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Review on Wheat Stem Rust Disease Management

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Abstract: **Wheat stem rust is one of the most important diseases of wheat worldwide and causes significant reduction in yield of the crop. In Ethiopia the damage caused by wheat stem rust can be more serious than any other cereal disease. It can destroy thousands of hectares of a healthy crop with a high yield potential in less than a month. Wheat stem rust is a major production constraint in most wheat-growing areas of Ethiopia. This review discusses recent information on economic importance, epidemiology, disease cycle and management of wheat stem rust. It also presents the wheat stem rust disease management methods such as cultural, chemical, biological and use of host resistance methods. Under host resistance method, information on types of resistance, sources of resistance as well as the current strategies to mitigate threat caused by ug99 race and its lineages have been presented.**

Keywords: **Disease, Management, Stem rust, Wheat, Genetic resistance, Cultural practices, Chemical control.**

1. INTRODUCTION

Wheat is one of the most important and significant cereal staple food crops in the world, both in terms of food production and for providing the total amount of food calories and protein in the human diet (Curtis *et al*., 2002 ; Gupta *et al*., 2008). It is a source of food and livelihoods for over a billion people in developing countries (FAO, 2008). However, wheat production is constrained by various wheat diseases caused by fungal, bacterial, and viral pathogens. Of these, diseases caused by the rust fungi have since long been a major concern and problem for breeders, farmers and commercial seed companies (Wiese, 1977). Rust diseases of wheat are among the oldest known diseases and are important worldwide (Singh *et al.,* 2005). Of the three rust diseases of wheat, stem rust remains as the major factor that limits wheat production in most wheat growing regions of the globe (MdAktar-Uz-Zaman *et al*., 2017). It is the most destructive disease of wheat in several wheat-growing countries around the world and can cause up to 100% yield loss if susceptible cultivars are grown and the environment is favorable (Roelfs, 1985a; Roelfs *et al*., 1992; Leonard and Szabo, 2005;Park, 2007; Hodson, 2014). Stem rust of wheat has been successfully controlled through genetic resistance for about three decades (Singh *et al.,* 2002). However, in recent years, it has gained significance as new virulence traits have evolved in stem rust pathogen populations, demonstrating the vulnerability of broadly used wheat cultivars across the globe (Pretorius *et al.,* 2000). The emergence of the Ug99 race in Uganda in 1998, its subsequent geographical expansion within Africa, to the Middle East, and the appearance of Ug99 variants indicate the imminent threat to wheat production (Singh *et al.,* 2011). Estimates suggest that 90% of wheat varieties in the world are susceptible to Ug99, justifying elevated concerns about food security (Singh *et al.,* 2011). Similarly, other non-Ug99 races have appeared in various parts of the world, reducing the efficacy of the newly identified and deployed sources of resistance. The 'Digalu' race caused a devastating epidemic in Ethiopia in 2014 and a similar race has been reported in Germany (Olivera *et al*., 2017). In 2016, another 'broadly' virulent race was detected in an outbreak in Sicily (Bhattacharya, 2017). In Ethiopia, stem rust epidemics has knocked out major cultivars such as Enkoy with Sr36 gene in 1994; and Digalu with SrTmp gene in 2013 and 2014, causing 100 percent yield loss (Badebo and Hundie, 2016). The Digalu race (TKTTF) which is different from the Ug99 race

(TKTTSK) is dominant across the major wheat growing regions of Ethiopia (Badebo and Hundie, 2016) and becomes a major threat to wheat production in the country. The high virulence diversity and evolution rate of the pathogen makes a considerable proportion of wheat germplasm at risk in the country (Admassu *et al*., 2009).

2. ECONOMIC IMPORTANCE OF WHEAT STEM RUST DISEASE

Historically, stem rust has caused major devastation to wheat crops in most of the wheat growing areas of the world (Roelfs *et al.,* 1992). Damage due to stem rust is usually greatest when the disease becomes severe before the grain is completely formed. Widespread epidemics have been documented for Australia, Europe, and North America (Luig, 1985; Roelfs, 1985a; Zadoks and Bouwman, 1985). Epidemics also occur regularly in Africa, China, and Asia (Saarii and Prescott, 1985). Furthermore, highlands of Kenya, Ethiopia, Panama States, Brazil and South India are reported to be the hot spot areas for stem rust (CIMMYT, 1989). The losses due to stem rust of wheat alone in these countries ranged from 40% to 100% on susceptible varieties (CIMMYT, 1989). Losses in Southern Germany, Romania and Bulgaria can reach as high as 60-80% (Roelfs, 1985b). Reports also showed that yield reduction due to *Pgt* could reach up to 50% within a month under favorable conditions (Roelfs and Long, 1987). In developing countries, 20-30 million tones annual yield loss has been estimated (Haldore *et al*., 1982). In USA, early severe epidemics has resulted in losses of up to 356 millions of US dollars based on wheat price in late 1995 (Roelfs, 1985a). In Canada it was estimated at 270 million Canadian dollars based on annual acreage yield loss of 25% expected if susceptible cultivars are grown. Apart from losses in grain yield, stem rust can significantly affect the grain quality (Roelfs, 1985b).

In Ethiopia, earlier reports showed that losses in wheat yield due to stem rust have been estimated to be 61% (Eshetu, 1985) whereas other reports indicated losses ranging from 67 to 100% on commercial wheat cultivars (Shank, 1994). For example, stem rust epidemics occurred in 1994 on variety Enkoy resulted in 58% yield loss (Beyene, 2018). Similarly, recent reports indicated that stem rust epidemics occurred in the Southern wheat production region during 2013, 2014 and 2015 for three consecutive years on variety Digalu resulted in yield loss of 100% in main wheat growing areas (David, 2016; Beyene, 2018). The epidemic caused on variety Digalu for three consecutive years was by a non-Ug99 pathotype of *Puccinia graminis tritici*, designated as TKTTF or Digelu race (Hailu *et al* 2015; Beyene, 2018). Generally, the estimated annual losses due to race Ug99 reached to approximately USD $3 billion in Africa, the Middle East and South Asia (Singh *et al*. 2006).

3. EPIDEMIOLOGY OF WHEAT STEM RUST DISEASE

In wheat stem rust disease development, the disease cycle starts with the exposure of the new wheat crop to stem rust inoculum. The source of inoculum is different under different environments. In regions with warm climates, but without barbery, the volunteer plants carry the spores over summer and urediospores from the infected volunteer plants are the source of initial inoculum for wheat planted in the next growing season to start a disease cycle (Leonard and Szabo 2005). In Ethiopia, the main sources of inoculum are endogenous urediospores whereas exogenous urediospores can also have a certain contribution to be a source of inoculum. Migration of Ug99 urediospores from Kenya to Ethiopia can be taken as a good example. In the regions with cold climates and barbery, aeciospores are the main source of initial inocula for wheat stem rust. Aeciospores are produced on barberry, the most common alternate host of the pathogen (Leonard and Szabo 2005). On barberry, *P.graminis* starts its life cycle by producing black thick walled, diploid teliospores that keep *P.graminis* dormant overwinter (Roelfs 1985a). After karyogamy, which forms a diploid nucleus from the fusion of two haploid nuclei, meiosis begins and results in four haploid basidiospores. In spring, each teliospore germinates to produce two identical thin walled haploid basidiospores (Roelfs 1985a; Leonard and Szabo 2005). Mature basidiospores are carried by air currents to reinfect barberry. Basidiospores germinate and form a haploid mycelium growing on the leaf surface. From the mycelium, pycnia are produced on the upper leaf surface of barberry. Pycnia produce receptive hyphae that serve as female gametes and pycniospores served as male gametes (Roelfs 1985a). Pycniospores are produced in honeydew that is attractive to insects, and rain splashing helps disperse pycniospores. When pycniospores are paired with receptive hyphae, cross-fertilization occurs successfully and dikaryotic mycelium forms. Then a cup-shaped dikaryotic aecium forms to release aeciospores. Normally aeciospores stalked in chains produced on barberry are transported by wind to start a new disease cycle in susceptible wheat cultivars (Roelfs 1985a; Leonard and Szabo 2005). In wheat, stem rust infection mainly occurs on stems and leaf sheaths. Within two weeks after inoculation, a brick-red structure, called a rust pustule also known as a uredium containing urediospores appears at the point of inoculation. In a later developmental

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stage, another type of spore called teliospore, which is a black overwintering spore, is produced in telia (Cummins and Hiratsuka, 2003) to conclude the disease cycle of stem rust in wheat and to start a new life cycle in barberry. However, in warm climates and without barbery, the first spores to infect the young wheat plants are urediospores. They generally come from infected volunteer plants. Here, disease occurs without the help of barberry and urediospores are source of the initial inoculum to start a new disease cycle.

The development of stem rust in wheat is favored by warm temperature (18-30^{0}C) with high relative humidity. The minimum, optimum and maximum temperatures for spore germination are 2°, 15° to 24°, and 30°C, respectively and for sporulation, 5°, 30° and 40°C, respectively (Roelfs *et al.*, 1992; Singh *et al* 2002), thus providing a vast range of favorable environmental conditions. Urediospores initiate germination within 1–3 h of contact with free moisture over a range of temperatures. In field conditions, 6–8 h of dew period or free moisture from rains is required for the completion of infection process. The onset of the disease is marked by eruption of elongated, brown pustules on the stalk, leaf sheath and leaves, the stalk being often most severely attacked (Leonard and Szabo, 2005). These pustules (Uredia) may be about 6-10 mm in length and frequently run into one another. They burst early exposing a brown powder (consisting of the urediospores) and are surrounded by prominent epidermal frings (Singh, 2005). One uredium can produce at least 100,000 urediospores and each urediospore has the potential to produce a new infection that will cause similar damage on the same plant or another wheat plant. In heteroecious rusts such as wheat stem rust, urediospores can reproduce themselves and re-infect wheat multiple times (Leonard and Szabo 2005). These multiple cycles of infection, sporulation, and re-infection can produce very destructive epidemics in wheat fields within just a few weeks (Leonard, 2001). Several generations of this spore type may be produced in a single growing season. Consequently explosive epidemics can occur during favorable environmental conditions (Roelfs *et al.*, 1992). Especially in warm, humid climates, it can be severe due to favorable conditions for disease development (Singh *et al.*, 2002). Moreover, it can cause severe yield losses in susceptible cultivars of wheat in environments favorable for disease development (Leonard and Szabo 2005). It is also most severe when a crop maturity is delayed.

Apart from dissemination to newly emerged tissues of the same plant or adjacent plants to cause new infections, the urediospores can be transported through wind in long distances. Long-distance transport through prevailing winds is known to occur across the North American Great Plains (Roelfs, 1985), from Australia to New Zealand, and rarely to a distance of about 8000 km from southern Africa to Australia (Luig, 1985). In the case of long-distance dispersal, spore depositions on crops in a new area are often associated with rain showers. Stem rust urediospores are rather resistant to atmospheric conditions if their moisture content is moderate (20–30%).

4. LIFE CYCLE OF WHEAT STEM RUST PATHOGEN

Stem rust of wheat is caused by a parasitic fungus *Puccinia graminis* f.sp. *tritici*, and the fungus is heteroecious which means that two unrelated hosts, such as wheat and barberry, are required to complete its life cycle (Leonard and Szabo 2005). Wheat is the primary host where the pathogen spends most time, and barberry is the secondary host. The fungus can reproduce itself only in living host plants. It has five types of spores at different developmental stages: pycniospores, aeciospores, uredospores, teliospores, and basidiospores (Leonard 2001a).

The sexual stage of the life cycle takes place on the alternate host and asexual reproduction takes place on the primary host (Leonard and Szabo, 2005). Teliospores overwintering on infected straw germinate annually in conjunction with the development of new growth of leaves of the barberry host (Roelfs, 1985). Each teliospore consists of two cells each containing two haploid nuclei that undergo karyogamy early in teliospore development. After karyogamy, meiosis begins but is 14 arrested in diplonema during dormancy (Boehm *et al.*, 1992). Both cells germinate to produce a basidum to which the four haploid nuclei migrate upon completion of meiosis.

Within the basidum, the four nuclei are separated by three transverse septa. From each basidum a sterigma elongates, through which the haploid nuclei migrate into the developing basidiospore as it forms at the tip of the sterigma (Roelfs, 1985). In the basidiospore, the haploid nuclei undergo mitosis to produce two identical haploid nuclei. Basidiospores are ejected and carried by air currents to the barberry host, on which they infect younger leaves. The structure produced from infection is a flask shaped pycnia on the adaxial leaf surface. Two gametic cells of the pycnia are involved in sexual recombination between the + and – mating types. The male gametes are the pycniospores which are extruded from the pycnium in a drop of nectar, making them available for dissemination among pycnia by insects and rain. The female gametes are flexuous hyphae that extend out of the top of the pycnium. The contact of a pycniospore with the nectar of an opposite mating type induces the formation of a pyncial cap of the pycniospore (Anikster *et al.*, 1999). When the pycniospore contacts a flexuous hypha, fusion of the cells occurs and the haploid nucleus migrates through flexuous hypha, then through the monokaryotic hyphae to the cells at the base of the pycnium (Johnson and Newton, 1946). The dikaryotic state is established with the division and subsequent union of + and – gametes. The result of this union is the production of a dikaryotic aecium directly under the pycnium, which eventually ruptures the abaxial leaf surface through which chains of dikaryotic aeciospores are, produced which are capable of infecting the wheat host (Roelfs, 1985). Aeciospores infecting the wheat host produce a dense mat of hyphae below the host epidermis. From these, hyphae sporophores emerge to produce dikaryotic urediospores leading to the formation of the visible infection structure known as the uredinium. Infections generally take place on the stems and leaf sheaths of the wheat host. Urediospores then re-infect wheat hosts, causing secondary infections on the same plants or primary infections on other plants. As wheat host plants begin to senesce, the uredinia cease urediospore production and produce teliospores. From then on, the infection structure is called a telium (Cummins and Hiratsuka, 2003). The uredial stage is able to persist throughout the year on wheat. The disease cycle starts with the exposure of the new wheat crop to stem rust inoculum either by aeciospores from barberies or urediospores from volunteer plants.

5. WHEAT STEM RUST DISEASE MANAGEMENT

A number of methods were practiced in the past and are being practiced at present, to manage wheat stem rust disease. However, none of them were totally satisfactory by themselves. Moreover, management of cereal rust diseases is complex because of their rapid dissemination and the frequency of evolution of new physiologic races and thus demands a perfect knowledge of all the elements of epidemics that are interrelated (Singh, 2005). Therefore, a combination of different strategies should be used to manage cereal rusts in wheat production.

5.1 CULTURAL PRACTICES

The wheat stem rust control strategy could be through application of different cultural practices (Peterson, 1965; Roelfs *et al.*, 1992). Cultural practice is important because it reduces environmental pollution and delays disease onset and hence its severity. The starting time of an epidemic is critical to the amount of damage that it causes. The date of disease onset is directly related to the development of an epidemic (Hamilton and Stakman, 1967) and is probably the single most important factor in determining the severity of the epidemic (Roelfs, 1985a). The use of early maturing varieties helps to escape the occurrence of the disease (Roelfs *et al*., 1992; Singh *et al.*, 2002). Early sown wheat crops also escape the damage of rust diseases due to growth stage and time of infection (Yeshi and Mengistu, 1999) and thus, help to reduce the time of exposure of the crop to the pathogen and hence reduce yield loss. The success of implementing these methods depends on sufficient knowledge of the epidemiology of stem rust in a particular area and it is only feasible where inoculum is exogenous and arrives well into the cropping season (Roelfs *et al*., 1992; Singh *et al.*, 2002). However, in some environments, early planting can lead to early heading and there is risk of head frosting that can be as damaging as the rust. Rust severity may be further increased by excessive nitrogen fertilization resulting in denser stands and delayed maturity (Knott, 1989). Therefore, avoiding excess nitrogen and frequent irrigation are generally helpful in controlling stem rust (Mehrotra, 1980; Roelfs, 1984). In areas where the disease oversummers, destruction of volunteer whets and other susceptible grasses several weeks before planting also reduces inoculum level and delays initial infection. Hollaway and Brown (2005) also recommended heavy grazing of self-sown susceptible wheat by cattle over summer season to reduce the amount of rust inoculum in the following season crop. Green-bridge management is equally important as other practices of controlling the disease because it helps to minimize inoculum carry over (Zadoks and Bouwman, 1985; Roelfs, *et al.*, 1992; Hollaway, 2007; 2014). Since rust survives from one season to the next on living plant material (mainly self-sown cereals), the removal of the green bridge with tillage or herbicides is an effective control measure for epidemics that would result from endogenous inoculum and is essential to reduce the amount of inoculum present to infect a new crop (Roelfs *et al.*, 1992).

Mixed cropping of wheat with other suitable crops gives good crop insurance even if the main crop fails. In a mixed crop, there is species diversity within a field, and as a result, the rate of disease spread is delayed, consequently reducing the terminal disease severity. If high-yielding strains of all the crops are available, then the very practice of mixed farming can be exploited to minimize disease losses. Using multi-lines or varietal mixtures are also recommended because they are effective in reducing the levels of inocula and disease (FAO, 2008; Kumar, 2012) It has also been reported that the eradication of barberry bushes and other alternate hosts from different wheat growing areas has significantly reduced the incidence of the disease (Hink, 1964; Peterson, 1965; Harmanson, 1968; Roelfs *et al*., 1987; Roelfs *et al*., 1992; McVey *et al*., 1997; McVey *et al*., 1999; Schumann and Leonard, 2011). The eradication of barberry plants may control the disease by cutting down the life cycle of fungus. It is the most effective method in those countries where the pathogen completes its life cycle on alternate host (Dubin and John, 2009; Lidiya, 2018**).** Other reports also indicated that barberry eradication from areas that was serving as breeding ground for sexual reproduction of *Puccinia graminis f.sp. tritici* resulted in elimination of the sources of local, often early epidemics of stem rust of wheat, thus increasing the useful life of resistance genes in wheat (Roelfs and Groth, 1980;Groth and Roelfs 1982; Singh, *et al*., 2002; Jin *et al*., 2008). Furthermore, Barberry eradication affects the frequency and severity of stem rust epidemics by delaying disease onset by about 10 days, reducing the initial inoculum level, decreasing the number of pathogenic races and stabilising them (Roelfs, 1985). In 1980, study was conducted for the presence and influence of barberry plants on rust development in Ethiopia. The presence of barberry plants around Debre-Sina and Menagesha area in the country was known but the rust samples collected from these barberry plants did not infect the wheat crop and other hosts of the disease ((Sorokina *et al*., 1980; Dmitriev *et al*., 1980; Scientific Phytopathological Laboratory, 1980). However, recent study proved that the barbay plant serves as alternate host for wheat stem rust (Woldeab *et al*., 2016).

5.2 CHEMICAL CONTROL

Chemical means of control becomes quite important as a second line of defense when new virulent races of rust attack wheat varieties that have previously been resistant to prevalent races and if such a new race becomes wide spread in wheat producing areas before plant breeders have had sufficient time to develop a suitable resistant wheat variety (Loughman *et al*., 2005). In other words, fungicides could be used in emergency cases, or could be an integral part of diseases management program. However, fungicides incur additional cost to farmers and could be detrimental to the environment (Roelfs *et al*., 1992). Singh (1990) stressed that effective and economic chemical control of rust depends on reliable forecasts of the progress of rust epidemics. Roelfs (1988) reported that chemical control of stem rust has been effectively used in areas of production with subsidized production costs. A number of fungicides are highly effective against stem rust and have been used to control the disease successfully (Hollaway, 2011). Agrios (2005) reported that two applications of Zinc-ion-Maneb mixture reduce the damage from stem rust by 75% if this application is in accordance with weather condition forecasts favoring stem rust epidemics. Furthermore, Agrios (2005) also indicated that systemic fungicides especially triadimefon is important in controlling stem rust when applied as one or two sprays at one to three weeks interval during the onset of disease. Similarly, in southern Australia Propiconazole and tebuconazole, achieved economic control of wheat stem rust when applied at early disease onset (Ciara *et al*., 2004). Therefore, early disease detection and immediate application of fungicides should be considered in the control of stem rust with fungicides (Peterson, 2001; Hollaway, 2011). It has also been reported that stem rust becomes more difficult to control if the crop is highly infected. This is because fungicides reduce only subsequent rust severity on plant parts that were slightly infected at the time of fungicide application, but they are not effective on plant parts that were heavily infected (Beard *et al.*, 2004). Generally, fungicides will give better control of stem rust when applied early in the epidemic (Loughman *et al*., 2005). A late, low level occurrence of stem rust (after mid-dough) will have little impact on yield (Schumann and Leonard. 2011).

In Ethiopia, currently, most of the commercial wheat varieties are highly susceptible to race Ug99 and its lineages and also to non-Ug99 race of stem rust (Netsanet, 2014). Therefore, it is not possible to grow a wheat crop without the application of a fungicide. Therefore, fungicides will play a role in the integrated management of the disease until new varieties with improved resistance are released (Netsanet, 2014.). Yeshi (1988) reviewed chemical disease control in wheat and reported that triadimefon and Propiconazole to be effective for the control of stem rust. Bekele (2003) reported Propiconazole (Tilt) and Futiafol to be effective against rusts in Bale and Arsi zones. Likwise, Mengistu *et al.*, (1991) and Getaneh (1996) reported that fungicides such as Bayleton (triadimefon) 25% W. P. at 0.5 kg/ha, Tilt (propiconazol) 250 EC at 0.5 l/ha and Oxycarboxine and Mebenil have been found effective against stem rust of wheat. CIMMITY (2005) also reported that chemical intervention is used on an emergency basis when high infections are observed and losses are expected. Both Large-scale and small-scale farmers in Ethiopia use fungicides to control rusts. However, most small-scale farmers do not use extensively as to large-scale farmers because of high cost of chemicals in local markets. The large-scale wheat growers in Arsi and Bale regions of Ethiopia spend annually around 0.5 million US dollars to control rusts successfully and to maintain high productivity Kebede, *et al*, 2010).

5.3 BIOLOGICAL CONTROL

Biological control methods of rusts can also be exploited as some biological agents such as Xanthomonasuredovorus (Loban, 1988), Erwiniauredovora (James and Baker, 1983) and fungi Darlucafilum (Zillinsky, 1983; Temam, 1984; Loban, 1988) have been found to parasitize/hyperparasitize the urediospores of the pathogen. Though it is indicated that hyperparasites are effective as biocontrol for rust fungi in the literature, there is no initiated preliminary and investigative research going on or initiated on such issues in Ethiopia so far.

5.4 HOST PLANT RESISTANCE

The use of resistant cultivars is the most important and the most practical method of controlling stem rust of wheat (Watson, 1970; Wolfe, 1985; Roelfs and Long, 1987; Zwer *et al.*, 1992; Bahadur *et al.*, 1993; McVey *et al.*, 1997; Mamluk *et al*., 2000; Agrios, 2005; Schumann and Leonard, 2011; Hollaway, 2014).Moreover, it is the principal mechanism of controlling cereal rusts (Johnson, 1981; Roelfs *et al*., 1992; Chen, 2005; Boyd, 2005; Hei *et al*., 2014) and is the best strategy for resource poor farmers in the developing world (McIntosh *et al*., 2009; Beyene, 2018). It is also the most environmentally friendly and profitable strategy for commercial farmers if they grow genetically resistant varieties using different resistance genes (McIntosh *et al*., 2009; Beyene, 2018). The major advantages of genetic resistance includes**:** reduction or avoidance of the dependence on chemical control, non-detrimental effect on the environment and demanding no action by farmers once the cultivar is selected. But it has also limitations that include: it requires knowledge of the pathogen virulence and evolution, short life of genetic resistance (boom and bust) and lack of possibility to change after planting the crop (Roelfs *et al.*, 1992). There may be several reasons for short life of resistance genes: resistance may have been selected empirically without adequate knowledge of pathogen virulence, thus inappropriate resistance genes have been used; only single resistance genes may have been used in any one cultivar; new virulences rapidly evolved in the pathogen (CABI, 2018). Deployment of stem rust resistant cultivars provided an annual protection estimated at $ 124 millions in Australia (Zwer *et al.*, 1992). Similar estimation provided an annual protection of $ 217 million per year in Canada due to the use of resistance cultivars against wheat stem rust disease. Hence, use of resistant cultivars against Ug99 is crucial for stem rust management currently (Singh *et al*., 2008). Emergence and spread of new races of stem rust pose an imminent threat to wheat production worldwide and this requires the rapid development of wheat cultivars with durable resistance to stem rust (Rolfs *et al*., 1992). The durability of effective resistance genes can be enhanced by deploying them as pyramids in cultivars (Singh *et al.*, 2006). To date, about fifty eight stem rust resistance genes have been identified and some of them have been mapped on different chromosomes in wheat and its relatives (McIntosh *et al.* 1998).All these genes are race specific except Sr2 that has provided durable non-race-specific slow-rusting adult plant resistance (McIntosh *et al*., 1995; Spielmeyer *et al*., 2003; Singh *et al*., 2006; Singh *et al*., 2007). Among these resistance genes, some genes deployed in commercial cultivars worldwide remained effective individually or in combination with other Sr genes until recently (Spielmeyer *et al.*, 2003). Moreover, the Sr2 complex in combination with other resistance genes showed effective protection against Ug99 (Singh *et al.*, 2006). Resistance gene Sr26 provides resistance to current stem rust races of wheat in Australia (Mago *et al*., 2005). Most deployed resistance genes are susceptible to Ug99 or overcome by virulence of Ug99 except few genes such as Sr2.

In Ethiopia, the use of resistant cultivars has been the major strategy to control stem rust (Hai *et al*., 2014). Several rust resistant varieties have been developed since the beginning of wheat research in the country (Temesgen *et al.*, 1995). Under large-scale production, resistance to stem rust and yellow rust became ineffective, limiting the duration of cultivation despite wide adaptability and high productivity of the cultivars. These rapid breakdowns of resistance genes of Ethiopian wheat cultivars are associated with inadequate knowledge of the virulence present in the pathogen population and the disease screening protocol, which is inadequate to identify and select the resistant wheat lines (CIMMYT, 2005). In addition, continuous release and wide cultivation of CIMMYT originated bread wheat genotypes with common parentage could be the most important factor for fast evolution of rust pathogens in Ethiopia (Ayele, 2002).

5.4.1 TYPES OF HOST RESISTANCE

Studies of the interaction between cereal rusts and their hosts show a very close relationship between the genetics of the pathogen and of the host in the expression of disease (Stubbs *et al*., 1986). Host-pathogen interaction could be specific or non-specific (Roelfs *et al*., 1992). Commonly plant pathologists divide resistance in to two major categories (Stubbs *et al*., 1986). These are vertical and horizontal or specific and non-specific. Resistance is also categorized based on growth stages**:** seedling and adult plant resistances (Singh, 1990), where one is inherited independent of the other (Singh, 1990). Temperature is one of the critical factors that plays an important role in the expression of *Sr* genes in wheat; usually low temperatures favor the expression of greater resistance whereas at high temperatures there is a tendency for breakdown of resistance (Leonard and Szabo, 2005). According to Parlevliet (1995), durable resistance is a quantitative term that indicates a relatively long period of effectiveness of the resistance when exposed to the pathogen under investigation. The components of the durable resistance include infection frequency, infectious period, latency period and the size of the colony and lesion (Parlevliet, 1979). Slow rusting resistance is a type of resistance whereby the rate of pathogen development is retarded without much chlorosis like that of the hypersensitive type (Ohm and Shaner, 1976). Cultivars with slow rusting resistance usually exhibit low terminal severity, reduced size of pustules, longer latency period, low sporulation and small number of pustules (Wilcoxson *et al*., 1975).

5.4.2 SOURCES OF RESISTANCE

The deployment of single genes for resistance can lead to profound changes in the population structure of *Puccinia graminis tritici*. The large scale cultivation of wheat lines carrying single genes for resistance deployed on a large scale places tremendous directional selection pressure on stem rust pathogen populations towards the predominance of pathotypes virulent to the resistance gene (Van der Plank, 1968). The large scale deployment of a highly resistant single gene effective against a large fraction of the pathogen population and the subsequent evolution of the pathogen population towards virulence is known as the 'boom and bust' cycle (Sun and Yang, 1999). The inefficacy of the resistance gene is not due to changes in the gene itself but to the proliferation of mutants in the pathogen population with an aberrant avirulence gene (Roelfs *et al*., 1992). These individuals are able to proliferate on hosts carrying the cognate resistance gene for the avirulence gene that was mutated. The aberrant pathogens come to predominate the population, as they are the only individuals able to proliferate on the widely deployed host carrying the defeated gene. The opportunity for sexual reproduction by *Puccinia graminis tritici* is strictly dependent on its alternate host, the plant barberry. However, without the opportunity for sexual union of mating types and recombination during meiosis, most common genotypes of *Puccinia graminis tritici* have adapted to strictly asexual reproduction (Zambino *et al.* 2000). In this adaptation they have lost the ability to produce teliospores and induce recombination through meiosis. In asexual reproduction, the main source of variation is mutation (McDonald and Linde, 2002). Resistance to *Puccinia graminis tritici* is conferred by genes that interact with pathogen virulence genes in a gene-for-gene manner (Flor, 1955). It is in this relationship a particular stem rust resistance gene present in the host is cognate to an avirulence gene in the stem rust pathogen. In many cases, a single resistance gene can effectively control one or more strains of particular pathogen, and breeders have used resistance genes in conventional resistance breeding programs for decades (McDowell and Woffenden 2003). These stem rust resistance genes came from common wheat or wheat relatives. Twenty resistance genes including Sr6, Sr28, Sr29 and SrTmp were identified in common wheat, T. aestivum; seven including Sr2 were from T.turgidum; three Sr genes (Sr21, Sr22, and Sr35) were from T. monococcum; four Sr genes including Sr24, Sr25, and Sr26 were from Agropyronelongatum; Sr31 and Sr1A.1R were from Secalecereale; Sr36 and Sr37 were from T. timopheevi; one each was from T. ventricosum (Sr38) and T. araraticum (Sr40), respectively (Singh *et al.* 2006) All these catalogued Sr genes are race specific, except gene Sr2.

At present, 58 Sr genes have been designated, with three gene loci having multiple alleles (McIntosh *et al.* 1995) and other stem rust resistance genes exist with temporary designation status. Several of the genes derived from wild relatives present on small chromosomal introgression segments have been relied upon breeding programs and have been deployed commercially. Some of the Sr genes have been widely deployed in commercial wheat cultivars. Sr2, derived from T. turgidum is on chromosome 3BS, and has conferred durable rust resistance against all virulent races of *P. graminis* worldwide for more than 50 years. It has been deployed in many wheat cultivars worldwide (McIntosh *et al.* 1995). Sr2 as a slow rust resistance gene shows partial resistance with variable levels of disease on adult plants grown in the field when it is used alone (Singh *et al.* 2006). The effect of Sr2 can be enhanced by adding race-specific Sr genes (Kota *et al*. 2006). Pseudo-black chaff, a dark pigmentation around the stem internodes and glumes is closely associated with Sr2 and has been used as a morphological marker to select for the gene (Hayden *et al.* 2004). Sr24 was originally derived from A. elongatum and has been integrated into many wheat lines in South America, Australia and CIMMYT (Singh *et al*. 2006). The stem rust resistant variety Agent has a spontaneous translocation between chromosomes 3Ag of A. elongatum and 3DL of bread wheat (Smith *et al*. 1968). Amigo, another wheat variety that has a 1AL.1RS translocation from Insave rye, has two Sr genes: one on rye chromosome 1RS and the other, Sr24, on 1BS (Mago *et al.* 2005a). Sr26 is translocated from

A. elongatum to chromosome 6AL of wheat (Knott 1968). Sr26 has not been widely deployed in commercial wheat varieties due to the yield penalty associated with the gene (The *et al*. 1988). Sr31, a strong resistance gene derived from *Secale cereale* introduced to bread wheat through a 1B/1RS translocation, has been deployed in winter and spring wheat varieties in China, Europe, India, and USA (McIntosh *et al.* 1995). Enhanced stem rust resistance was reported when it was stacked with Sr25 (Tomar and Menon 2001). Sr36, derived from *T. timopheevi* was originally transferred into two hard red spring wheat lines, CI12632 and CI12633 (Tsilo *et al*. 2008). Sr36 is located on chromosome 2BS, and has been deployed in many Australian wheat cultivars (Bariana *et al*. 2001) and some soft winter wheat cultivars in the USA (Jin and Singh 2006).

The unique virulence profile of Ug99 (Pgt race TTKSK and derivatives) makes it a tremendous threat to wheat production worldwide. For many years Sr31 provided seemingly durable resistance globally but inevitably selection pressures led to the development of virulence in Ug99. Developing lines with adequate and durable resistance to Ug99 has presented unique and challenging problem to wheat scientists worldwide with the majority of genes conferring resistance coming from wild relatives. Many of the effective resistance genes are present on large translocations and are associated with linkage drag.

Field evaluations in 2006 and 2007 in Kenya and greenhouse evaluations at the USDA Cereal Disease Laboratory have elucidated Sr genes effective against Ug99 (Singh *et al* 2008). These include Sr22, Sr25, Sr26, Sr27, Sr28, Sr32, Sr33, Sr35, Sr37, Sr39, Sr40, Sr44 and SrTmp and have been transferred into wheat backgrounds. However, deployment of these genes in commercial cultivars is still in its infancy due to their presence on large alien translocations that have deleterious effects on important agronomic characteristics (Singh *et al* 2008). At the present time, the research of stem rust in wheat is focusing on identifying more resistance genes to control Ug99 (CornellUniversity, 2009). In general, identification and deployment of new genes for rust resistance must be the ongoing requirements of world wheat breeding programs, as the existing genes become ineffective due to rapid and dangerous evolution of new races or pathotypes (Singh *et al.*, 2008). New resistance genes to wheat rusts can be found among the wild relatives of cultivated wheat that have evolved with their parasites and have grown along with cultivated wheat during the last several thousand years (Manisterski*et al.,* 1988). Generally, cultivated wheat and closely related grasses can be sources of specific and non specific resistance genes against wheat stem rust pathogen (Roelfs *et al*., 1992; Johnson, 1994, Singh *et al*., 2008).

5.5 CURRENT STRATEGIES TO MITGATE THREAT CAUSED BY UG99 RACE AND ITS LINEAGES

Reducing the area planted to susceptible cultivars in risk areas of East Africa, Arabian Peninsula, North Africa, Middle East and West-South Asia is the best strategy if major losses are to be avoided (Hodson, 2014). The "Borlaug Global Rust Initiative" is using the following strategies to reduce the possibilities of major epidemics: 1) monitoring the spread of race Ug99 beyond eastern Africa for early warning and potential chemical interventions, 2) screening of released varieties and germplasm for resistance, 3) distributing sources of resistance worldwide for either direct use as varieties or for breeding, and 4) breeding to incorporate diverse resistance genes and adult plant resistance into high-yielding adapted varieties and new germplasm. Population monitoring through trap nurseries was recommended by a CIMMYT expert panel (CIMMYT, 2005). Trap nurseries are used for evaluating disease resistance sources thoroughly by monitoring changes in the pathogen population. It can also be a source of pathogen cultures and for evaluating new germplasm (Ferrara, 2008; Lidya, 2018). The USDA‟s cereal rust laboratory in Minnesota is helping in race characterization by providing assistance in developing stem rust nurseries at various locations in Africa and Asia to determine presence and migration of Ug99 and other races in these areas (CIMMYT, 2005). Ethiopia is one of the target county benefited a lot from this initiative. In 1968, the first international congress of Plant Pathology in London recommended global surveys for diseases such as wheat stem rust in order to determine regional differences in virulence (Park *et al.,* 2010; Lidya, 2018). For global monitoring of cereal rust pathogens, they provided a broad outline for the global cereal rust monitoring system (GCRMS) (Hodson, 2014; Lidya, 2018). The success of this GCRMS is dependent on the mutual cooperation at the international level by providing quality information on the incidence of rusts and the pathotypes present (Park *et al*., 2010).

The best long-term strategy to mitigate the threat from Ug99 race and its lineages is to identify resistant sources among existing materials, or develop resistant wheat varieties that can adapt to the prevalent environments in countries under high risk, and release them after proper testing while simultaneously multiplying the seed (Singh *et.al.,* 2008). An aggressive strategy to promote these resistant varieties in farmers' fields is the only viable option as resource poor as well as commercial farmers in most of Africa, Middle East and Asia. Resource poor farmers cannot afford chemical control or may not be able to apply chemicals in the event of large scale epidemics due to their unavailability for timely application. Potential epidemics following the spread of Ug99 or its variants can be avoided if current susceptible cultivars occupying most of the wheat areas in the primary risk areas in the predicted migration path are reduced. Screening in Kenya during 2005, 2006 and 2007 has identified a few resistant released varieties or advanced breeding materials at various stages of testing in most of the countries that submitted their materials for screening. One strategy is to find ways to ensure that the best, high-yielding resistant materials occupy at least 5% of total wheat area distributed throughout the wheat region and are readily available. This might be via seed supply through procurement in the case that Ug99 establishment is evident in a particular country.

Identification and promotion of new stem rust resistant varieties that have significantly enhanced yield potential than current varieties, in conjunction with other desirable traits is probably the best strategy to ensure their fast adoption and succeed in replacing the existing popular but susceptible varieties. Testing of new wheat lines with adequate resistance to Ug99 in various countries has indicated that new wheat materials with higher yields than current varieties can be a reality. Thus, development and deployment of resistant varieties is one of the key tools for wheat rust management. These could only be achieved by having effective contingency planning for organized fast-track release of new varieties and accelerated seed multiplication under pinned by flexible policies, and commitments by national and/or international community of stakeholders (Osborn and Bishaw, 2009).A framework for fast track variety testing and release and accelerated seed multiplication was undertaken to address the objectives of the different projects as follows: identifying stem rust (Ug99) and yellow rust resistant wheat elite lines combined with better agronomic performance, fast track testing and release of new rust-resistant wheat varieties through national dialogue with stakeholders, popularizing and demonstrating newly released rust resistance wheat varieties in collaboration and partnership with extension services and development practitioners, accelerating seed multiplication of promising lines (pre-release) or released varieties (post-release) to produce sufficient amount of early generation seed (breeder, pre-basic and basic seed), accelerating large-scale certified seed production of released varieties by partnering with existing public and/or private seed sector, distributing small seed-packs of released varieties to initiate on-farm seed production mobilizing farmers and assisting in informal varietal diffusion, strengthening the infrastructure and human resources capacity of key stakeholders including farmers and monitoring and evaluation of project deliverables including adoption and impact studies (Zewdie, 2016)

Under the BGRI, CIMMYT, ICARDA and a number of NARS from developed and developing countries have tested thousands of accessions in Kenya and Ethiopia. A number of elite lines with adequate resistance against Ug99 and with up to 15% yield increase have been identified through such collaborative effort. Some of these materials were distributed as part of Elite Bread Wheat Yield Trials (EBWYT) and Stem Rust Resistance Screening Nurseries (SRRSN) by CIMMYT and ICARDA (Zewdie, 2016). The wheat research strategy against the threat of stem rust race Ug99 and other rusts anchored on the following activities: screening national germplasm (old varieties, commercial varieties, promising lines, breeding materials) for resistance against Ug99 in hot spots, identifying resistance genes that are effective against Ug99 and local races of stem rust, yellow rust and leaf rust that carries durable resistance using molecular tools and incorporating diverse resistance genes into adapted cultivars and evaluate them in hot spots to develop new high yielding varieties. From the outset, several accessions have been screened in Kenya and shared globally with NARS through CIMMYT and ICARDA as part of EBWYT and SRRSN since 2005. In general, BGRI, placed emphasis on prevention, by promoting the development and planting of resistant cultivars, use of certified seeds, rapid seed multiplication, training of farmers, strengthening surveillance and emergency response capacities, promoting research – extension – farmer linkages and international cooperation. Therefore, development and deployment of resistant varieties, adequate surveillance systems and effective plant protection strategies are important elements of an integrated wheat rust control strategy to replace widely grown Ug99 race & its lineages susceptible varieties and ensure national, regional and global food security (Osborn and Bishaw 2009).

6. CONCLUSION

Wheat is the world's most important crop and the rusts are present wherever wheat is grown. Rust diseases of wheat are among the oldest known diseases and are important worldwide. Of the three rust diseases of wheat, stem rust remains as the major factor that limits wheat production in most wheat growing regions of the globe. It is the most destructive disease of wheat in several wheat-growing countries around the world and can cause up to 100% yield loss if susceptible cultivars are grown and the environment is favorable. Stem rust of wheat has been successfully controlled through genetic resistance for about three decades. However, in recent years, it has gained significance as new virulence traits have evolved in the pathogen populations, demonstrating the vulnerability of broadly used wheat cultivars across the globe. The emergence of the Ug99 race in Uganda in 1998, its subsequent geographical expansion within Africa, to the Middle East, and the appearance of Ug99 variants indicate the imminent threat to wheat production.

A number of methods were practiced in the past and are being practiced at present, to manage wheat stem rust disease. However, none of them were totally satisfactory by themselves. Moreover, management of rust diseases is complex because of their rapid dissemination and the frequency of evolution of new physiologic races and thus demands a perfect knowledge of all the elements of epidemics that are interrelated. Therefore, a combination of different strategies should be used to manage rusts in wheat production. However, the use of resistant cultivars is the most important and the most practical method of controlling stem rust of wheat and is the best strategy for resource poor farmers in the developing world. It is also the most environmentally friendly and profitable strategy for commercial farmers if they grow genetically resistant varieties using different resistance genes.

Estimates suggest that 90% of wheat varieties in the world are susceptible to Ug99, justifying elevated concerns about food security. Reducing the area currently occupied by susceptible varieties in the primary risk areas of Africa, Arabian Peninsula, Middle East, and West-South Asia with resistant ones should become an immediate priority. It is highly advisable to release and promote varieties that have durable adult plant resistance or have effective race-specific resistance genes in combinations to prevent further evolution and selection of new virulence that lead to boom-and-bust cycles of production. This will also allow reduction of inoculum in high-risk areas and thus reduce risks of its spread to secondary risk areas. Migration of Ug99 to new areas should also be monitored carefully through field surveys, monitoring nurseries and GIS tools to provide an early warning, which could allow chemical interventions if necessary and guide decision making.

The emergence of Ug99 race of stem rust pathogen as a global threat to wheat production has highlighted the need and benefits of public-funded wheat research and improvement where germplasm carrying useful traits and information can be readily shared to ensure a sustainable production of staple food crops at low cost and with the least negative environmental impacts. However, to succeed much needs to be done, especially to ensure that seed of high yielding, stem rust resistant materials is made available to as many farmers as possible to ensure that their wheat crop is not destroyed by stem rust. Moreover, a combined strategy including regular disease surveys, strengthening research capacity, development of new rust resistant varieties and ensuring their adoption, can lead to effective management of rust diseases and boost wheat production.

Generally, there should be a need for a collective fight against the disease and this requires all partners, affected countries or those at risk, national plant protection services and research institutes, researchers, international centers and organizations, and investors; to be actively engaged. There is nothing gained from isolationism and everything to be gained from working together, cooperating and sharing information. Furthermore, the risks posed on wheat production by the emerging rust races capable of spreading quickly over continents, need intensified international collaboration and coordination. Strengthening national capacities is particularly critical to enable countries develop and implement in an effective manner their contingency plans for prevention of rust outbreaks. The global wheat rust programm should be re-focusing on re-enforcing national capacities and international collaboration for improved prevention and rapid response. These national and international efforts need adequate resources to be effective.

In Ethiopia, wheat rusts remain major threats for wheat production. Stem rust is one of the major threats to wheat production because of the extreme level of damage the disease causes to susceptible varieties. There is a recurrent epidemic of stem rust by locally evolved or migrated from the neighboring countries. Stem rust epidemics has knocked out major cultivars such as Enkoy with Sr36 gene in 1994; and Digalu with SrTmp gene in 2013 and 2014, causing 100 percent yield loss. The Digalu race (TKTTF) which is different from the Ug99 race (TKTTSK) is dominant across the major wheat growing regions of Ethiopia and becomes a major threat to wheat production in the country. The high virulence diversity and evolution rate of the pathogen makes a considerable proportion of wheat germplasm at risk in the country.

The recurrent epidemic of stem rust in Ethiopia is due to fast break down of newly developed resistant cultivars. The factors that contribute to the fast break down of resistant genes are cultivation of wheat after wheat, deployment of few mega cultivars with major genes over a large area, the presence of bimodal rainfall at different wheat growing regions of the country and thus, green bridge to the pathogen survival all over the year. All contribute for the occurrence of epidemics.

Currently, most of commercial bread wheat varieties released by the national wheat research program of the country are susceptible to new races of stem rust including Ug99 variants and Digalu race. Thus, there is a need for farmers to use improved wheat genotypes possessing high resistance to the new races of stem rust pathogen population. This requires, new strategy to screen and identify resistant wheat genotypes by screening both at seedling and adult plant stage to confirm adult plant resistant.

The rapid breakdown of resistant genes in newly developed varieties, require for continuous research on biology and management of the stem rust disease as well as the development of new resistant varieties. The continual development of cultivars with a combination of different types of resistance can reduce inoculum and prevent the pathogen population from increasing to epidemic levels in future. The rapid breakdown of resistant genes in newly developed varieties; also needs fast track variety release, accelerated seed multiplication, popularization and promotion of rust resistant wheat varieties, rust disease early warning system, wheat value chain development and creating awareness among policy makers and farmers about the threat of rusts in general and stem rust in particular.

The short longevity of rust resistance and the periodic outbreak of rust epidemics pose serious threat of food security for over 4.5 million small-scale farmers engaged in wheat production in the highlands of Ethiopia. This condition requires integrated wheat rust management by combining varietal resistance, cultural practices and chemical control.

With respect to varietal resistance; developing wheat varieties with diversified stem rust resistant genes and strengthening the global partnership especially with CGIAR and NARS from neighboring countries are important activities for the national research system, particularly for wheat breeding program of the country. The development of resistant varieties need to be coupled with adopting, fast-track variety release and accelerated seed multiplication in partnership with various stakeholders along the seed value chain to ensure fast replacement, adequate variety demonstration, popularization, and dissemination of resistant varieties to create awareness and demand for seed from farmers, enhance the adoption of resistant varieties through improved market linkages and value chain development activities, devising an effective rust surveillance system for early warning coupled with adequate preparedness for chemical control as a priority in case of rust out breaks.

The other component of the integration is introducing legumes and wheat to break the monoculture and ensure sustainable diversification and intensification of the framing systems; and devising a strategy for expanding irrigated wheat production through development of varieties adapted to the lowland.

Fungicides are also one of the components of integrated management of wheat stem rust. They can be a valuable tool in increasing yields and profitability of wheat production, especially if disease susceptible varieties are grown and, where the disease pressure is only moderate. But combining fungicides with host resistance offers the best monetary return when disease pressure is high. This should be linked to accurate disease forecasting and timely application of chemicals.

The stem rust pathogen populations in Ethiopia are highly variable. Therefore, it is necessary for the national wheat improvement program to monitor the virulence composition and dynamics in the pathogen population and utilize currently effective stem rust resistance genes in the improvement program.

On the other hand, to avoid fast breakdown of stem rust resistance genes in the wheat varieties, the breeding efforts of the country should focus on selecting for minor genes, based on adult plant resistance. This kind of resistance is especially important for countries like Ethiopia which are considered to be under high risk and where survival of the pathogen for several years is expected due to favorable environmental conditions.

It takes many years to develop new stem rust resistant varieties in convention breeding methods. This requires the use of biotechnology to accelerate the breeding process and make available stem rust resistant wheat varieties in short period of time. It is evident that recent experiences demonstrated that the conventional approach of development and deployment of

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rust-resistant varieties alone will not address the impeding risk of wheat production in the country. Therefore, it is important to develop an integrated strategy to elevate the rust threats. Developing a capacity for rust surveillance, use of chemical control and diversification of wheat-based production system are some of the measures need to be taken in addition to rust-resistant varieties.

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