ N latitude and 37°4′0″- 37°30′0″ E longitude. The district is bordered on the south and west by Abay River, on the northwest by West Gojjam Administrative Zone, on the north by *Machakel*, and the east by *Gozamen district*. About 99% of the *district* is mid-altitude, with an average annual temperature between 18 and 27 °C and an average annual rainfall of 1150 mm and situated between 800 and 2600 meters above sea level altitude range. The area mainly consists of plain topography (85%) while the rest (15%) is undulating topography. The moderately fertile red soils are the dominant soil type in the area (Habtamu Kefale and Ahadu Menzir, 2019). The area consists of 85% nitosol, 0.5% vertisol, and 14.5% brown mixed soil types with exchangeable acidity 0.57- 0.78 cmkg/kg (DEDAO, 2023 unpublished).

3.1.2. Sample size, techniques, and procedures

The assessment of yellow rust was conducted in *Debre Elias district* during the 2023 main cropping season under rain fed conditions on farmer’s fields. From the *district*, four *kebele* administrations were selected using a purposive sampling method based on wheat production potential and disease problem. A total of 100 farmer fields were assessed from the four *kebele* administrations namely; *Guay, Degolma, Tijagotor*, and *Gofichima kebele* administrations.

The number of representative farmer fields in each *Kebele* administration was determined using proportional sampling method based on population size and fields were selected randomly by simple random sampling method. A total of 35, 30, 20, and 15 sample farmer fields were assessed from 2200, 1700, 1450, and 400 wheat producers in *Guay, Degolma, Tijagotor*, and *Gofichima kebele* administrations respectively. In each farmer field, the survey data were collected through a systematic sampling method using Quadrate (1m x 1m) by walking along the two diagonals of wheat fields in ‘‘X’’ patterns (Stubbs *et al*., 1986). The assessment was conducted at the critical stage of disease appearance.

3.1.3. Data collection

During the survey, quantitative and qualitative primary data (agronomic data, disease incidence, severity, and prevalence) were recorded and calculated scientifically. During the field assessment, agronomic techniques and altitude were recorded on each bread wheat farm field in order to ascertain the relationship between bread wheat yellow rust incidence and severity with independent variables. Agronomic practices like, varieties grown, previous crops (Maize, Wheat and *Teff*), planting density (low, medium, and high), planting date (third week of July, fourth week of July and first week of August), growth stages (heading, early milking and late milking), and management practices on each farm field were collected. To get the necessary data from the farmers, survey questionnaires were also used, and administered in-person interviews. Data on agronomic practices were collected by interviewing growers and by observing fields of farmers.

In each farmer field, ten randomly selected wheat plants within the quadrate were counted as infected / non-infected and used to calculate average values (Stubbs *et al*., 1986). The disease parameters were collected as per the following standard formula;

Disease incidence (%) = $\frac{\text{Number of diseased plants in a quadrate}}{\text{Total number of plants assessed in a quadrate}} X\ 100$ (Chavdarov, 2006)

Prevalence (%) = $\frac{\text{Number fields affected by the disease}}{\text{Total number of fields assessed}} X\ 100$

Disease severity: it was recorded on 10 randomly selected plants on the basis of the percentage of leaf area infected using the modified cobb-scale (Peterson *et al.*, 1948). Disease severity was calculated by the formula:

$$\text{Disease severity (\%)} = \frac{\text{Area of leaf affected}}{\text{Total area of plant examined}} \times 100$$

3.1.4. Survey data analysis

The survey data were analyzed using Statistical Package for Social Sciences (SPSS) software version 25 to determine the incidence, severity, and prevalence of disease. The data were subjected to descriptive statistical analysis like mean, range, and percent of the disease incidence and severity over the district, varieties grown, the altitude range, previous crop, plant density, sowing time, crop growth stage, and management practices. Analysis was conducted to ascertain the relationship between bread wheat yellow rust incidence and severity with independent variables.

The association between yellow rust disease incidence and severity with independent variables was analyzed using a logistic regression model with the SAS version 9.4 procedure (SAS Institute, 2024). The importance of multiple independent variables that affect the response variable was assessed using a logistic regression model and the probability of the given binary outcome as a function of the independent variables was calculated.

3.2. The Effect of Integrated use of Fungicide and Host Resistance against Yellow Rust Disease of Bread Wheat

A field experiment was carried out to determine the integrated effects of fungicide application and varieties on the incidence and severity of yellow rust on bread wheat, and yield and yield-related parameters under natural conditions at *Guay Kebele* administration in *Debre Elias District*.

3.2.1. Description of the experimental site

The field experiment was conducted under rain-fed conditions at *Guay Kebele* Administration on the farmer's field level in *Debre Elias district*, East Gojjam Administrative zone, during the 2023 main cropping season. The experimental site was chosen based on wheat production potentials and hot spot areas for the development of yellow rust disease. The experimental site is geographically located at 10°18′47″N latitude and 37°19′27″E longitudes with an elevation of 2155 m.a.s.l. The soil is moderately acidic with a pH of 5.18. Wheat, Maize, *Teff*, Barley, and Niger seed are the major crops produced in the area.

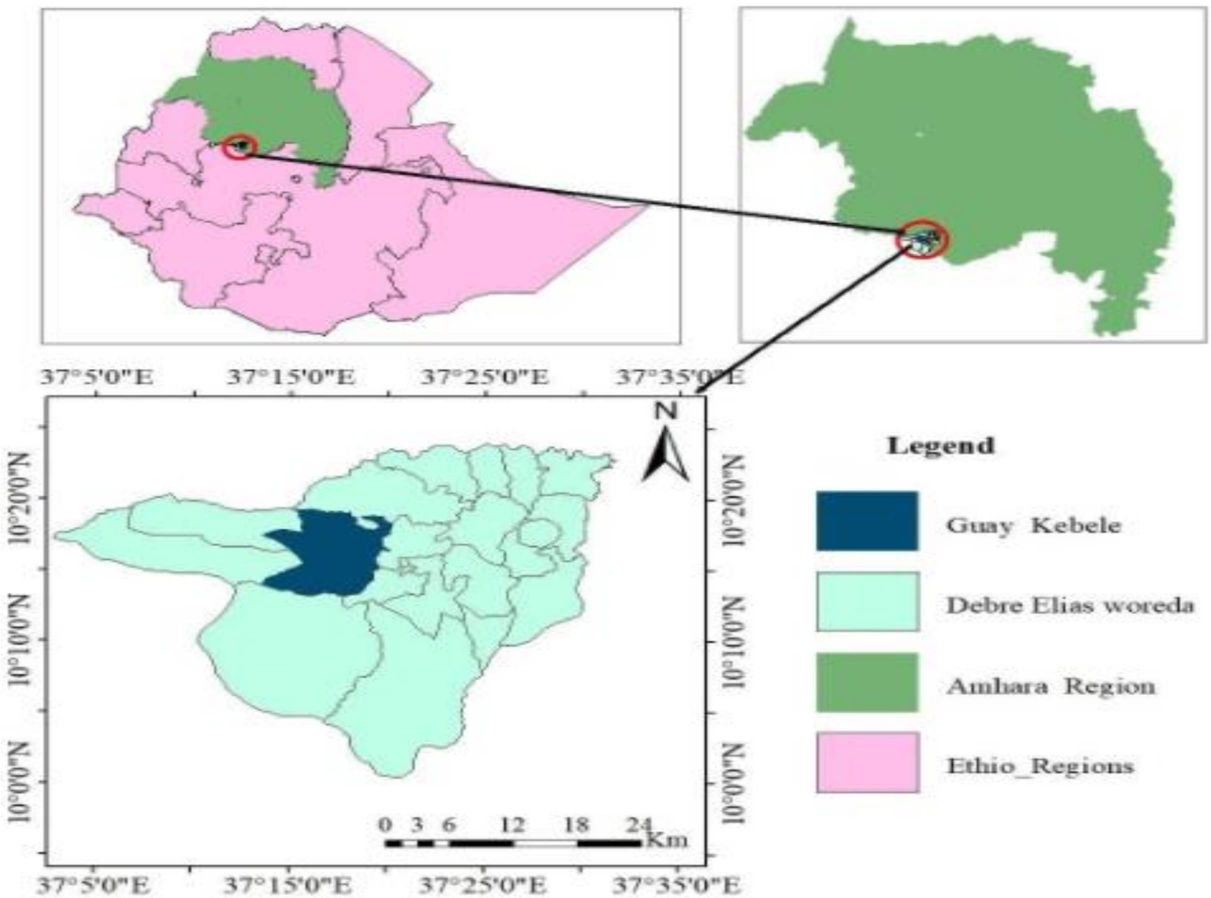


Figure 3.1: Map of the study area (Source: Extracted by Yekedem Amare)

3.2.2. Experimental materials

The treatment consists of three bread wheat varieties namely: Danda'a (resistant), Ogolcho (moderately resistant) and Kakaba (susceptible) having different resistance levels to yellow rust. The three varieties were obtained from Amhara Seed Enterprise (ASE). These bread wheat varieties were selected based on adaptability, yield potential and widely used in the study area. Nativo SC 300 and Kanzole 25% EC were used as a fungicide component. The seeds of each bread wheat variety were sown in rows at a rate of 150 kg ha^{-1}on a well-prepared seedbed and 200 kg ha^{-1} of urea (½ at sowing and ½ at the tillering stage) and 150 kg ha^{-1} of NPSB fertilizers were applied manually. A recommended manufacturing product rate of 0.75 L ha^{-1} of Nativo SC 300 and 0.5 L ha^{-1} of Kanzole 25% EC fungicides were applied with 200 L ha^{-1} and 250 L ha^{-1} of water respectively. The fungicides were obtained from Debre Elias legally authorized pesticide shops.

Table 3.1: Description of bread wheat varieties used for field experiment

Variety	Year of release	Releasing center	Yield at the time of release (t ha^{-1})		Reaction to YR	Altitude (m.a.s.l)	RF (mm)
			On station	On farm			
Ogolcho	2012	KARC	2.8 – 4	2.2 - 3.5	MR	1600 – 2100	400 -500
Kakaba	2010	KARC	3.5 - 5.5	2.5 – 5	S	1500 – 2200	500- 800
Danda’a	2010	KARC	3.5 – 5.5	2.5 – 5	R	2000 – 2600	> 600

YR = Yellow Rust, RF = Rainfall, KARC = Kulumsa Agricultural Research Center, MR = Moderately Resistance, S = Susceptible, R = Resistance

Source: Ministry of Agriculture (MoA, 2016)

Table 3.2: Description of fungicides for field experiment

Trade name	Common name	Registration number	Active ingredients	Recommendation ha^{-1}	Mode of action
Nativo SC 300	Trifloxystrobin +Tebuconazole	ET/FN/186/2014	Trifloxystrobin 100gm/l + Tebuconazole 200 gm/l	0.75 Liter	Systemic
Kanzole 25% EC	Propiconazole	ET/FN/YR01/2021	Propiconazole 250 gm/l	0.5 Liter	Systemic

EC = Emulsified Concentration, SC = Solid Concentration

Source: Ministry of Agriculture (MoA, 2016) and product package booklet.

3.2.3. Treatments, experimental design and procedures

The experiment had nine treatments (three wheat varieties Ogolcho, Danda’a and Kakaba are combined with two fungicides Nativo SC 300 (Trifloxystrobin +Tebuconazole) and Kanzole 25% EC (Propiconazole) and one unsprayed as a control). A total of 27 experimental units or plots were used with a single plot size 1.5 m^2 (1m x 1.5m). Each plot consisted of five rows with 0.3 m inter row spacing. The distance between blocks and plots was 1 m and 0.5 m respectively. The net and gross experimental areas were 40.5 m^2 and, 84.5 $m^{2,}$ respectively. The experiment was laid out in Randomized Complete Block Design (RCBD) with three replications in factorial arrangement. The treatments were assigned randomly using a lottery randomization method within blocks. The bread wheat crop was sown manually in row on a well-prepared seedbed. Knapsack sprayer was used to spray the fungicides. Spraying of fungicides was started on the first appearance of yellow rust symptoms. During fungicide application, plastic sheets were used to prevent spray drift effect. Weed was removed manually and other agronomic practices were applied uniformly for each plot based on the crop production package recommendations.

Table 3.3: Treatment combinations of the field experiment

Treatment number	Treatment combinations
T1	Danda'a + Nativo SC 300
T2	Danda'a + Kanzole 25% EC
T3	Danda'a + Unsprayed
T4	Ogolcho + Nativo SC 300
T5	Ogolcho + Kanzole 25% EC
T6	Ogolcho + Unsprayed
T7	Kakaba + Nativo SC 300
T8	Kakaba + Kanzole 25% EC
T9	Kakaba + Unsprayed

3.2.4. Data collection

The disease parameter data were recorded every 10 days interval from the first appearance of disease symptom up to the crop attaining its physiological maturity on site. Yield and yield components of wheat were collected from the middle rows of middle plants in each experimental plot. Space was left at both sides of the plot at the time of data collection in order to minimize border effect (Getachew Gudero, 2020).

3.2.4.1. Disease data

Days to first disease symptom appearance: was recorded by counting the number of days from time of sowing to first disease symptoms observed on the leaves of the plant.

Disease incidence: yellow rust incidence was recorded from ten randomly selected plants per plots at every 10 days interval starting from the first appearance of disease symptom up to maturity. Percent of disease incidence was calculated by counting diseased and total number of plants assessed in each plot using the following formula (Chavdarov, 2006).

$$\text{Disease incidence (\%)} = \frac{\text{number of diseased plants}}{\text{Total number of assessed plants}} \times 100$$

Disease severity: it was recorded on 10 randomly selected and pre tagged plants in a 10 days interval starting from the time of disease appearance until the crop attained its physiological maturity and the average was taken. It was recorded on the basis of the percentage of leaf area infected using the modified cobb-scale (Peterson *et al.*, 1948). Disease severity was calculated by the formula:

$$\text{Disease severity (\%)} = \frac{\text{Area of leaf affected}}{\text{Total area of plant examined}} \times 100$$

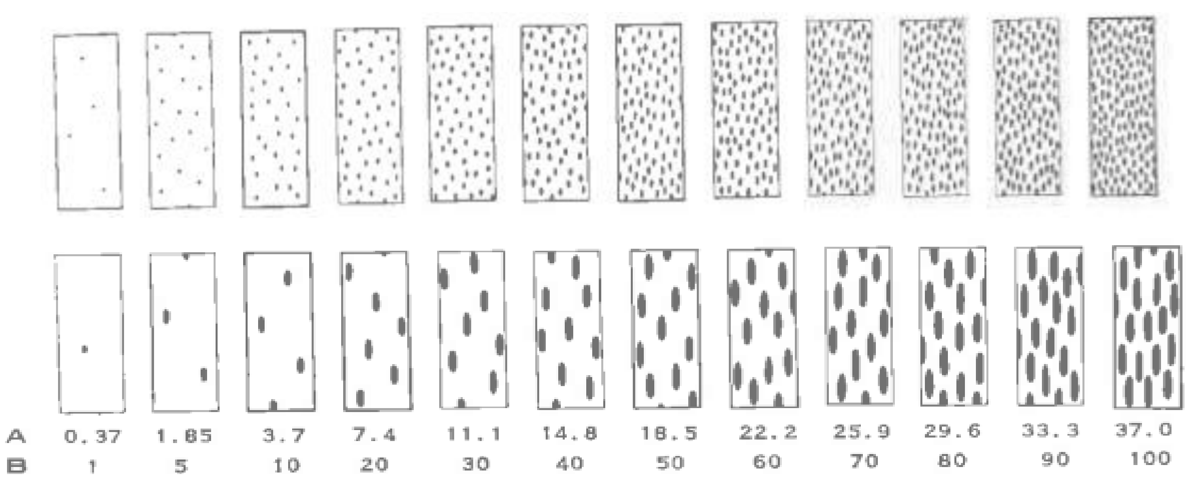


Figure 3.2: Modified cobb-scale for yellow rust response value (Peterson *et al.,* 1948)

Percent disease control (PDC %): the percent yellow rust severity control was calculated based on the final yellow rust severity using the following formula:

PDC (%) = $(\frac{\text{PST}-\text{PSU}}{\text{PSU}})\ x\ 100$

Where, PDC = percent disease control, PST= percent severity in treated plot (both sprayed and unsprayed plot), PSU = percent severity in untreated plot (unsprayed or control plot) within each respective varieties (Roelfs *et al*., 1992).

Coefficient of infection (CI): It was calculated by multiplying the final yellow rust severity data with a constant value of the variety's resistance level for field response. The field constant values of host field response for immunity=0, resistance (R) = 0.2, moderately resistance (MR) = 0.4, intermediate resistance (MRMS) = 0.6, moderately susceptible (MS) = 0.8, moderately susceptible to susceptible (MSS) = 0.9 and susceptible (S) = 1 (Roelfs *et al*., 1992).

Area under disease progress curve (AUDPC): AUDPC value was calculated for each treatment using the following formula and the value expressed in % days^{-1}. Area under disease progress curve (AUDPC) is the region between the disease progress curve and the X-axis of the graph. A formula that considers the number of times the disease severity was assessed, the disease severity at each evaluation period, and the length of the epidemic is used to calculate the area under the disease progress curve, which is used to summarize the progression of disease severity.

$$AUDPC\ (\%\ /day) = \sum_{i=1}^{n\_1}[0.5(xi + 1 + xi)(ti + 1 - ti)]$$

Where n is the total number of assessments, t_i is the time of the ith assessment in days from the first assessment date, x_i is percentage of disease severity at ith assessment. AUDPC value was used in analysis of variance to compare the amount of disease among plots with different treatments (Campbell and Madden, 1990).

Disease progress rate (r): It was determined by the repeated assessment of the percentage of leaf area affected by yellow rust disease in each plot starting from the onset of the disease. Logistic, r = ln [(Y/1-Y)] (Van der Plank, 1963) and Gompertz, r = -ln [-In(Y)] (Berger, 1981) model were compared for estimation of disease progression parameters from each treatment. Where r is disease progress rate, Y is disease severity, and ln = Natural logarithm.

The transformed data were regressed over time to determine the rate. The goodness of fit of the models was tested based on the magnitude of the coefficient of rate determination (R^2). The model, which has a higher coefficient of rate determination for the treatments, was used to calculate the disease progress rate. There was a higher coefficient of determination (R^2) on the Gompertz model than on the logistic model. The data was better fitted to the Gompertz model than the logistic model. Therefore, the disease progress rate in yellow rust was estimated and compared using the Gompertz model.

3.2.4.2. Agronomic data

Days to 50% heading: The number of days from sowing to the time when 50% of plants showed head on each plot was recorded.

Days to 90% physiological maturity: it was recorded by counting the number of days from sowing to the date when 90% of the plant's population physiologically changed to a yellowish color.

Plant height: was measured on 10 randomly selected plants in each plot from the ground surface to the tip of the spike excluding awns, and the average was taken.

Spike length: the length of spike was measured in centimeters on 10 pre-tagged plants excluding awns.

Number of grains per spike: the average number of grains of the main stem of the ten pre-tagged plants was recorded by counting the grains that obtained from each spike of pre-tagged plants.

Thousand-kernel weight: it was taken by measuring the weight of randomly selected thousand grains by using sensitive balance from each plot.

Above ground biomass yield: the above ground biomass was measured by weighting the total above ground parts per plot with balance.

Grain yield: Grain yield in kilogram per plot was recorded and translated to t ha^{-1}.

Straw yield: The weight of straw was measured per plot.

Relative yield loss: The relative losses in yield and yield components of each variety were calculated by the formula;

$$\mathrm{RL}(\%) = \frac{\mathrm{Yp-Yup}}{\mathrm{Yp}} x100,$$

Where, RL% =percentage of relative loss Yp = (plots yield with maximum protection) Yup = yield of unprotected plot with different levels of disease within the respective varieties (Cortes *et al*., 2000).

Percent yield increment (PYI %): Grain yield increments of each bread wheat variety were determined as percentages of those of protected plots of the respective variety. Relative yield increment was calculated by using the formula:

$$PYI\ (\%) = \frac{\text{grain yield of protected plot} - \text{yield of control plot}}{\text{Yield of control plot}} \times 100$$

Where, PYI % = Percent yield increment within each respective variety

3.2.5. Data analysis

Data on, disease, yield and yield related parameters were subjected to analysis of variance appropriate for RCBD in the factorial experiment to determine the treatment effects using Statistical Analysis System (SAS) version 9.4 software. Least significance difference (LSD at 5% probability level) was used to separate treatment means (Gomez and Gomez, 1984). Correlation analysis was performed to determine the relationship between disease parameters (the independent variable) and yield parameters in the field plots.

3.2.6. Partial budget analysis

Partial budget analysis was done using average yields for each treatment produced and the total expenses that have been expended during the experiment. CIMMYT (1988) budget analysis method was used for the analysis. Total variable cost, gross benefit, net benefit (NB), and marginal rate of return (MRR) were the attributes used in the partial budget analysis. Total input variable costs, which were expended during the execution of the experiment, were the total of all input variable costs (including fungicides and labor for fungicide spraying costs). The cost of Nativo SC 300 fungicide and Kanzole 25% EC was 3800 Birr liter^{-1} and 1800 Birr liter^{-1} respectively, obtained from pesticide companies and local distribution agencies. The cost of daily labor was 300 birr per day for spraying fungicide. During harvesting season, local market prices for bread wheat grain and straw yield were 55 birr kg^{-1} and 10 birr kg^{-1}, respectively.

The net benefit was the difference between the gross benefit and the total variable costs, whereas the gross benefit was incurred as the product of the wheat grain yield and market price. To account for management differences, yield and straw yield data collected at the time of harvest from each treatment were adjusted downward by 10% to reflect the variation between the experimental yield and the yield that farmers might have expected from the same treatment. Because, it assumes to have optimum crop density, timely labor availability, and better field management as compared with farmers. The dominance analysis method, was used to identify potentially profitable treatments, involved ranking the treatments based on their total variable costs (TVC) in ascending order to eliminate treatments costing more but producing a lower net benefit (NB) than the next lowest costing treatment (Table 4.24). For each pair of ranked undominated treatments, marginal rate of return (MRR %) was calculated as described by CIMMYT (1988). The following formulas were used to compute partial budget and marginal rate of return (MRR) analysis.

GB = AjY * farm selling price

AjY = AvY− (AvY∗0.1) Where, GB = gross benefit, AjY = adjusted yield, AvY = average yield obtained from the field.

Net field benefits (NB) = Gross field benefits (GB) - Total Variable costs (TVC) and

MRR = $\frac{DNI}{DIC} * 100$ Where, MRR = marginal rate of return; DNI = difference in net income compared with control; and DIC = difference in input cost compared with control (CIMMYT, 1988).

CHAPTER 4: RESULTS AND DISCUSSION

4.1. Assessment of Bread Wheat Yellow Rust Disease

4.1.1. Disease prevalence

During the assessment, the majority of the farmer's bread wheat fields were late sown as compared to the previous bread wheat sowing time, due to a shortage of fertilizer and rainfall at the time of sowing in the study area. Most of the varieties observed in the district during survey time were Kakaba, Ogolcho and kingbird bread wheat varieties. From the total surveyed farm fields, 88% of fields were infected by yellow rust disease. Yellow rust was prevalent in all assessed *kebele* administrations, in which a maximum of (94.28%) disease prevalence was observed in *Guay kebele* administration and a minimum of (80%) was recorded in *Gofichima kebele* administration (Table 4.1). This might be due to the variation in climate condition, agronomic practices, altitude, and management practices applied in the area. The result showed a highest prevalence of yellow rust disease was observed in the district at the time of the study.

Table 4.1: Prevalence, mean incidence and severity of yellow rust in each *Kebele* administrations of the study area during 2023 main cropping season

District	Kebele	N	Prevalence (%)	Average incidence (%)	Average severity (%)
Debre Elias	Guay	35	94.28	46.93	31.99
	Degolma	30	83.33	37.37	24.41
	Tijagotor	20	90.00	47.81	33.70
	Gofichima	15	80.00	34.76	22.75
Overall		100	88.00	42.41	28.67

N = Number of farmers field assessed

4.1.2. Disease incidence

The survey result showed that the mean incidence of yellow rust disease was prevalent in all surveyed *kebele* administrations with varying degrees of incidence. The disease incidence in the *district* ranged from zero to 96.67% and the overall mean incidence was 42.41%. A higher mean incidence (47.81%) was recorded in *Tijagotor* followed by *Guay kebele* administration

(46.93%) and a lower mean incidence (34.76%) was recorded in *Gofichima kebele* administration (Table 4.1).

Bread wheat fields that were covered by Ogolcho variety (69.03%), sown in the 4th week of July (52.82%), and at heading growth stage (46.13%) with high plant density had the highest mean incidence as compared to their respective variable classes. Additionally, highest mean incidence was shown on the fields previously covered by wheat crop (56.26%), found at an altitude range ≥2167 (44.86%) and fields which were unsprayed (49.25%). Whereas, the lowest mean incidence was recorded in wheat fields covered by Kingbird variety (13.61%), sown late in the 1st week of August (28.03%), and which were at late milking growth stage (31.98%). The lowest yellow rust mean incidence was also shown on fields that were previously covered by *Teff* crop (14.54%) with an altitude range <2167 (37.67%) and which were sprayed with fungicide for disease control (34.05%) (Table 4.2).

According to Yitagesu Tadesse *et al*. (2023), the intensity of wheat diseases vary among sites, based on agro-ecologies (favourable weather conditions), the cultivars used, and specific production practices. Similarly, Ashagre Asnakew (2021) stated that high altitude and susceptible wheat variety are good factors for the occurrence of yellow rust disease. He also reported that yellow rust occurs at the early stage of wheat and a higher incidence of 0-100% was recorded at the Milk stage than other (dough and maturity) growth stages. Meyer *et al*. (2021) also reported that the prevalence of yellow rust intensity (disease incidence or severity) increases with increasing altitude.

4.1.3. Disease severity

Survey results indicated that the severity of yellow rust disease in the study area ranged from 0 to 88.75% and the overall mean severity was 28.67%. The maximum mean severity (33.70%) was recorded in *Tijagotor* followed by *Guay kebele* administration (31.99%), while the minimum (22.75%) was recorded in *Gofichima kebele* administration (Table 4.1). The highest mean severity was recorded on fields covered by Ogolcho variety (50.91%), sown at the 4th week of July (35.83%), which were at heading growth stage (31.48%) with high plant density (40.79%), previously covered by wheat crop (36.97%) with an altitude range ≥2167 (31.77%) and fields which were unsprayed (36.61%). However, fields which were covered by kingbird variety (6.05%), sown at the 1st week of August (18.83%), at late milking growth stage (18.39%) with low plant density (12.19%), previously covered by *Teff* crop (8.92%) with an altitude range <2167 (22.66%) and fields which were sprayed with fungicide (18.98%) had the lowest mean severity (Table 4.2).

The study result showed that varieties, time of sowing, field history, altitude, cropping system, plant density, growth stage and weather condition had an influence on the severity of yellow rust. It demonestrated that, growing susceptible bread wheat varieties, using monocrop ping system of wheat production, and improper spacing (dense spacing) has increased yellow rust severity to the highest level. On the other hand, sowing resistance bread wheat varieties, applying crop rotation, and proper spacing showed yellow rust severity reduction. Similarly, Yitagesu Tadesse *et al*. (2023) reported that various wheat cultivars had different responses against the disease during assessment. He reported that Ogolcho cultivar had the highest mean yellow rust incidence of 59% and severity (73%) as compared to others. The current study is also supported by Meyer *et al*. (2021), who reported that yellow rust severity increases with increasing altitude. According to Ashagre Asnakew, (2021), Wheat growth stage also has an additional effect on yellow rust infection. A high severity (0-60%) was recorded at milk stage and lowest severity was recorded at maturity stage.

Table 4.2: Incidence and severity of bread wheat yellow rust disease for independent variables in the study area during 2023 main cropping season

Variable	Variable classes	N	Incidence (%)		Severity (%)	
			Range	Mean	Range	Mean
District	Debre Elias	100	0-96.67	42.41	0-88.75	28.67
PC	Wheat	26	0-96.67	56.26	0-88.75	36.97
	Maize	63	0-91.67	41.57	0-83.33	28.70
	Teff	11	0-37.25	14.54	0-28.75	8.92
Varieties	Ogolcho	35	21-96.67	69.03	22.5-88.75	50.91
	Kakaba	50	0-85.75	32.42	0-73.45	19.89
	Kingbird	15	0-56.67	13.61	0-19.75	6.05
TS	3rd July	36	0-87.50	37.69	0-79	25.40
	4rth July	44	0-96.67	52.82	0-88.75	35.83
	1st August	20	0-70	28.03	0-61.25	18.83
PD	Low	4	0-37.25	20.56	0-28.75	12.19
	Medium	63	0-91.67	36.04	0-83.33	23.37

	High	33	0-96.67	57.23	0-88.75	40.79
GS	Heading	48	0-96.67	46.13	0-88.75	31.48
	Early milking	33	0-95	43.02	0-83.33	30.51
	Late milking	19	0-71.67	31.98	0-48.75	18.39
DM	Sprayed	45	0-73.3	34.05	0-53.30	18.98
	Unsprayed	55	0-96.67	49.25	0-88.75	36.61
Altitude	<2167	34	0-69.25	37.67	0-53.75	22.66
	≥2167	66	0-96.67	44.86	0-88.75	31.77

N = Number of farmer fields, PC = Previous crop, TS = Time of sowing, PD = Plant density, GS = Growth stage, DM = Disease management

4.1.4. Association of independent variables with disease severity

The variables were entered into the logistic regression model and the association result showed all the independent variables; such as *Kebele*, time of sowing, plant density, growth stage, varieties, field history, altitude, and management practices had a very highly significant (P < 0.01) association with yellow rust severity as a single predictor in the logistic regression model (Table 4.3). The result demonstrated that, all the above listed independent variables are important factors, that have an influence on the intensity of yellow rust disease of bread wheat.

Table 4.3: Independent variables used as single predictor of disease outcome in logistic regression modeling of yellow rust severity and likelihood ratio test for Type 3 analysis

Variables	Df	Yellow rust severity LRT	
		DR	Pr>x2
Kebele	3	36.00	<.0001
Altitude	1	18.02	<.0001
Variety	2	860.91	<.0001
Previous crop	2	61.58	<.0001
Time of sowing	2	162.19	<.0001
Growth stage	2	13.08	0.0014
Plant density	2	20.45	<.0001
Disease Management	1	198.95	<.0001

DF = Degree of freedom, LRT = Likelihood ratio test, DR = Deviance reduction, Pr = Probability of $\chi 2$ value exceeding the deviance reduction, χ^2 = Chi square test values of the model

4.2. Field Experiment

4.2.1. Disease onset and incidence

The analysis of variance showed that there was a highly significant (p<0.01) difference on days to first disease symptom appearance among varieties. The first yellow rust disease symptom appeared early at the booting stage of the crop on both Ogolcho and Kakaba bread wheat varieties (44 DAS) and at the heading stage on resistant variety Danda'a (53 DAS) (Table 4.4). This might be due to the difference in varieties resistance against yellow rust.

Table 4.4: The main effects of varieties and fungicides on days to first disease symptom appearance

Treatments		DFDSA
Variety	Danda'a	53.89^a
	Ogolcho	44.33^b
	Kakaba	44.56^b
LSD (0.05)		1.50
CV (%)		3.16
P-value		<.0001

DFDSA = Days to first disease symptom appearance, LSD = Least significant difference, CV = Coefficient of variation, P- value = Probability value

The analysis of variance revealed that the main effects of varieties and fungicides had a very highly significant (p<0.01) effect at the second (56 DAS), third (66 DAS), fourth (76 DAS), fifth (86 DAS) and Sixth (96 DAS) date of assessment of disease incidence. However, on the first (46 DAS) disease assessment date, varieties had a very highly significant (p<0.01) effect but fungicide showed non-significant (p>0.05) effect (Appendix Table 1). This is due to yellow rust disease incidence data was recorded before fungicide application and the fungicide had no effect on the incidence of yellow rust at the first disease incidence assessment date. On the first date of disease assessment, the highest mean incidence was recorded on Ogolcho variety (16.67%) followed by Kakaba (8.89%), whereas no disease incidence (0.00%) was recorded on Danda'a variety (Table 4.5).

At the second time of disease assessment, there was a significant difference in yellow rust mean incidence among varieties and fungicides. The highest mean incidence (33.33%) was recorded on Ogolcho variety followed by Kakaba variety (20.00%) and the highest (26.67%)

of mean incidence was recorded on unsprayed plots. While, the lowest mean incidence (10.00%) was recorded on resistant variety Danda'a and 15.56% was recorded on Nativo SC 300 fungicide (Table 4.5).

Generally, the study result showed that, there was a highest mean yellow rust incidence (46.67%, 55.56%, 66.67% and 74.44%) on Ogolcho variety on 66 DAS, 76 DAS, 86 DAS and 96 DAS respectively and 42.22%, 55.56%, 70.00% and 80.00% were recorded in 66 DAS, 76 DAS, 86 DAS and 96 DAS respectively on unsprayed plots. Whereas, the lowest (16.67%, 25.56%, 36.67% and 43.33%) disease incidence was recorded on Danda'a variety and 25.56%, 30%, 38.89% and 42.22% was recorded on Nativo SC 300 fungicide on 66 DAS, 76 DAS, 86 DAS and 96 DAS respectively (Table 4.5). There was a maximum mean incidence recorded on Ogolcho variety (74.44%), followed by Kakaba (62.22%) and Danda'a variety (43.33%) at sixth time of yellow rust assessment than fifth, fourth, third, second and first time of disease assessment. It indicates the increment in progress of the disease from initial to final time of disease assessment due to the polycyclic nature of the pathogen.

The current result demonstrated that the highest mean incidence was observed on Ogolcho variety and unsprayed plots while the lowest mean disease incidence was recorded on Danda variety and Nativo SC 300 fungicide treated plots. It indicated that Danda'a was the best performing variety among tested varieties and from fungicide, Nativo SC 300 was better in effectively reducing yellow rust disease incidence. The result also showed that the moderately resistant variety Ogolcho was highly affected by yellow rust than the susceptible variety Kakaba during the time of study. This might be due to either introduction of exotic races or evolution of new local races of pathogens and changes in environmental factors.

According to Metiku Kebede *et al.* (2023), the resistance gene of released resistance bread wheat varieties will break through time due to the evolution of new races or prevailing environmental factors. The current result contradicts with the result of Taddese Sintie (2021), who reported that at the first date of yellow rust assessment higher incidence (15.5%) was recorded on susceptible (Picaflor) variety, medium (13.0%) at moderately resistant variety (Ogolcho) and no incidence (0.0%) on resistant wheat variety (kingbird). Jørgensen *et al*. (2024), also reported *P. striiformis* ability to produce new virulent races that can overcome varietal resistance has resulted in sudden epidemics in varieties previously regarded as resistant.

Table 4.5: The main effects of fungicide and varieties on yellow rust disease incidence

Treatments		Mean incidence (%) on different date of assessment					
		46 DAS	56 DAS	66 DAS	76 DAS	86 DAS	96 DAS
Varieties	Danda'a	0.00[c]	10.00[c]	16.67[c]	25.56[c]	36.67[c]	43.33[c]
	Ogolcho	16.67[a]	33.33[a]	46.67[a]	55.56[a]	66.67[a]	74.44[a]
	Kakaba	8.89[b]	20.00[b]	34.44[b]	44.44[b]	55.56[b]	62.22[b]
P-value		<.0001	<.0001	<.0001	<.0001	<.0001	<.0001
Fungicide	Nativo	7.78[a]	15.56[c]	25.56[b]	30.00[c]	38.89[c]	42.22[c]
	Kanzole	10.00[a]	21.11[b]	30.00[b]	40.00[b]	50.00[b]	57.78[b]
	Unsprayed	7.78[a]	26.67[a]	42.22[a]	55.56[a]	70.00[a]	80.00[a]
LSD(0.05)		3.47	4.86	4.66	5.85	6.73	6.34
CV (%)		40.73	23.02	14.31	13.99	12.72	10.58
P-value		0.3183	<.0007	<.0001	<.0001	<.0001	<.0001

DAS = Days after sowing, LSD = Least significant difference, CV = Coefficient of variation, P- value = Probability value

4.2.2. Severity of yellow rust

The analysis of variance showed that the main effects of variety had a highly significant ($p<0.01$) effect on the first date (46 DAS) of yellow rust severity assessment but fungicides showed non-significant effect ($p>0.05$) (Appendix Table 2). This is because, at the first date of assessment yellow rust severity data was recorded before fungicide application and fungicides had no any influence on the severity of yellow rust. The highest mean yellow rust severity (2.06%) was recorded on Ogolcho variety followed by Kakaba (1.18%); whereas, there was no disease severity (0.00%) observed on Danda'a variety at the first date of severity assessment (Table 4.6). This indicates that Danda'a variety showed better performance than Kakaba and Ogolcho varieties. It is strengthened by the study of Metiku Kebede *et al.* (2023), who stated bread wheat varieties Danda'a and Shorima exhibited the best level of resistance to yellow rust infection. On the other hand, the moderately resistant Ogolcho variety was more susceptible to yellow rust than the susceptible Kakaba variety. This could be attributed to either the change in environmental factors or the evolvement of exotic or new local races of pathogens. Similarly, Meyer *et al*. (2021) noted that stripe rust prevalence was low for a number of years following the introduction of the wheat variety Digalu (till 2015). However, the prevalence of the disease increased dramatically to over 90% in 2016 and remained high in subsequent years. This sharp increase in stripe rust prevalence on Digalu coincides with the year of first detection of stripe rust race PstS11 in Ethiopia. However, the result is opposed with the result of Adane Fentaye and Abaynew Jemal (2024) finding, who reported that the Ogolcho and Lemu varieties showed better performance than the local and Hidase varieties.

Table 4.6: Main effect of bread wheat varieties on stripe rust severity of the first date of assessment (46 DAS)

Treatments		Mean severity at 46 DAS
Variety	Danda'a	0.00[c]
	Ogolcho	2.06[a]
	Kakaba	1.18[b]
LSD (0.05)		0.34
CV (%)		31.97
P-value		<.0001

DAS = Days after sowing, LSD = Least significant difference, CV = Coefficient of variation, P- value = Probability value

After the second date (56 DAS) of yellow rust severity assessment, analysis of variance revealed that the interaction effect of variety and fungicide was highly significant ($p<0.01$) on severity of yellow rust (Appendix Table 2). At the second date of severity assessment, the highest mean severity (11.67%) was observed on Ogolcho followed by Kakaba variety (7.19%) with nil application. Whereas, the lowest mean severity (0.75%) was recorded on Danda'a variety treated with Nativo SC 300 fungicide (Table 4.7). The result demonstrated highest yellow rust severity was recorded on untreated plots as compared to treated ones. It is in line with the finding of Melka Kecha and Amin Mohammed (2023), who reported that lowest levels of yellow rust severity were observed on the Danda'a variety with jeba fungicide, while the highest severity level were observed on the Hidase variety with nil application.

Table 4.7: Interaction effects of fungicide and varieties on yellow rust severity

Treatments		Mean severity/%/ on different date of assessment				
Varieties	Fungicide	56 DAS	66 DAS	76 DAS	86 DAS	96 DAS
Danda'a	Nativo	0.75[f]	2.67[g]	8.69 [e]	11.19[f]	14.19[g]
	Kanzole	1.50[ef]	4.67[f]	8.83[e]	11.36[f]	19.89[f]
	Unsprayed	3.50[d]	8.94[d]	20.33[c]	33.42[d]	43.33[c]
Ogolcho	Nativo	4.42[cd]	10.67[c]	20.28[c]	32.92[d]	33.81[d]
	Kanzole	6.39[b]	12.42[b]	30.00[b]	39.22[c]	43.24[c]

	Unsprayed	11.67^{a}	18.39^{a}	52.07^{a}	80.70^{a}	89.08^{a}
Kakaba	Nativo	3.00^{de}	7.28^{e}	16.28^{d}	23.75^{e}	30.37^{e}
	Kanzole	5.81^{bc}	8.58^{d}	20.33^{c}	34.44^{d}	41.36^{c}
	Unsprayed	7.19^{b}	12.25^{b}	30.04^{b}	56.25^{b}	80.48^{b}
LSD(0.05)		1.55	0.76	2.26	2.06	2.41
CV (%)		18.28	4.62	5.68	3.32	3.16
P-value		0.0024	0.0006	<.0001	<.0001	<.0001

DAS = Days after sowing, LSD = Least significant difference, CV = Coefficient of variation, P- value = Probability value

At the final disease severity assessment (96 DAS), the maximum mean severity was recorded on unsprayed Ogolcho (89.08%) followed by Kakaba variety (80.48%), whereas, the minimum (14.19%) was recorded on Danda'a variety treated with Nativo SC 300 fungicide (Table 4.7). This variation could be attributed due to the difference in fungicide efficacy and genetic makeup of varieties. The result is in line with Yared Tesfaye *et al*. (2018) finding, who reported that treatments with fungicide application significantly reduced stripe rust severity to the lowest level as compared to the unsprayed check. In addition to this, the result demonstrated that Nativo SC 300 fungicide showed highest levels of efficacy on yellow rust severity reduction compared to other tested fungicides.

4.2.3. Final yellow rust severity and percent disease control

The analysis of variance showed the interaction effect of variety and fungicide had a highly significant (p<0.01) effect on the final yellow rust severity (Appendix Table 2). At the final date (96 DAS) of severity assessment, the highest mean severity (89.08%) was recorded on unsprayed Ogolcho followed by Kakaba variety (80.48%), whereas the lowest mean severity (14.19%) was recorded on Danda'a variety treated with Nativo SC 300 fungicide (Table 4.8). Among tested varieties and fungicides, variety Danda'a and Nativo SC 300 fungicide had best performance in effectively reducing yellow rust severity during the time of the study, while Ogolcho variety and unsprayed plots had low performance. Similarly, Kasa *et al*. (2018) reported the highest (50%) final yellow rust severity was recorded on Ogolcho variety while the lowest (10%) was recorded on Danda'a variety in Arsi Robe during 2014 year of study.

Table 4.8: Interaction effects of fungicide and varieties on final yellow rust severity and percent disease control

Varieties	Fungicide	FYRS (%)	PDC (%)

Danda’a	Nativo	14.19[g]	67.25
	Kanzole	19.89[f]	54.10
	Unsprayed	43.33[c]	0
Ogolcho	Nativo	33.81[d]	62.05
	Kanzole	43.24[c]	51.46
	Unsprayed	89.08[a]	0
Kakaba	Nativo	30.37[e]	62.26
	Kanzole	41.36[c]	48.61
	Unsprayed	80.48[b]	0
LSD(0.05)		2.41	
CV (%)		3.16	
P-value		<.0001	

FYRS = Final yellow rust severity, PDC = Percent disease control, LSD = Least significant difference, CV = Coefficient of variation, P- value = Probability value

In case of percent disease control, the analysis result showed that the application of fungicide had a better effect on yellow rust severity reduction. The highest percent disease control 67.25%, 62.26% and 62.05% was gained from Danda’a, Kakaba and Ogolcho varieties treated with Nativo SC 300 fungicide, respectively (Table 4.8). Nativo SC 300 fungicide followed by Kanzole 25% EC had better advantages for disease control over unsprayed plots. It is strengthened by the result of Yared Tesfaye *et al*. (2018), who reported that test fungicides showed comparable and better levels of efficacy on stripe rust disease severity reduction compared to the unsprayed check.

4.2.4. Coefficient of infection

In case of varieties, the lowest coefficient of infection was recorded on Danda’a followed by Kakaba variety, whereas the highest coefficient of infection was obtained from Ogolcho variety. Similar result is reported by Metiku Kebede *et al.* (2023), who reported that the highest ACI (average coefficient of infection) 79.6% was recorded on Ogolcho variety and medium ACI was recorded on Kakaba variety (30.6%), while the lowest (16.6%) was obtained from Danda’a variety.

The analysis of variance showed that, coefficient of infection was highly significantly ($p<0.01$) affected by the interaction effect of varieties and fungicides (Appendix Table 3). The maximum coefficient of infection (89.08%) was obtained from unsprayed Ogolcho variety, followed by (43.24%) of Ogolcho variety with Kanzole 25% EC fungicide, while the minimum coefficient of infection (2.84%) was obtained from Danda’a variety with Nativo SC

300 fungicide followed by Danda’a variety with Kanzole 25% EC (3.98%) (Table 4.9). The result also showed that a higher coefficient of infection was recorded on untreated plots of all varieties as compared to treated plots. Similarly, Metiku Kebede *et al.* (2024) reported that the maximum ACI were recorded on untreated plots of Digalu (70%), Hidase (52.1%), Danda’a (37.6%), and Honkolo (17.5%) bread wheat varieties.

Table 4.9: Interaction effect of fungicide and varieties on coefficient of infection

Varieties	Fungicide	FYRS (%)	CI (%)
Danda’a	Nativo	14.19^{g}	2.84^{h}
	Kanzole	19.89^{f}	3.98^{h}
	Unsprayed	43.33^{c}	8.67^{g}
Ogolcho	Nativo	33.81^{d}	33.81^{c}
	Kanzole	43.24^{c}	43.24^{b}
	Unsprayed	89.08^{a}	89.08^{a}
Kakaba	Nativo	30.37^{e}	12.15^{f}
	Kanzole	41.36^{c}	16.54^{e}
	Unsprayed	80.48^{b}	32.19^{d}
LSD(0.05)		2.41	1.28
CV (%)		3.16	2.74
P-value		<.0001	<.0001

FYRS = Final yellow rust severity, CI = Cofficient of Infection, LSD = Least significant difference, CV = Coefficient of variation, P- value = Probability value

4.2.5. Area under disease progress curve (AUDPC)

There were highly significant ($p<0.01$) differences in AUDPC value among the interaction of varieties and fungicides (Appendix Table 4). The highest AUDPC value of 2083.68 % day^{-1} was recorded on unsprayed Ogolcho variety, followed by 1465.72 % day^{-1} on unsprayed Kakaba, while the lowest AUDPC value of 304 % day^{-1} was obtained from Danda’a variety with Nativo SC 300 fungicide (Table 4.10). The highest AUDPC value was obtained from unsprayed plots as compared to fungicide sprayed ones, while the lowest AUDPC value was recorded on plots treated with Nativo SC 300 fungicide. The result is in line with Getachew Gudero (2020) study, who stated that the highest AUDPC value for yellow rust was recorded on unsprayed plots of each varieties; while, a significantly reduced levels of yellow rust AUDPC values were recorded from fungicide treated plots.

Area under disease progress curve is the true measure of disease parameter because it is directly related with the yield loss. The resistance level of the bread wheat cultivar was estimated by AUDPC. This is because; AUDPC represents both the amount of rust infection and the rate at which the disease or pathogen has increased during an epidemic (Metiku Kebede *et al.,* 2023).

Table 4.10: Interaction effects of varieties and fungicide on AUDPC of yellow rust

Varieties	Fungicide		
	Nativo	Kanzole	Unsprayed
Danda'a	304.00[h]	363.02[g]	878.60d[e]
Ogolcho	861.80[e]	1107.30[c]	2083.68[a]
Kakaba	660.70[f]	904.30[d]	1465.72[b]
LSD(0.05)	41.69		
CV (%)	2.51		
P-value	<.0001		

LSD = Least significant difference, CV = Coefficient of variation, P- value = Probability value

4.2.6. Disease progress curve and rate

The disease symptom was observed first on Ogolcho and Kakaba varieties at the booting growth stage and at the heading stage of Danda'a bread wheat varieties. The yellow rust disease progress curve showed a difference in disease progress among treatments due to the influence of variety and fungicide combination. Starting from disease onset up to maturity of the crop, the mean severity of yellow rust reached 89.08% and 80.48% on unsprayed Ogolcho and Kakaba varieties, respectively. However, the lower yellow rust mean severity (14.19%) was scored on the Danda'a variety treated with Nativo SC 300 fungicide. The application of Nativo SC 300 fungicide showed a significant disease progress reduction in all varieties as compared to other fungicides (Figure 4.1).

The disease progress curve showed that the disease on unsprayed plots progressed at a faster rate than fungicide-treated one (disease progressed at a slower rate). The progress of the disease has increased at a high rate from disease onset up to the fourth date of assessment. This might be due to the presence of a high number of inoculum, healthy tissue, and fewer management practices, while after the fourth date of assessment, the disease progress increased at a low rate due to the effectiveness of fungicides, lack of nutrients, plant maturity, and inoculum reduction or death. The result also showed that the application of fungicide was effective in reducing the progress of the disease by decreasing the amount of inoculum and increasing the resistance ability of varieties. It is supported by Adane Fentaye and Abaynew

Jemal (2024) result, who reported the disease progress curve of the untreated plot was higher or progressed at a faster rate than the treated plot.

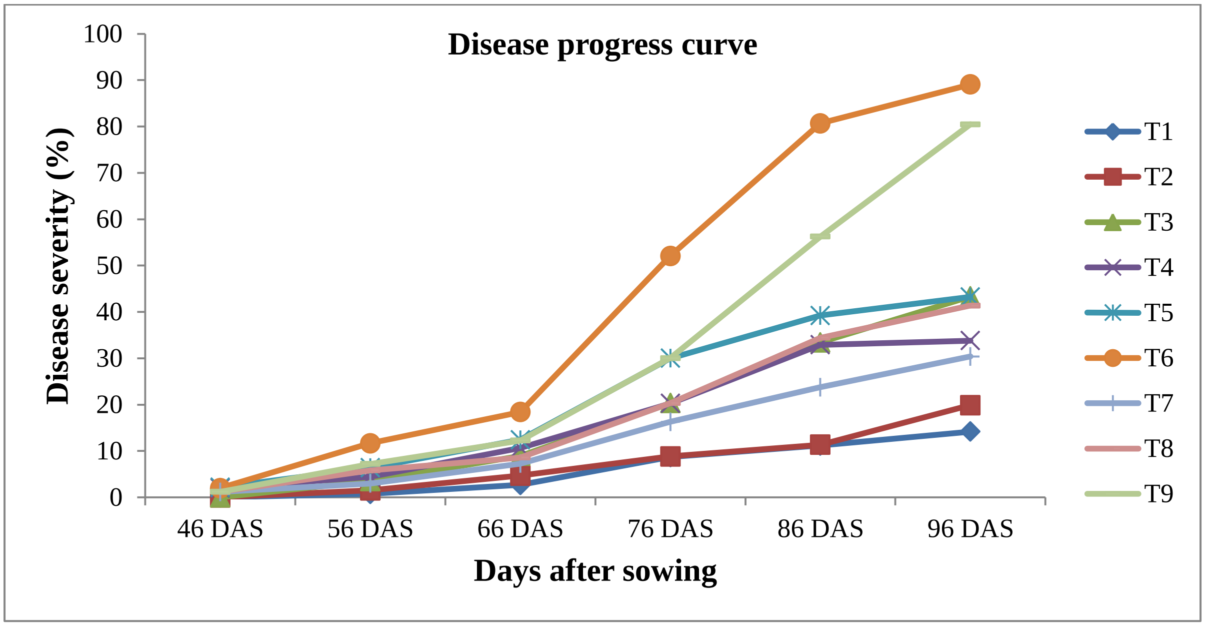


Figure 4.1: Yellow rust disease progress curve

Hint: T1 = Danda'a with Nativo fungicide, T2 = Danda'a with Kanzole fungicide, T3 = Unsprayed Danda'a, T4 = Ogolcho with Nativo fungicide, T5 = Ogolcho with Kanzole fungicide, T6 = Unsprayed Ogolcho, T7 = Kakaba with Nativo fungicide, T8 = Kakaba with Kanzole fungicide, T9 = Unsprayed Kakaba.

The analysis of variance showed that there was a highly significant ($p<0.01$) difference in disease progress rate among the interaction of varieties and fungicides (Appendix Table 5). The highest disease progress rates (0.07919 units day^{-1}) was observed on unsprayed Ogolcho variety, whereas, the lowest disease progress rates (0.02253 units day^{-1}) and (0.02266 units day^{-1}) were observed on Danda'a variety treated with Nativo SC 300 and Kanzole 25% EC fungicides respectively. Nativo SC 300 fungicide reduced yellow rust progress rate by 0.02253, 0.02762 and 0.02833 units day^{-1} on Danda'a, Kakaba, and Ogolcho varieties respectively (Table 4.11). Application of Nativo SC 300 was the most effective in slowing down yellow rust disease progress during the time of study as compared to other fungicides tested.

The current result demonstrated that the progress of disease has increased at a faster rate on unsprayed plots than treated ones and increased at a slower rate on resistance varieties and fungicide treated plots. It is supported by the study of Alemu Ayele *et al*. (2019), who reported infection rate of yellow rust was low (0.13 units' day^{-1}) on untreated plots of the resistant variety (Wane) and high (1.16 units' day^{-1}) on the susceptible variety (Kubsa) at Bekoji. The result is also in line with the work of Adane Fentaye and Abaynew Jemal Jenber (2024), who reported unsprayed plots of all varieties showed the highest disease progress rates as compared to the sprayed ones across the locations. Getachew Gudero (2020) also reported that disease progress rate of yellow and stem rusts were slowed down by the application of fungicides. As evidenced in the current experiment, the fungicide treatments were effective in markedly slowing down the progress of the disease.

Table 4.11: Interaction effects of varieties and fungicide on disease progress rate of yellow rust

Varieties	Fungicide		
	Nativo	Kanzole	Unsprayed
Danda'a	0.02253^{f}	0.02266^{f}	0.03772^{c}
Ogolcho	0.02833^{de}	0.03182^{d}	0.07919^{a}
Kakaba	0.02762^{e}	0.03182^{d}	0.06286^{b}
LSD(0.05)	0.0073		
CV (%)	5.55		
P-value	<.0001		

LSD = Least significant difference, CV = Coefficient of variation, P- value = Probability value

4.2.7. Crop phonological parameters

4.2.7.1. Days to 50% heading

The result of the study showed that the main effects of varieties had a highly significant effect ($p<0.01$) on days to 50% heading. However, fungicide application had no significant effect ($p>0.05$) on days to 50% heading (Appendix Table 7). The shortest days to 50% heading was recorded from Kakaba variety (61.56 days), while the longest days to 50% heading was recorded from Danda'a (70.89 days) followed by Ogolcho (67.00 days) (Table 4.12). The variation in days to 50% heading could be attributed to the genetic makeup of varieties. This result was in line with previous findings, in which there was a significant difference in days to 50% heading among bread wheat varieties (Habtamu Kefale and Ahadu Menzir, 2019; Adane Fentaye and Abaynew Jemal, 2024).

Table 4.12: The main effects of bread wheat varieties and fungicides on days to 50% heading

Treatments		DH
Variety	Danda'a	70.89[a]
	Ogolcho	67.00[b]
	Kakaba	61.56[c]
P-value		<.0001
Fungicide	Nativo	66.89[a]
	Kanzole	66.56[a]
	Unsprayed	66.00[a]
LSD (0.05)		1.45
CV (%)		2.18
P-value		0.4389

DH = Days to 50% Heading, LSD = Least significant difference, CV = Coefficient of variation, P-value = Probability value

4.2.7.2. Days to 90 % physiological maturity

Days to 90% physiological maturity of bread wheat was highly significantly (P<0.01) affected by the interaction of varieties and fungicides (Appendix Table 8). The shortest days to 90% physiological maturity (94.67 days) was recorded on unsprayed Ogolcho variety, whereas the longest days to 90% physiological maturity (114.33 days) was recorded on Danda'a treated with Nativo SC 300 (Table 4.13). This significant variation on days to 90% physiological maturity might be due to the varietal difference in genetic constituents and through the action of fungicides. The time of physiological maturity of plots treated with fungicides was longer than untreated ones. It is supported by the finding of Mulugeta Zenebe (2022), who reported that plots with no fungicide treatment reached physiological maturity earlier than the treated ones.

The result demonstrated that the disease hastens the time of physiological maturity of the crop. The reason behind is that, the pathogen consumes the plant nutrients and water, thereby reducing the plant vigour, causing desiccation of leaves and results in crop death before the plant attains the right time physiological maturity (Khushboo *et al*., 2021). On the other hand, fungicides slow the degradation of chlorophyll and leaf protein which allows plants to keep their leaves stay green longer during late development stages that lead to late maturation (Ali *et al*., 2014).

Table 4.13: Interaction effects of varieties and fungicides on days to 90% physiological maturity (DPM)

Varieties	Fungicide		
	Nativo	Kanzole	Unsprayed
Danda’a	114.33[a]	112.67[ab]	111.00[b]
Ogolcho	110.67[b]	105.33[c]	94.67[f]
Kakaba	104.00[c]	101.00[d]	97.33[e]
LSD(0.05)	2.64		
CV (%)	1.44		
P-value	<.0001		

LSD = Least significant difference, CV = Coefficient of variation, P- value = Probability value

4.2.8. Growth parameters

4.2.8.1. Plant height

The analysis of variance showed that the interaction of varieties and fungicide had a highly significant ($P < 0.01$) effect on plant height (Appendix Table 9). The tallest (98.77cm) plant height was obtained from Ogolcho followed by Danda’a varieties (97.40 cm) treated with Nativo SC 300, whereas the shortest plant height of 83.53cm was obtained from unsprayed Kakaba bread wheat variety (Table 4.14). It indicated that the tallest plant height was recorded on fungicide treated plots as compared to untreated plots. In addition, the variation in plant height among treatments may also be attributed to the genetic makeup of the varieties and due to the influence of the disease. According to Kabna Asefa *et al*. (2024), the Variation in plant height among varieties might be due to the variation in genetic makeup and the influence of fungicide. The same result was also obtained from Melka Kecha and Amin Mohammed (2023), who reported fungicide treated plots resulted in a longer plant height than untreated plots. Similarly, Adane Fentaye and Abaynew Jemal (2024) also reported that there was a significant difference in plant height among varieties between nil and fungicide treated plots. According to Khushboo *et al*. (2021), yellow rust disease reduces plant vigor, causes desiccation of leaves and also severe early infection can result in stunted growth of the plants.

Table 4.14: The interaction effects of varieties and fungicides on plant height (cm)

Varieties	Fungicides		
	Nativo	Kanzole	Unsprayed
Danda’a	97.40[ab]	94.90[bc]	94.80[bc]
Ogolcho	98.77[a]	94.73[c]	86.67[e]

Kakaba	90.27[d]	88.37[de]	83.53[f]
LSD(0.05)	2.64		
CV (%)	1.65		
P-value	0.0007		

LSD = Least significant difference, CV = Coefficient of variation, P- value = Probability value

4.2.8.2. Spike length

The statistical analysis result revealed that spike length was significantly (p<0.05) affected by the interaction of variety and fungicide (Appendix Table 10). The longest spike length (11.25cm) was recorded from the combination of Ogolcho with Nativo SC 300 fungicide, whereas the shortest spike length (8.53 cm) was recorded from unsprayed Kakaba variety (Table 4.15). The result demonstrated that plots treated with fungicides produced longer spike length than untreated ones. This is supported by the result of Melka Kecha and Amin Mohammed (2023), who reported the highest spike length was recorded in Danda'a with jeba fungicide, whereas the lowest spike length was recorded in the untreated Hidase variety.

Table 4.15: The interaction effects of Varieties and fungicides on spike length (cm)

Varieties	Fungicide		
	Nativo	Kanzole	Unsprayed
Danda'a	10.22[bc]	9.77[cd]	9.34[de]
Ogolcho	11.25[a]	10.35[b]	9.20[e]
Kakaba	9.65[cde]	8.59 [f]	8.53[f]
LSD(0.05)	0.57		
CV (%)	3.43		
P-value	0.0275		

LSD = Least significant difference, CV = Coefficient of variation, P- value = Probability value

4.2.9. Yield and yield related parameters

4.2.9.1. Number of grains per spike

The analysis of variance indicated that there was a highly significant (p<0.01) difference among treatment combinations in the number of grains per spike (Appendix Table 11). The highest number of grains per spike (67.20) was obtained from the combination of Danda'a with Nativo SC 300 and Danda'a with Kanzole 25% EC (64.47) fungicides respectively, while the lowest number of grains per spike (36.47) was obtained from unsprayed Ogolcho variety (Table 4.16). The result showed that a highest number of grains per spike were obtained from fungicide treated plots than untreated ones within each respective variety. This result is in line with the work of Melka Kecha and Amin Mohammed (2023), who reported that the application of fungicides increased the number of grains per spike compared with the unsprayed check. It is also supported by the work of Yared Tesfaye *et al*. (2018), who reported a relatively higher number of grains per spike was obtained from fungicide treated plots over untreated plots.

Table 4.16: The interaction effects of varieties and fungicides on number of grains per spike

Varieties	Fungicide		
	Nativo	Kanzole	Unsprayed
Danda'a	67.20[a]	64.47[ab]	57.40[c]
Ogolcho	55.07[cd]	53.47[de]	36.47[f]
Kakaba	61.53[b]	53.93[de]	51.87[e]
LSD(0.05)	3.16		
CV (%)	3.28		
P-value	<.0001		

LSD = Least significant difference, CV = Coefficient of variation, P- value = Probability value

4.2.9.2. Thousand Kernel weight

The analysis of variance revealed that the interaction effect of variety and fungicides was highly significant (p<0.01) on a thousand kernel weight of bread wheat (Appendix Table 12). The maximum thousand kernel weight (43.53g) was recorded from Danda'a followed by Kakaba variety (40.39g) with Nativo SC 300 fungicide, whereas the minimum thousand kernel weight (11.34g) was recorded from unsprayed Ogolcho variety (Table 4.17). It indicated that a higher thousand kernel weight was obtained from fungicide treated plots as compared to unsprayed ones. The result is strengthened by the work of Yared Tesfaye *et al*. (2018), who reported maximum thousand grain weight was recorded in fungicide treated plots, whereas the lowest thousand grain weight was obtained from unsprayed check. According to Metiku Kebede *et al*. (2023), yellow rust negatively affected the kernel quality and quantity of produce through shriveling of wheat kernels.

Table 4.17: The interaction effects of Varieties and fungicides on thousand kernel weight (g)

Varieties	Fungicide		
	Nativo	Kanzole	Unsprayed
Danda'a	43.53[a]	34.34[c]	25.48[d]
Ogolcho	39.09[b]	24.32[d]	11.34[f]

Kakaba	40.39[b]	33.52[c]	19.92[e]
LSD(0.05)	2.34		
CV (%)	4.47		
P-value	<.0001		

LSD = Least significant difference, CV = Coefficient of variation, P- value = Probability value

4.2.9.3. Above ground biomass yield

The analysis of variance showed that the interaction of variety and fungicide had a significant ($p<0.05$) effect on above ground biomass yield (Appendix Table 13). Variety Danda'a followed by Kakaba with Nativo SC 300 fungicide produced the highest 13.42 t ha^{-1} and 11.93 t ha^{-1} of above ground biomass yield respectively. Whereas, the lowest amount of above ground biomass yield (4.22 t ha^{-1}) was obtained from unsprayed Ogolcho (Table 4.18). The result demonstrated that there was a decreased in above ground biomass yield on the untreated plots as compared to fungicide treated plots. It is in line with the study of Tesfaye Abdissa *et al*. (2024) and Kabna Asefa *et al*. (2024), who reported that there was a statistically significant difference in above ground biomass between the treated and untreated (control) plots.

Table 4.18: The interaction effects of Varieties and fungicides on above ground biomass yield (t/ha)

Varieties	Fungicide		
	Nativo	Kanzole	Unsprayed
Danda'a	13.42[a]	10.73[c]	7.56[f]
Ogolcho	9.91[cd]	8.89[e]	4.22[h]
Kakaba	11.93[b]	9.24[de]	6.44[g]
LSD(0.05)	0.88		
CV (%)	5.56		
P-value	0.0247		

LSD = Least significant difference, CV = Coefficient of variation, P- value = Probability value

4.2.9.4. Grain yield

The analysis of variance revealed that the integrated use of variety and fungicide showed a significant ($p<0.05$) difference in grain yield (Appendix Table 14). The result showed that the highest (4.55 t ha^{-1}) grain yield was obtained from Danda'a variety, followed by Kakaba variety (4.11 t ha^{-1}) with Nativo SC 300 fungicide. Whereas the lowest grain yield (0.98 t ha^{-1}) was recorded from unsprayed Ogolcho variety (Table 4.19).

From the result, higher yield was obtained from plots treated with Nativo SC fungicide than others. Ogolcho variety produced the lowest grain yield amount as compared with Danda'a and Kakaba bread wheat variety. This is due to Ogolcho variety was highly affected by the disease than others at the time of study. The result is supported by the report stated, that the highest grain yield was recorded in Danda'a applied with jeba fungicide (2916 kg ha^{-1}), followed by Shorima applied with Natura fungicide (2533 kg ha^{-1}) and the lowest grain yield was recorded from the Hidase variety applied with nil application (882 kg ha^{-1}). Different studies from different areas have demonstrated yield increases in wheat is due to fungicide application and resistant varieties (Melka Kecha and Amin Mohammed, 2023).

Table 4.19: The interaction effects of Varieties and fungicides on grain yield (t ha^{-1}) of bread wheat

Varieties	Fungicide		
	Nativo	Kanzole	Unsprayed
Danda'a	4.55^{a}	3.62^{c}	2.36^{e}
Ogolcho	3.85^{bc}	2.64^{e}	0.98^{g}
Kakaba	4.11^{b}	3.27^{d}	1.96^{f}
LSD(0.05)	0.33		
CV (%)	6.27		
P-value	0.0356		

LSD = Least significant difference, CV = Coefficient of variation, P- value = Probability value

4.2.9.5. Straw yield

The analysis of variance revealed that the interaction of variety and fungicide had a highly significant ($p<0.01$) effect on straw yield (Appendix Table 15). The highest straw yield was recorded on Danda variety (8.87 t ha^{-1}), followed by Kakaba variety (7.82 t $ha^{-1}$with Nativo SC 300 fungicide, while the lowest straw yield (3.24 t ha^{-1}) was recorded from unsprayed Ogolcho variety (Table 4.20). Similar to that of grain yield, higher straw yield was gained from fungicide treated plots than untreated ones. According to Adane Fentaye and Abaynew Jemal (2024), varieties treated with fungicide more than twice application produced a higher straw yield than varieties with nil application.

Table 4.20: The interaction effects of Varieties and fungicides on straw yield of bread wheat

Varieties	Fungicide		
	Nativo	Kanzole	Unsprayed

Danda’a	8.87[a]	7.11[b]	5.20[d]
Ogolcho	6.06[c]	6.24[c]	3.24[e]
Kakaba	7.82[b]	5.98[c]	4.49[d]
LSD(0.05)	0.76		
CV (%)	7.20		
P-value	0.0059		

LSD = Least significant difference, CV = Coefficient of variation, P- value = Probability value

4.2.9.6. Relative yield loss

Relative yield loss was calculated to compare the yield losses that occurred between treatment combinations due to yellow rust. The study result revealed that the maximum grain yield loss (74.55%) was recorded on the unsprayed Ogolcho variety and the minimum yield loss was recorded on Danda’a (20.44%) and Kakaba (20.44%) varieties with Kanzole 25% E.C fungicide (Table 4.21). The result showed that fungicide application resulted in a lower grain yield loss by the disease as compared to nil application. The result also indicated that Nativo SC 300 fungicide was effective in decreasing the yield losses on the three bread wheat varieties. The result is supported by the work of Getachew Gudero (2020), who reported that grain yield loss of up to 69.64% was recorded on unsprayed plots of Ogolcho as compared to fungicide-sprayed plots of other evaluated varieties. Similarly, Adane Fentaye and Abaynew Jemal (2024), reported that all treated plots had the lowest grain yield loss compared to untreated plots.

Table 4.21: The effects of combinations of varieties and fungicides on relative yield loss of bread wheat

Varieties	Fungicide	GY (t ha^{-1})	RYL (%)
Danda’a	Nativo	4.55	0
	Kanzole	3.62	20.44
	Unsprayed	2.36	48.13
Ogolcho	Nativo	3.85	0
	Kanzole	2.64	31.43
	Unsprayed	0.98	74.55
Kakaba	Nativo	4.11	0
	Kanzole	3.27	20.44
	Unsprayed	1.96	52.31

GY = Grain yield, RYL = Relative yield loss

4.2.9.7. Percent yield increment

The result showed that there was increments of grain yield in all tested varieties from unsprayed to Nativo SC 300 fungicide-treated plots. The highest percent yield increments were observed on the Ogolcho variety (292.86%) with Nativo SC 300, followed by Ogolcho with Kanzole 25% E.C (169.39%), whereas the lowest yield increment was observed on the Danda’a variety with Kanzole 25% E.C (53.39%) (Table 4.22). The result demonstrated that, there were a relatively lower percent yield increments on resistance varieties than others as a result of fungicide application. It indicates that the application of fungicide is critical to reduce grain yield loss, even if the varieties are susceptible to the disease. Nativo SC 300 fungicide application resulted in a higher grain yield increment of up to 292.86%, 109.69%, and 92.80% on unsprayed plots of Ogolcho, Kakaba and Danda’a respectively. The result is in line with Alemu Ayele *et al*. (2019), who reported Twice application frequency of Epoxiconazol e + Thiophante-methyl resulted in a significant (P<0.01) grain yield increment of up to 95.3%, 76.4%, and 1086.8% at Bekoji and 129.7%, 135.5%, 2883.2% at Meraro on unsprayed plots of Lemu, Danda‘a, and Kubsa, respectively. In addition, yield increments because of fungicide applications were relatively lower on the resistant variety Wane than others.

Table 4.22: The effects of combinations of varieties and fungicides on percent yield increment (PYI) of bread wheat

Varieties	Fungicide	GY (t/ha)	PYI (%)
Danda’a	Nativo	4.55	92.80
	Kanzole	3.62	53.39
	Unsprayed	2.36	0
Ogolcho	Nativo	3.85	292.86
	Kanzole	2.64	169.39
	Unsprayed	0.98	0
Kakaba	Nativo	4.11	109.69
	Kanzole	3.27	66.84
	Unsprayed	1.96	0

GY = Grain yield, PYI = Percent yield increment

4.3. Correlation analysis of Disease, Yield and Yield Related Parameters of Wheat

Correlation analysis among disease, yield, and yield-related parameters was conducted using Pearson correlation to show the linear association between them. The result revealed that, disease parameters including FYRS, AUDPC, coefficient of infection and DPR had a strong, positive and highly significant ($p < 0.01$) correlation between them and highly significant ($p < 0.01$) negative correlation with yield and yield-related parameters (NGPS, TKW and grain yield). AUDPC had a strong positive correlation with FYRS ($r = 0.967^{**}$), CI ($r = 0.913^{**}$) and DPR ($r = 0.938^{**}$). The coefficient of infection was also positively correlated with FYRS ($r = 0.799^{**}$), AUDPC ($r = 0.913^{**}$) and DPR ($r = 0.807^{**}$) (Table 4.23).

Similarly, yield and yield related parameters showed a strong, positive and highly significant ($p < 0.01$) correlation within each other and highly significant ($p < 0.01$) negative correlation with disease parameters. Grain yield had a strong positive correlation with NGPS ($r = 0.846^{**}$) and TKW ($r = 0.979^{**}$). However, NGPS, TKW and GY had a strong negative correlation with FYRS ($r = -0.884^{**}$, $r = -0.899^{**}$ and $r = -0.913^{**}$), AUDPC ($r = -0.957^{**}$, $r = -0.891^{**}$ and $r = -0.903^{**}$), CI ($r = -0.924^{**}$, $r = -0.759^{**}$ and $r = -0.751^{**}$) and DPR ($r = -0.849^{**}$, $r = -0.872^{**}$ and $r = -0.885^{**}$) (Table 4.23). Generally, the result showed that there was a strong negative correlation between disease parameters and yield and yield related parameters. The result is in line with the report of Adane Fentaye and Abaynew Jemal (2024), who stated disease parameters had a very high to sufficiently high degree of negative correlation with yield and yield components but a positive correlation between them.

Table 4.23: Correlation on yellow rust disease parameters, and yield and yield related parameters of bread wheat

	NGPS	TKW	GY	FYRS	AUDPC	CI	DPR
NGPS	1						
TKW	0.826^{**}	1					
GY	0.846^{**}	0.979^{**}	1				
FYRS	-0.884^{**}	-0.899^{**}	-0.913^{**}	1			
AUDPC	-0.957^{**}	-0.891^{**}	-0.903^{**}	0.967^{**}	1		
CI	-0.924^{**}	-0.759^{**}	-0.751^{**}	0.799^{**}	0.913^{**}	1	
DPR	-0.849^{**}	-0.872^{**}	-0.885^{**}	0.966^{**}	0.938^{**}	0.807^{**}	1

NGPS = Number of grains per spike, TKW = Thousand kernel weight, GY = Grain yield, FYRS = Final yellow rust severity, AUDPC = Area under disease progress curve, CI = Coefficient of infection, DPR = Disease progress rate, ** Correlation is significant at the 0.01 significance level.

4.4. Regression of AUDPC and Grain Yield

Regression is a helpful statistical concept that used to estimate the effect of explanatory (independent) variable on the dependent variable. It is the best analytical model used to predict the relationship between dependent and independent variables. The relationship between yellow rust disease and grain yield was expressed using a linear regression between AUDPC and grain yield for predicting bread wheat grain yield loss due to the disease. The result of regression analysis between grain yield and AUDPC showed a very highly significant ($P<0.001$) negative or inverse relationship between them (Figure 4.2). An equation of $y = -0.0019x + 4.854$ was generated after linear regression analysis of grain yield and AUDPC and the graph indicated that for every one-unit increase in AUDPC values, there was 0.0019 t ha^{-1} grain yield loss on bread wheat varieties.

The linear regression analysis of grain yield and AUDPC predicts that about 83.22% of grain yield loss was recorded due to yellow rust disease during the time period of the study. It is in line with Getachew Gudero (2020) finding, who stated there were 0.0226 unit of grain yield loss on wheat varieties for every one-unit increase in AUDPC value and the contribution of AUDPC in grain yield reduction was 43.50%. Generally, the result showed that as AUDPC value of yellow rust increased, the grain yield of bread wheat varieties was decreased and goes toward zero asymptote, which indicated the inverse relationship between AUDPC and grain yield of wheat. The negative sign of the linear regression equation indicates the inverse relation of the disease and the yield and the adverse effects of the disease on bread wheat yield. The closer the point to the line showed the stronger relationship between the disease and the grain yield regarding yield loss (Figure 4.2).

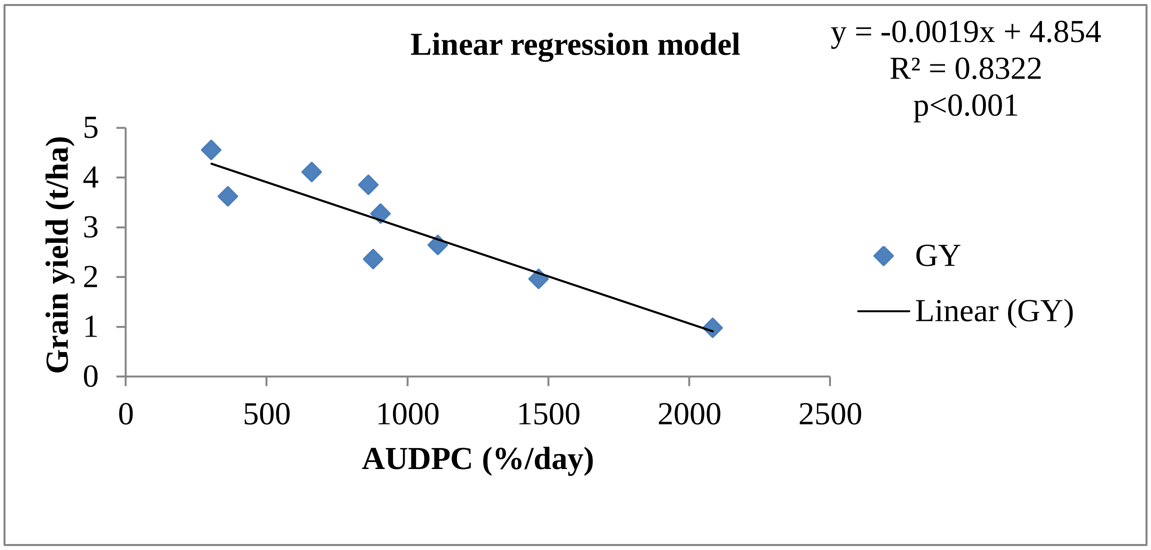


Figure 4.2: Linear regression of grain yield of bread wheat and yellow rust AUDPC

4.5. Partial Budget Analysis

The Partial budget analysis showed that fungicide application on three bread wheat varieties gave high net benefit as compared to unsprayed treatments. The maximum net benefit (302,150 birr ha^{-1}) was gained from Danda'a variety, followed by Kakaba variety (270,750 birr ha^{-1}) treated with Nativo SC 300 fungicide, however the minimum net benefit (77,600 birr ha^{-1}) was gained from unsprayed Ogolcho variety (Table 4.24). Generally, higher net benefit was obtained from fungicide treated varieties than untreated ones. From the two tested fungicides, Nativo SC 300 fungicide gave higher net benefit than others.

The analysis result showed that the maximum marginal rate of return (6558.33%) was obtained from the combination of Danda'a variety with Kanzole 25% EC followed by the combination of Danda'a variety with Nativo SC 300 fungicide (3079.49%) (Table 4.25). The MRR indicated that for every 1.00 birr investments on the combinations of Danda'a variety with Kanzole 25% EC and Danda'a variety with Nativo SC 300 fungicide, the producers expect to recover their investment and obtain additional 65.58 and 30.79 birr, benefit respectively. According to CIMMYT (1988), the dominance analysis demonstrated that the undominated treatments shown acceptable marginal rate of returns that were >100%. From all tested combinations Danda'a variety with Nativo SC 300 fungicide provided the highest net benefit (302,150 birr ha^{-1}) with an acceptable marginal rate of return (3079.49%). According to Getachew Gudero (2020) result, economic analysis revealed that combined use of variety and fungicide application provided the highest net benefit and marginal rate of return.

Table 4.24: Partial budget analysis for the management of yellow rust disease of bread wheat at *Debre Elias district* during 2023 cropping season

Trt	AGY	ASY	GB	FC	FSLC	TVC	NB
D+NA	4.10	7.98	305300	2850	300	3150	302150
D+KA	3.26	6.40	243300	900	300	1200	242100
D+UN	2.12	4.68	163400	0	0	0	163400
O+NA	3.47	5.45	245350	2850	300	3150	242200
O+KA	2.38	5.62	187100	900	300	1200	185900
O+UN	0.88	2.92	77600	0	0	0	77600
K+NA	3.70	7.04	273900	2850	300	3150	270750
K+KA	2.94	5.38	215500	900	300	1200	214300
K+UN	1.76	4.04	137200	0	0	0	137200

Trt = Treatments, AGY = Adjusted grain yield t ha^{-1}, ASY = Adjusted straw yield t ha^{-1}, GB = Gross benefit birr ha^{-1}, FC = Fungicide cost birr ha^{-1}, FSLC = Fungicide spraying labor cost birr ha^{-1}, TVC = Total variable cost birr ha^{-1}, NB = Net benefit birr ha^{-1}, MRR = Marginal rate of return %

Table 4.25: Dominance analysis and marginal rate of return

Trt	AGY (t/ha)	ASY (t/ha)	GB (birr/ha)	TVC (birr/ha)	NB (birr/ha)	MRR (%)
D+UN	2.12	4.68	163400	0	163400	-
O+UN	0.88	2.92	77600	0	77600	D
K+UN	1.76	4.04	137200	0	137200	D
D+KA	3.26	6.40	243300	1200	242100	6558.33
O+KA	2.38	5.62	187100	1200	185900	D
K+KA	2.94	5.38	215500	1200	214300	D
D+NA	4.1	7.98	305300	3150	302150	3079.49
O+NA	3.47	5.45	245350	3150	242200	D
K+NA	3.7	7.04	273900	3150	270750	D

Trt = Treatments, AGY = Adjusted grain yield, ASY = Adjusted straw yield, GB = Gross benefit, TVC = Total variable cost, NB = Net benefit, MRR = Marginal rate of return, D = Dominated

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

5.1. Conclusions

Yellow rust was among the most devastating wheat rust diseases that resulted in severe yield losses in the study area. Survey results indicated that yellow rust was a major constraint, and most of the assessed fields were subjected to yellow rust disease with 88% prevalence, 42.41% incidence, and 28.67% mean severity in the *district*. There was a varied disease intensity level between assessed fields due to the influence of factors like varieties used by farmers, management practices, altitude, field history, plant density, crop growth stage, time of sowing, and environmental factors. In the present study, the Ogolcho bread wheat variety showed susceptibility to yellow rust; however, it was moderately resistant to yellow rust disease at the time of release. The highest disease intensity was recorded on fields found at higher altitudes, sown in the fourth week of July, which had high plant density and were unmanaged, previously covered with wheat crops and at the heading growth stage's.

The evidence of the current study concluded that the integrated use of variety with fungicide application provided a noticeable effect in reducing yellow rust disease intensity and in increasing yield attributes of bread wheat. The combined use of Nativo SC 300 fungicide with Danda'a bread wheat variety showed a better result in yellow rust management and resulted in an increment of yield and yield-related attributes. However, the unsprayed plots of all varieties showed the highest incidence, severity, AUDPC, coefficient of infection, and yield loss and they resulted in low yield and economic returns as compared to the sprayed ones. Partial budget analysis also revealed that the highest (302150 birr ha^{-1}) NB and acceptable MRR (3079.49%) were obtained from the combination of Danda'a variety with Nativo SC 300 fungicide. The result of this study indicated that the application of effective fungicides, even on susceptible varieties, could minimize yellow rust disease of bread wheat and give maximum net benefit. Moreover, Danda'a was the best-performing variety in almost all circumstances and gave maximum economic return as compared to others. Thus, the application of Nativo SC 300 fungicide in combination with Danda'a bread wheat variety was the most effective option in managing yellow rust disease as well as improving the production and productivity of wheat in *Debre Elias district*.

5.2. Recommendations

Based on the current finding, the combination of the Danda'a bread wheat variety with Nativo SC 300 fungicide showed the best performance in most of the parameters and gave good results in all circumstances. As a result, it could be suggested for efficient management of yellow rust disease and optimization of wheat production in the study area and elsewhere with similar agro-ecological conditions. The study was conducted in a specific site and a single year, so the experiment should be repeated across different environments and years in order to set a solid recommendation.

Yellow rust pathogen is known for its ability to generate diverse races that overcome specific resistance genes of the cultivar and increase epidemics on crops due to the change in environmental weather conditions. As a result, the resistance ability of bread wheat varieties to the disease does not last for a long period of time. Therefore, greater effort should have to be made to develop improved cultivars with non-race-specific, durable and high level resistance, and develop accurate forecast models for more effective, profitable, and sustainable management of yellow rust disease of bread wheat.

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7. APPENDICES

Appendix Table 1: ANOVA table for disease incidence at different days after sowing

Days	Source of variation	DF	SS	MS	F cal.	P value
46 DAS	Replication	2	7.41	3.70	0.31	0.7394
	Variety	2	1251.85	625.93	52.00	<.0001
	Fungicide	2	29.63	14.81	1.23	0.3183
	Variety*Fungicide	4	59.26	14.81	1.23	0.3371
	Error	16	192.59	12.037		
	Total	26	1540.74			
	CV	40.73				
56 DAS	Replication	2	22.22	11.11	0.47	0.6330
	Variety	2	2466.67	1233.33	52.24	<.0001
	Fungicide	2	555.56	277.78	11.76	0.0007
	Variety*Fungicide	4	44.44	11.11	0.47	0.7566
	Error	16	377.78	23.611		
	Total	26	3466.67			
	CV	23.02				
66 DAS	Replication	2	118.52	59.26	2.72	0.0960
	Variety	2	4096.296	2048.15	94.13	<.0001
	Fungicide	2	1340.74	670.37	30.81	<.0001
	Variety*Fungicide	4	14.81	3.70	0.17	0.9505
	Error	16	348.15	21.76		
	Total	26	5918.52			
	CV	14.31				
76 DAS	Replication	2	51.85	25.93	0.76	0.4853
	Variety	2	4140.74	2070.37	60.43	<.0001
	Fungicide	2	2985.19	1492.59	43.57	<.0001
	Variety*Fungicide	4	81.48	20.37	0.59	0.6716
	Error	16	548.15	34.26		
	Total	26	7807.41			
	CV	13.99				
86 DAS	Replication	2	7.41	3.70	0.08	0.9220
	Variety	2	4140.74	2070.37	45.63	<.0001
	Fungicide	2	4474.07	2237.037	49.31	<.0001
	Variety*Fungicide	4	14.81	3.70	0.08	0.9869
	Error	16	725.93	45.37		
	Total	26	9362.96			
	CV	12.72				
96 DAS	Replication	2	22.22	11.11	0.28	0.7625
	Variety	2	4422.22	2211.11	54.90	<.0001
	Fungicide	2	6488.89	3244.44	80.55	<.0001
	Variety*Fungicide	4	222.22	55.56	1.38	0.2852
	Error	16	644.44	40.28		

	Total	26	11800.00
	CV	10.58	

CV= Coefficient of variation, DF= Degree of freedom, SS= Sum square, MS=Mean square, F cal. = F calculated, P value = Probability value, DAS= Days after sowing

Appendix Table 2: ANOVA table for disease severity at different days after sowing

Days	Source of variation	DF	SS	MS	F cal.	P value
46 DAS	Replication	2	0.19	0.095	0.80	0.4654
	Variety	2	19.15	9.57	80.65	<.0001
	Fungicide	2	0.015	0.007	0.07	0.9368
	Variety*Fungicide	4	0.042	0.011	0.09	0.9846
	Error	16	1.899	0.12		
	Total	26	21.296			
	CV	31.97				
56 DAS	Replication	2	0.77	0.39	0.48	0.6276
	Variety	2	142.16	71.08	88.14	<.0001
	Fungicide	2	102.37	51.18	63.47	<.0001
	Variety*Fungicide	4	21.46	5.37	6.65	0.0024
	Error	16	12.90	0.81		
	Total	26	279.67			
	CV	18.28				
66 DAS	Replication	2	0.10	0.05	0.26	0.7750
	Variety	2	317.74	158.87	818.50	<.0001
	Fungicide	2	193.0038	96.50	497.18	<.0001
	Variety*Fungicide	4	6.87	1.72	8.85	0.0006
	Error	16	3.11	0.19		
	Total	26	520.82			
	CV	4.62				
76 DAS	Replication	2	2.59	1.295	0.76	0.4839
	Variety	2	2087.44	1043.72	612.24	<.0001
	Fungicide	2	1779.21	889.60	521.84	<.0001
	Variety*Fungicide	4	381.02	95.26	55.88	<.0001
	Error	16	27.28	1.70		
	Total	26	4277.53			
	CV	5.68				
86 DAS	Replication	2	3.53	1.77	1.24	0.3149
	Variety	2	4759.42	2379.71	1674.42	<.0001
	Fungicide	2	6029.24	3014.62	2121.16	<.0001
	Variety*Fungicide	4	641.58	160.39	112.86	<.0001
	Error	16	22.74	1.42		
	Total	26	11456.52			
	CV	3.32				
96 DAS	Replication	2	6.32	3.16	1.23	0.3183
	Variety	2	4650.65	2325.32	904.74	<.0001
	Fungicide	2	10052.68	5026.34	1955.65	<.0001
	Variety*Fungicide	4	666.23	166.56	64.80	<.0001

Error	16	41.12	2.57
Total	26	15417.02	
CV	3.62		

CV= Coefficient of variation, DF= Degree of freedom, SS= Sum square, MS=Mean square, F cal. = F calculated, P value = Probability value, DAS= Days after sowing

Appendix Table 3: ANOVA table of coefficient of infection on bread wheat yellow rust disease

Source of variation	DF	SS	MS	F cal.	P value
Replication	2	4.99	2.49	4.58	0.0267
Variety	2	11944.23	5972.11	10974.9	<.0001
Fungicide	2	3729.61	1864.80	3426.92	<.0001
Variety*Fungicide	4	2239.67	559.92	1028.95	<.0001
Error	16	8.71	0.54		
Total	26	17927.195			
CV	2.74				

CV= Coefficient of variation, DF= Degree of freedom, SS= Sum square, MS=Mean square, F cal. = F calculated, P value = Probability value

Appendix Table 4: ANOVA table on AUDPC of bread wheat yellow rust

Source of variation	DF	SS	MS	F cal.	P value
Replication	2	2310.31	1155.15	1.99	0.1690
Variety	2	3178675.66	1589337.83	2739.09	<.0001
Fungicide	2	3761539.08	1880769.54	3241.34	<.0001
Variety*Fungicide	4	367110.23	91777.56	158.17	<.0001
Error	16	9283.90	580.24		
Total	26	7318919.18			
CV	2.51				

CV= Coefficient of variation, DF= Degree of freedom, SS= Sum square, MS=Mean square, F cal. = F calculated, P value = Probability value

Appendix Table 5: ANOVA table on DPR of bread wheat yellow rust

Source of variation	DF	SS	MS	F cal.	P value
Replication	2	0.00002808	0.00001404	2.95	0.0814
Variety	2	0.00161227	0.00080614	169.20	<.0001
Fungicide	2	0.00628037	0.00314018	659.11	<.0001
Variety*Fungicide	4	0.00121331	0.00030333	63.67	<.0001
Error	16	0.00007623	0.00000476		
Total	26	0.00921025			
CV	5.69				

CV= Coefficient of variation, DF= Degree of freedom, SS= Sum square, MS=Mean square, F cal. = F calculated, P value = Probability value

Appendix Table 6: Model fit summary for temporal progress of bread wheat yellow rust at Debre Elias district during 2023 main cropping season

Variety	Fungicide	Rep	Logistic model (L)		Gompertz model (G)		Model fitted
			DPR (unit/day)	R^2 (%)	DPR (unit/day)	R^2 (%)	
Danda'a	Nativo	1	0.073388	93.84	0.020948	93.12	L
	Nativo	2	0.07386	88.21	0.022242	92.17	G
	Nativo	3	0.085831	84.69	0.02441	86.89	G
Danda'a	Kanzole	1	0.060258	93.67	0.020209	97.41	G
	Kanzole	2	0.062352	97.99	0.02257	98.78	G
	Kanzole	3	0.075877	91.18	0.025212	95.17	G
Danda'a	Unsprayed	1	0.079121	96.30	0.035692	99.29	G
	Unsprayed	2	0.076813	97.97	0.04241	84.07	L
	Unsprayed	3	0.076297	97.86	0.035069	99.82	G
Ogolcho	Nativo	1	0.052478	94.56	0.024256	95.19	G
	Nativo	2	0.070784	89.85	0.030838	94.23	G
	Nativo	3	0.066007	92.72	0.029908	95.09	G
Ogolcho	Kanzole	1	0.061065	91.06	0.030638	92.95	G
	Kanzole	2	0.067565	91.26	0.033158	93.84	G
	Kanzole	3	0.062062	95.60	0.031652	97.34	G
Ogolcho	Unsprayed	1	0.10776	97.04	0.076611	96.44	L
	Unsprayed	2	0.111515	98.10	0.078538	97.04	L
	Unsprayed	3	0.116086	97.64	0.082408	96.81	L
Kakaba	Nativo	1	0.06257	97.36	0.026222	99.34	G
	Nativo	2	0.06906	95.67	0.028959	98.50	G
	Nativo	3	0.069001	93.87	0.027685	97.49	G
Kakaba	Kanzole	1	0.07028	97.14	0.03283	97.84	G
	Kanzole	2	0.066233	97.24	0.031929	97.86	G
	Kanzole	3	0.062224	96.62	0.030705	96.76	G
Kakaba	Unsprayed	1	0.102987	98.90	0.063001	95.28	L
	Unsprayed	2	0.099881	98.70	0.061802	94.97	L
	Unsprayed	3	0.102277	98.89	0.063772	95.00	L

Rep = replication, DPR = Disease progress rate

Appendix Table 7: ANOVA table of days to 50% heading for bread wheat varieties

Source of variation	DF	SS	MS	F cal.	P value
Replication	2	0.52	0.26	0.12	0.8843
Variety	2	395.63	197.81	94.53	<.0001
Fungicide	2	3.63	1.81	0.87	0.4389
Variety*Fungicide	4	1.48	0.37	0.18	0.9470
Error	16	33.481	2.09		
Total	26	434.74			
CV	2.18				

CV= Coefficient of variation, DF= Degree of freedom, SS= Sum square, MS=Mean square, F cal. = F calculated, P value = Probability value

Appendix Table 8: ANOVA table of days to 90% physiological maturity as a result of variety and fungicide interaction

Source of variation	DF	SS	MS	F cal.	P value
Replication	2	0.89	0.44	0.19	0.8275
Variety	2	696.22	348.11	150.08	<.0001
Fungicide	2	344.00	172.00	74.16	<.0001
Variety*Fungicide	4	137.78	34.44	14.85	<.0001
Error	16	37.11	2.32		
Total	26	1216.00			
CV	1.44				

CV= Coefficient of variation, DF= Degree of freedom, SS= Sum square, MS=Mean square, F cal. = F calculated, P value = Probability value

Appendix Table 9: ANOVA table of plant height on the combination of variety and fungicides

Source of variation	DF	SS	MS	F cal.	P value
Replication	2	8.63	4.32	1.86	0.1884
Variety	2	331.25	165.62	71.22	<.0001
Fungicide	2	233.17	116.58	50.13	<.0001
Variety*Fungicide	4	79.91	19.98	8.59	0.0007
Error	16	37.21	2.33		
Total	26	690.17			
CV	1.65				

CV= Coefficient of variation, DF= Degree of freedom, SS= Sum square, MS=Mean square, F cal. = F calculated, P value = Probability value

Appendix Table 10: ANOVA table of spike length on bread wheat varieties

Source of variation	DF	SS	MS	F cal.	P value
Replication	2	0.06	0.03	0.25	0.7785
Variety	2	8.33	4.17	38.02	<.0001
Fungicide	2	8.298	4.15	37.87	<.0001
Variety*Fungicide	4	1.59	0.397	3.63	0.0275
Error	16	1.75	0.11		
Total	26	20.03			
CV	3.43				

CV= Coefficient of variation, DF= Degree of freedom, SS= Sum square, MS=Mean square, F cal. = F calculated, P value = Probability value

Appendix Table 11: ANOVA table of number of grains per spike on bread wheat varieties

Source of variation	DF	SS	MS	F cal.	P value
Replication	2	3.26	1.63	0.49	0.6219
Variety	2	970.995	485.497	145.67	<.0001
Fungicide	2	758.14	379.07	113.74	<.0001
Variety*Fungicide	4	188.30	47.08	14.13	<.0001

Error	16	53.32	3.33		
Total	26	1974.03			
CV	3.28				

CV= Coefficient of variation, DF= Degree of freedom, SS= Sum square, MS=Mean square, F cal. = F calculated, P value = Probability value

Appendix Table 12: ANOVA table of thousand kernel weight on tested bread wheat varieties

Source of variation	DF	SS	MS	F cal.	P value
Replication	2	0.33	0.17	0.09	0.9135
Variety	2	424.11	212.05	116.41	<.0001
Fungicide	2	2199.65	1099.82	603.77	<.0001
Variety*Fungicide	4	97.44	24.36	13.37	<.0001
Error	16	29.15	1.82		
Total	26	2750.67			
CV	4.47				

CV= Coefficient of variation, DF= Degree of freedom, SS= Sum square, MS=Mean square, F cal. = F calculated, P value = Probability value

Appendix Table 13: ANOVA table of above ground biomass yield on tested bread wheat varieties

Source of variation	DF	SS	MS	F cal.	P value
Replication	2	0.695	0.35	1.34	0.2887
Variety	2	37.86	18.93	73.21	<.0001
Fungicide	2	148.29	74.15	286.77	<.0001
Variety*Fungicide	4	3.87	0.97	3.74	0.0247
Error	16	4.14	0.26		
Total	26	194.85			
CV	5.56				

CV= Coefficient of variation, DF= Degree of freedom, SS= Sum square, MS=Mean square, F cal. = F calculated, P value = Probability value

Appendix Table 14: ANOVA table of grain yield on tested bread wheat varieties

Source of variation	DF	SS	MS	F cal.	P value
Replication	2	0.09	0.05	1.30	0.2994
Variety	2	4.78	2.39	65.78	<.0001
Fungicide	2	26.35	13.18	362.84	<.0001
Variety*Fungicide	4	0.49	0.12	3.35	0.0356
Error	16	0.58	0.04		
Total	26	32.29			
CV	6.27				

CV= Coefficient of variation, DF= Degree of freedom, SS= Sum square, MS=Mean square, F cal. = F calculated, P value = Probability value

Appendix Table 15: ANOVA table of straw yield on tested bread wheat varieties

Source of variation	DF	SS	MS	F cal.	P value
Replication	2	0.29	0.14	0.74	0.4915
Variety	2	15.85	7.93	40.91	<.0001
Fungicide	2	49.73	24.86	128.34	<.0001
Variety*Fungicide	4	4.20	1.05	5.42	0.0059
Error	16	3.099	0.19		
Total	26	73.17			
CV	7.20				

CV= Coefficient of variation, DF= Degree of freedom, SS= Sum square, MS=Mean square, F cal. = F calculated, P value = Probability value

APPENDIX OF FIGURES

Appendix Figure 1: Layout and land preparation of field experiment

Appendix Figure 2: After 50% emergence of bread wheat

Appendix Figure 3: After first weeding and side dressing stage of the crop

Appendix Figure 4: Crop stages at booting and beginning of heading stage and also time of yellow rust onset

Appendix Figure 5: Fully heading and disease development stages of the wheat crop

Appendix Figure 6: Crop stages when yellow rust severity became higher on susceptible Ogolcho variety

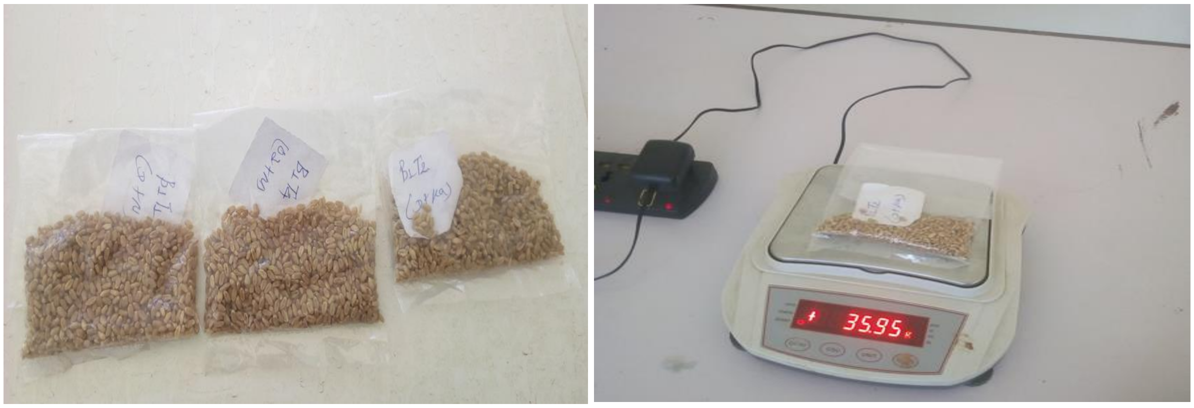
Appendix Figure 7: Early milking stages of the wheat crop

Appendix Figure 8: Maturity stages of the wheat crop

a) b)

Appendix Figure 9: Yellow rust symptom. a) Unsprayed Ogolcho variety b) Unsprayed resistance Danda'a variety

Appendix Figure 10: Disease assessment carried out on farmer fields with farmers



Appendix Figure 11: Grain yields that obtained from the experiment and subjected to laboratory tests

BIOGRAPHICAL SKETCH

The author, Yekedem Amare, was born in Debre Elias District, East Gojjam administrative zone, Amhara national regional state of Ethiopia; on January 25, 2000 G. C. She attended her elementary education in two separate places at *Mekersa Borabur* and *Guay* Elementary school from 2005 to 2013 and secondary education from 2013 to 2017 at *Debre Elias* Preparatory and General secondary School. After completing secondary education, she joined Debre Markos University College of Agriculture and Natural Resource in 2017, and graduated with the Degree of Bachelor of Science in Plant Science on January 23, 2021. After graduation and 5 months rest, she was employed in Debre Markos University as a Graduate assistance in June 8, 2021 and served there for 1 year. Then, she joined the School of Graduate Studies at Bahir Dar University College of Agriculture and Environmental Sciences in 2023 to pursue her M.Sc. degree in Plant Protection Program.