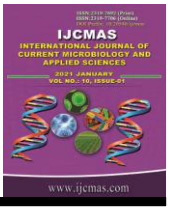
EXCELLENT PUBLISHERS

International Journal of Current Microbiology and Applied Sciences
ISSN: 2319-7706 **Volume 10 Number 01 (2021)**
Journal homepage: http://www.ijcmas.com



Review Article https://doi.org/10.20546/ijcmas.2021.1001.140

Epidemiology of Stripe Rust of Wheat: A Review

Sheikh Saima Khushboo[1]*, Vishal Gupta[2], Devanshi Pandit[3], Sonali Abrol[1], Dechan Choskit[1], Saima Farooq[4] and Rafakat Hussain[1]

[1]Division of Plant Pathology Sher-e-Kashmir University of Agricultural Sciences & Technology of Jammu, 180001, India
[2]Advanced Centre for Horticulture Research, Sher-e-Kashmir University of Agricultural Sciences & Technology of Jammu, Udheywalla 180 018, India.
[3]Shoolini University of Biotechnology and Management Sciences, Solan, H.P., 173229, India
[4]Central Institute of Temperate Horticulture (CITH), Srinagar, 191132, India

**Corresponding author*

ABSTRACT

Stripe rust caused by *Puccinia striiformis* f. sp. *tritici* is one of the most dreaded diseases of wheat worldwide.The disease is continually extending the geographical limits, showing movement towards warmer areas due to the appearance of more aggressive strains having affiliation towards higher temperatures. Yield losses in wheat are usually the result of reduced kernel number and size, low test weight, reduced dry matter, poor root growth and reduced kernel quality. Losses in the yield of wheat due to the disease primarily depended on the level of susceptibility, environmental conditions and the stage of infection. Comprehensive understanding and acquaintance about the disease is still lacking due to the scarcity information about its etiology and epidemiology. This review article gives an overall account of the history and impact of stripe rust on wheat, its present status, yield losses, life cycle, infection process and epidemiology.

Keywords

Stripe rust of wheat, Epidemiology, *Puccinia striiformis*

Article Info

Accepted:
12 December 2020
Available Online:
10 January 2021

History

Stripe rust of wheat is supposed to be prevalent even before human beings started cultivation of wheat as a staple food. However, the first report of the disease is attributed to Gadd, who observed it from Europe in the year 1777. Soon after in 1794, stripe rust appeared in epiphytotic proportions on rye in Sweden (Singh *et al.*, 2002). Severe epidemics of stripe rust all around the world with immense limiting potential of wheat yield, marked with profound economic importance makes it a global disease (Roelfs *et al.*, 1992). Although, the first record of the disease from the USA was in 1915, but no potentially serious outbreak was reported from there until 1960s (Line, 2002). In Eastern Australia, for the first time stripe rust was reported in 1979, which later spread to New Zealand in 1980 (Wellings *et al*., 1987), and after eight years it was reported from Western Australia. In South Africa the disease was first observed in 1996, where anew isolate of the pathogen was observed which was suggested to may have been derived from East Africa (Boyd, 2005).

Stripe rust has been more important in areas with cool and wet environmental conditions therefore, it occurs regularly in Northern Europe, the Mediterranean region, Middle East, Western United States, Australia, East African highlands, China, the Indian subcontinent, New Zealand and South America (Danial, 1994; Mamluk *et al*., 1996). However, recent disease outbreaks in countries closer to the equator, suggest a new level of adaptation by the pathogen to the varied temperature range (Khanfri *et al*., 2018).

Though stripe rust is distributed to all the continents except for Antarctica, yet it has been observed in epiphytotic conditions more frequently in the Pacific Northwest region of North America, South America, North Africa (Morocco, Algeria and Tunisia), East Africa (Ethiopia and Kenya), East Asia (Northwest and Southwest China), South Asia (India, Pakistan and Nepal), Oceania (Australia and New Zealand), the Nile Valley and Red Sea (Egypt and Yemen), West Asia (Lebanon, Syria, Turkey, Iran, Iraq and Afghanistan), Central Asia (Kazakistan, Uzbekistan, Tajikistan and Turkmenistan), Caucasus (Georgia, Armenia and Azerbaijan) and Europe (UK, Northern and Southern France, Netherlands, Northern Germany, Denmark, Spain and Sweden) (Solh *et al*., 2012; Sanders, 2018; Waqar *et al*., 2018). Epidemics of wheat stripe rust have occurred in North Africa and the Middle East in the 1970s (Saari *et al*., 1985). In Pakistan, Khan and Mumtaz (2004) reported yellow rust epidemic during 1995 on Pak 81 and Pirsabak 85 and on Inquilab 91, during 2003. Due to the favorable environmental conditions and cultivation of mega-varieties stripe rust is more prevalent in tropical areas of higher altitudes of North Africa, Mexico, Himalayan foothills of India and Pakistan (McIntosh, 1980).

Transcaucasia is considered as the center of origin for *Puccinia striiformis* f. sp. *tritici* (Hassebrauk, 1965; Stubbs, 1985). However, the recent studies regarding *P. striiformis* populations indicated the highest levels of genetic diversity and recombinant population structure from Himalayan and near-Himalayan regions, which suggest that this may be the area of its center of origin and diversity (Ali *et al*., 2014; Thach *et al*., 2016).

India has witnessed frequent rust epidemics in past several years resulting in heavy yield losses (Barclay, 1892), with a significant impact on the national wheat production (Nagarajan and Joshi, 1975). Rust epidemics have occurred during 1843 in Delhi and in 1884 and 1895 at Allahabad, Banaras and Jhansi. Later on, in 1905 the rust epidemic was reported from Punjab and sub-mountainous regions of Gorakhpur (Gupta *et al*., 2017). Nayar *et al.,* (1997) reported that leaf rust and stripe rust occurred each year from 1967 to 1974.Stripe rust is destructive and an important disease in the northern areas of India specially in Punjab, Haryana, Western Uttar Pradesh and Jammu & Kashmir, where frequent epidemics have occurred since 1982 (Nagrajan *et al*., 1982). Sporadic high incidence of stripe rust has been recorded from some parts of Punjab and north-western areas (Gangwar *et al*., 2013; Gupta *et al*., 2013; Ahanger *et al*., 2014).

Losses

Stripe rust is one of the most important diseases of wheat worldwide and it appears very early in the growing season. This results in the weak and stunted growth of the plants, causing severe yield losses up to 70 per cent (Khanfri *et al.*, 2018). Yield losses caused by stripe rust depends on several factors such as cultivar susceptibility, infection time, rate of disease development, duration of the disease, crop growth stage and weather conditions (Chen, 2005). About90-100 per cent grain yield losses has been reported on the susceptible cultivars, if the infection occurs at an early growth stage, as the crop remains under favorable conditions for a longer period (Afzal *et al.*, 2007). Losses of up to 20 and 75 per cent in wheat were reported in the USA (Doling and Doodson, 1968; Roelfs, 1978).

In Asia, about 46 per cent yield losses are attributed to the epidemics of stripe rust (Singh *et al.*, 2004). Epidemics in China (Wan *et al.*, 2004), Pakistan and Iran (Bimb and Johnson, 1997) has caused serious yield losses across different wheat growing seasons. Afzal *et al.*, (2007) reported the yield losses of 5.77, 6.63 and 14.90 per cent, by stripe rust, on Inqlab-91, Wafaq-2001 and Bakhtawar, respectively, in Pakistan. In 2010, Syria and Turkey were the most affected countries due to the disease, and half of their wheat harvest was lost, followed by Ethiopia (45%), Morocco and Uzbekistan (35%) (Yahyaoui and Rajaram, 2012). Due to the progressive increase of virulent pathotypes of *P. striiformis,* losses of ₹2 billion were reported during 1997 and 1998, in Pakistan (Hussain *et al.,* 2004). In South Africa during 1998, losses of nearly $2.25 million were estimated (Pretorius, 2004). Ahmad *et al.*, (1991) reported $8 million losses in three districts of Baluchistan. In 11 provinces of China, a widespread stripe rust epidemic infected about 6.6 million hectares of wheat, during 2001-2002, which had resulted in yield loss of 13 million tonnes (Wan *et al.*, 2004). Between 1999 and 2000, heavy yield losses from 20 to 40 per cent were reported in Central Asia (Morgounov *et al.*, 2004). In Australia during 2003, fungicides worth$40 million were used to manage the disease (Wellings *et al.*, 2004). During 2000, in at least 20 states of USA, severe yield losses of 9 million bushels of wheat were recorded (Markell *et al.*, 2008). In the last decades, more than 10-30 per cent crop losses with an estimated grain loss of 1-2 million tons has occurred due to several yellow rust epidemics in Turkey (Aktas and Zencirci, 2016).

India has witnessed significant losses of grain yield, generally in north-western regions, northern foothills and adjacent plains and in the Nilgiri and Pulney hills in the south due to cultivation of susceptible cultivars (Joshi, 1976). This is generally attributed to several factors, such as early appearance of the disease, congenial environmental conditions, load of inoculum and the susceptible cultivars (Srivastava *et al.*, 1984). Mehta (1950) estimated that the loss due to rust of the wheat was about ₹200 millions, every year. Drastic reduction in the yield due to stripe rust was observed during 2008-09, on the widely cultivated wheat variety PBW-343, with disease severity of 60S-80S, in the sub-mountainous districts of Punjab (Jindal *et al.*, 2012).

Present status

Puccinia striiformi sp. *tritici* is a substantial threat in all the wheat growing areas with a potential to cause extensive crop damages. It has been an important disease constraint to winter bread wheat production in Central Asia over the last 15 years (Absattarova *et al.*, 2002; Nazari *et al.*, 2008; Ziyaev *et al.*, 2011; Sharma *et al.*, 2013). Morgounov *et al.*, (2012) reported substantial increase in the severity of stripe rust between 2001 and 2010, in Central and Western Asia. This was responsible for the epidemics in different parts of Central Asia during 2009-2014 (Ziyaev *et al*., 2011; Sharma *et al*., 2013 and 2014). In 2014in Turkey, a new *P. striiformis* race, 'Warrior', was detected by the Central Research Institute for Field Crops (CRIFC) in Ankara and the Regional Cereal Rust Research Center (RCRRC) in Izmir. Earlier in 2011, this race was reported from the United Kingdom. Previously known resistant commercial cultivars of Turkey became susceptible to this new race (Khanfri *et al*., 2018). High frequencies of this new race 'Warrior' was reported from most of the European countries and North Africa (Mert *et al*., 2016). This race was also present in Morocco in 2013 and in Algeria in 2014 with relatively higher genetic diversity than other previous documented races of *P. striiformis* (Hovmoller *et al*., 2016).

Life cycle

Puccinia striiformis, an obligate biotrophic fungus (Voegele *et al*., 2009), belongs to the family Pucciniaceae within the order Pucciniales (Hibbett *et al*., 2007). It is highly diverse with respect to host preference and number of spore stages within the life cycle (Vander *et al*., 2007; Liu *et al*., 2010). Its life cycle, which had remained a mystery for more than a hundred years, requires two taxonomically unrelated hosts, graminaceous host for asexual reproduction and barberry for sexual reproduction (Jin *et al*., 2010; Berlin *et al*., 2017) and includes five types of different spores (Schwessinger, 2017). Urediniospores and teliospores of the fungus are dikaryotic, whereas, teliospores produce haploid basidiospores (Chen, 2005). The diakaryotic phase of its life cycle is confined to wheat, which is considered as the primary host. Urediniospores, teliospores and basidiospores are produced on the primary host. Towards the end of the season, when the nutrient supply in the infected tissue is on decline, lesions where urediniospores were produced, the telial stage is initiated. Teliospores present on the residual senesced tissues help the fungus to overcome the harsh conditions. With the commencement of the following spring, teliospores germinate to produce four haploid basidiospores. No alternate hosts of the fungus for the basidiospores to infect were known. Therefore, no pycnial and aecial stage of *P. striiformis* was known (Stubbs, 1985). However, recently, pycnial and aecialspore stages of the fungus has been identified on *Berberis* spp. (*B. chinensis*, *B. holstii*, *B. koreana* and *B. vulgaris*), that serve as alternate hosts for the *P. striiformis* (Jin *et al*., 2010).

Infection process

Stripe rust fungus, *P. striiformis*, infects the host by means of urediniospores, which after germination gains entry through stomata. The whole process of infection was studied by Cartwright and Russell (1981) using fluorescence microscopy. Urediniospores are mainly responsible for the initiation and spread of the disease (Chen, 2005; Bux *et al*., 2012). Urediniospores after landing up on the surface of a wheat leaf, adhere to it. Under optimum temperature and humidity conditions, urediniospore produces germ tube which grows towards stoma initiating primary infection in the stomatal cavity (Ma *et al*., 2009; Sorensen, 2012). 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 hypha, haustorial mother cell, and finally a haustorium. In the secondary infection, excessive network of mycelium is formed within the mesophyll tissue. The haustoria, which are localized between the host cell wall and the plasma membrane act as the nutrientabsorbing structures, taking up nutrients from the host. The fungus then forms sporogenic tissue, called uredinium, near the leaf surface and produces urediniospores, completing the asexual life cycle (Voegele *et al*., 2001; Kang *et al*., 2002; Wang *et al*., 2010; Zhang *et al*., 2012; Jiao *et al*., 2017). About seven days after the infection, chlorotic spots appear on the leaf surface, initiating sporulation which result in the formation of distinctive yellow streaks on leaf (Chen, 2005; Sorensen, 2012). Optimum temperature for spore germination is 10-12°C and the high temperature inhibits sporulation, it may also force the fungus to undergo a phase of dormancy. Under optimum conditions, the time between inoculation and sporulation is 12-13 days (Line, 2002).These spores have the ability of rapid germination in presence of moisture along with optimum temperature of 7 to 12°C (Waqar *et al*., 2018).

Symptoms

All growth stages of the crop are susceptible to infection by *P. striiformis* (Line, 2002). One week after the initial infection, the appearance of the first symptoms of stripe rust take place. Symptoms on the leaf sheaths, in the beginning look like small, yellow spots or flecks. On the leaf sheaths, glumes and awns, these spots then develop into long and narrow stripes of rust pustules. On maturity pustule break open and release yellow-orange masses of urediniospores (Mahajan *et al.*, 2017; Khanfri *et al*., 2018, Gupta *et al*., 2018). At the time of plant entering the senescence stage on during the stress phase, the infected tissues become brown and ultimately dry. The pathogen consumes the plant nutrients and water, thereby reducing the plant vigour causing desiccation of leaves. Severe early infection can even result in the stunted growth of the plants (Singh *et al.*, 2017; Wang and Chen, 2013; Chen, 2005). During the late growth phase of the host or due to the increase in the temperature, the production of urediniospore is followed by the production of teliospores. Teliospores are two-celled, dark brown, thick walled black spores which infect barberry *(Berberis* spp.) leaves, producing pycnia on the upper surface and aecia on the lower surface. Pycnia and aecia are also produced on the upper and lower surface of Oregon grape *(Mahonia aquifolium*) leaves, which also acts as an alternate host for *P. striiformis* (Wang *et al*., 2013; Khanfri *et al*., 2018). At the end of the growing season, large numbers of urediniospores can be produced and blown away from contaminated fields. Although most urediniospores are deposited near their source (Roelfs and Martell, 1984), some can be dispersed over considerable distances by the wind (Hirst and Hurst, 1967).

Epidemiology

In the presence of *P. striiformis* inoculum and susceptible host, the outbreak of stripe rust largely depends on the prevailing weather conditions, such as moisture, temperature and wind (Chen, 2005). Moisture, being an important abiotic factor, has direct influence upon the spore germination, infection, dispersal and survival of the pathogen. For urediniospores germination and subsequent infection of the host, continuous moisture for three hours is required (Rapilly, 1979). Relative humidity close to the saturation point before inoculation, increases the rate of spore germination (Line, 2002). Precipitation, especially light rains provide conducive conditions for infection. However, high moisture reduces the viability of spores, which adversely affects fresh infections and the spread of disease. Individual or cluster dispersal of urediniospores depends on the relative humidity (Chen, 2005).

Temperature also has its influence on the germination, infection and survival of spores.

Temperature range of 2.8-21.7°C is suitable for the germination of *P. striiformis* spores, whereas, 10-12°C is optimum for their faster germination (Line, 2002). The minimum and maximum temperature requirements for the growth of the pathogen are 3 and 20^0C, respectively (Sharp 1965; Tollenaar and Houston 1966; Stubbs 1967; Roelfs *et al*., 1992; Line, 2002). The latent period of *P. striiformis* varies among isolates and can be about 11 days under optimum conditions and up to 180 days under near freezing conditions (Sharp and Hehn 1963; Roelfs *et al*., 1992; Bux *et al*., 2012).Lower temperatures adversely affect survival of the pathogen and its further development may stopped below -10°C (Chen, 2005). Temperatures more than 30°C ceases development and survival of the pathogen. Infections usually occurs during nights, when there is dew formation and temperatures are also cool (Sorensen, 2012; Khanfri *et al*., 2018).

Quantification and distribution of inoculum

Molecular methods, especially the polymerase chain reaction (PCR), have been developed in the last decades for specific, sensitive and rapid detection of several plant pathogenic fungi (Lacourt and Duncan 1997; Grote *et al*., 2002; Ippolito *et al*., 2002). *Puccinia striiformis* f. sp. *tritici* causing stripe rust of wheat, a devastating disease with worldwide distribution (Zadoks, 1961; O'Brien *et al*., 1980; Li and Zeng, 2002; Line, 2002; Rollinson *et al*., 2002), being an obligate biotrophic, is difficult to culture on artificial media. Therefore, a PCR-based technique is very useful for its detection in host tissues (Aggarwal *et al*., 2017). Molecular methods, especially real-time PCR with species-specific primers, offer several advantages over microscopic spore counting of pathogen inoculum.

Dispersal of airborne inoculum from the source and its deposition on a crop is a complex process, which influenced by wind direction and turbulence (McCartney and Fitt, 1998; Aylor, 1999; Aylor, 2003; McCartney and West 2007). Recent developments in molecular biology have made it lot easier to estimate spore concentration above the canopy of wheat fields. This can provide a very useful data which may help in accurate prediction of epidemics, particularly where disease severity is influenced by the timing or amount of inoculum (West *et al*., 2008). Nowadays, spore traps for the detection of inoculum and real-time PCR assays, are being increasingly used to quantify the air borne inoculum of plant pathogens and to improve precision in disease risk management and fungicide applications (Luo *et al*., 2007; Rogers *et al*., 2009; 101 Duvivier *et al*., 2013; Wieczorek and Jørgensen, 2013; 103 Almquist and Wallenhammar, 2014; Chandelier *et al*., 2014; Duvivier *et al*., 2016). A real-time polymerase chain reaction (PCR) assay to quantify the inoculum level of *P. striiformis* in leaves by quantifying the latent infection levels and estimating potential disease intensity in the field (Pan *et al*., 2010). By targeting latent infection foci with fungicide applications, the initial inoculum was effectively lessened, reducing the build-up of rust epidemic (Yan *et al*., 2011).

Weather forecasting models

Various weather forecasting models have been developed for the management of several plant diseases (James, 1974; Zadoks, 1984; Hardwick, 1998; Xu, 1999; De Wolf *et al*., 2003; Audsley *et al*., 2005; Savary *et al*., 2006; De Wolf and Isard, 2007; Gupta *et al*., 2017) including stripe rust (Coakley and Line, 1981; Coakley *et al*., 1988; Line, 2002). Prediction model is based on the relationship between the environmental conditions and the severity of the disease (Kundal *et al*., 2006).

Among the different abiotic factors, temperature and moisture are the major limiting factors for the development of stripe rust epidemics and these have been used to develop forecasting models for the disease (Sharma-Poudyal and Chen, 2011). Forecasting systems for the plant diseases have been developed to reduce the use of fungicides or to make their judicious use. An accurate prediction is crucial for proper application of disease control measures in order to avoid crop losses and over application of fungicide. Such system not only reduces the cost of production but also promote the environmental safety for the operator and consumers by reducing chemical usage (Malicdem and Fernandez, 2015). Temperature has the most profound effect on the lifecycle of *Puccinia striiformis*, influencing its survival, dispersal, infection, latent period and sporulation, therefore, it has generally been used to develop forecasting models for stripe rust (Coakley and Line, 1981; Coakley *et al*., 1982; Coakley *et al*., 1988; Madden *et al*., 2007). Even time series models have been of interest since long, as they are used to predict epidemiological behaviours of the plant diseases by modelling historical surveillance data (Zhang *et al*., 2014).

Forecasting models have also been developed for the prediction of stripe rust of wheat (Coakley and Line, 1981; Coakley *et al*., 1988; Line, 2002). The relationships between temperature and stripe rust epidemics on winter wheat were quantified by Coakley and Line (1981) from 1963 to 1979. They found significant correlation between the disease index and cumulative negative (December 1 to January 31) and positive degree days (April 1 to June 30). Weather descriptors were used to develop simple linear regression models for predicting stripe rust severity (Coakley *et al*., 1982). Predictive models with multiple regression approach were developed to estimate disease intensity by analyzing temperature and other meteorological factors such as the amount and frequency of precipitation from 1968 to 1986 by Coakley *et al.*, (1988). However, simple linear models based on negative and positive degree days have been used mostly in forecasting for stripe rust (Line, 2002; Chen, 2005). Forecasting models for stripe rust disease severity with logistic regression approach was developed based on relative humidity (>87%), leaf wetness duration and mean relative humidity, that predicted infection with 93, 80 and 76 per cent accuracy, respectively (Eddy, 2009).The effect of epidemiological factors on the severity of stripe rust (cv. PBW 343), under early sowing conditions showed that maximum temperature, minimum temperature, morning vapour pressure, evening vapour pressure and micro meteorological parameters (canopy temperature and soil temperature) had significantly positive correlation with the severity of stripe rust, whereas, maximum relative humidity had significant negative correlation. The models revealed that thermic, and hydric variables contributed significantly for the variance in disease severity (Gupta *et al.*, 2017).

References

Absattarova, A, Baboev, S, Bulatova, K, Karabaev, M. Improvement of wheat yellow rust resistance in Kazakhstan and Uzbekistan through sub-regional co-operation. In: Johnson, R, Yahyaoui, A, Wellings, C, Saidi, A, Ketata, H. (eds) Meeting the challenge of yellow rust in cereal crops. Proceedings of the 1st regional conference on yellow rust in the Central and West Asia and North Africa Region, 8–14 May 2001, Karaj, Iran. ICARDA, Aleppo, Syria, 2002; 34–41.

Afzal, S. N., Haque, M. I., Ahmadani, M. S., Bashir, S. and Rehman, A. 2007. Assessment of yield losses caused by *Puccinia striiformis* triggering stripe rust in the most common wheat varieties. *Pakistan Journal of Botany*, 39: 2127–2134.

Aggarwal, P. K. 2008. Global climate change and Indian agriculture: impacts, adaptation and mitigation. *Indian Journal of Agricultural Sciences*, 78(11): 911–919.

Ahanger, R. A., Gupta, V., Bhat, H. A. and Dar, N. A. 2014 Management of yellow rust (*Puccinia striiformis*. West) of wheat and its impact on yield under Jammu sub-tropics of India .*The Bioscan*, 9(1): 215-218.

Ahmed, S., Rodriguez, A., Sabir, F., Khan, R. and Panah, M. 1991. Economic losses of wheat crops infested with yellow rust in highland Balochistan. pp.15. *MART/AZR Project Research Report No. 67*. Quetta (Pakistan): ICARDA.

Aktas, H. and Zencirci, N. 2016.Stripe rust partial resistance increases spring bread wheat yield in south-eastern Anatolia, Turkey. *Journal of Phytopathology*, 164: 1085–1096.

Ali, S., Gladieux, P., Leconte, M., Gautier, A., Justesen, A. F., Hovmoller, M. S., Enjalbert, J. and De Vallavieille-Pope, C. 2014. Origin, migration routes and worldwide population genetic structure of the wheat yellow rustpathogen *Puccinia striiformis* f. sp. *tritici*. *PLoS Pathogens*, 10(1):e1003903.

Almquist, C. and Wallenhammar, A. C. 2014. Monitoring of plantand airborne inoculum of *Sclerotinia sclerotiorum* in spring oil seed rape using real-time PCR. *Plant Pathology*, 64: 109–118.

Aylor, D. 2003. Spread of plant disease on a continental scale:role of aerial dispersal of pathogens. *Ecology*, 84: 1989–1997.

Aylor, D. E. 1999. Biophysical scaling and the passive dispersal of fungus spores: relationship t integrated pest management strategies. *Agricultural and Forest Meteorology*, 97: 275–292.

Barclay, A. 1892. Rusts and mildews in India. *Journal of Botany*, 30: 1-8.

Berlin, A., Samils, B. and Andersson, B. 2017. Multiple genotypes within aecial clusters in *Puccinia graminis* and *Puccinia coronata*: improved understanding of the biology of cereal rust fungi. *Fungal Biology and Biotechnology*, 4(1): 3.

Bimb, H.P. and Johnson, R. 1997. Breeding resistance to yellow rust in wheat. *Wheat program special report*. CIMMYT, Lisboa 27 ISSN: 0187-7787; ISBN: 968-6923-81-0. http://libcatalog.cimmyt.org/download/cim/63731.pdf

Boyd, L. 2005. Can Robigus defeat an old enemy?–Yellow rust of wheat. *The Journal of Agricultural Science*, 143(4):233-243.

Bux, H., Rasheed, A., Siyal, M. A., Kazi, A. G., Napar, A. A. and Mujeeb-Kazi, A. 2012. An overview of stripe rust of wheat (*Puccinia striiformis* f. sp. *tritici*) in Pakistan. *Archives of Phytopathology and Plant Protection*, 45(19): 2278-2289

Cartwright, D. and Russell, G. 1981. Development of *Puccinia striiformis* in a susceptible winter wheat variety. *Transactions of the British Mycological Society*, 76(2): 197-204.

Chandelier, A., Helsona, M., Dvorakb, M. and Gischera, F. 2014. Detection and quantification of airborne inoculum of *Hymenoscyphus pseudoalbidus* using real-time PCR assays. *Plant Pathology*, 63: 1296–1305.

Chen, X. 2005. Epidemiology and control of stripe rust (*Puccinia striiformis* f.sp. *tritici*) on wheat. *Canadian Journal of Plant Pathology*, 27(3): 314-337.

Coakley, S. M. and Line, R. F. 1981.

Quantitative relationships between climatic variables and stripe rust epidemics on winter wheat. *Phytopathology*, 71:461-467.

Coakley, S. M., Line, R. F. and McDaniel, L. R. 1988. Predicting striperust severity on winter wheat using an improved method for analysing meteorological and rust data. *Phytopathology,* 78:543-550.

Danial, D. L. 1994. Aspects of durable resistance in wheat to yellow rust. PhD thesis,Wageningen Agricultural University. The Netherlands.

De Wolf, E. D. and Isard, S. A. 2007. Disease cycle approach to plant disease prediction. *Annual Review of Phytopathology*, 45: 203-220.

Doling, D. A. and Doodson, J. K. 1968. The effect of yellow rust on the yield of spring and winter wheat. *Transactions of the British Mycological Society,* 51(3-4): 427-434.

Duvivier, M., Dedeurwaerder, G., Bataille, C., Proft, De, M. and Legrève, A. 2016. Real-time PCR quantification and spatio-temporal distribution of airborne inoculum of *Puccinia triticina* in Belgium. *European Journal of Plant Pathology,* 145: 405–420.

Eddy, R. 2009. *Logistic regression models to predict stripe rust infections on wheat and yield response to foliar fungicide application on wheat in Kansas*. M. Sc. Thesis. B.S. Kansas State University, Manhattan, Kansas.

Gangwar, O. P., Bhardwaj, S. C., Khan, H., Prasad, P. Singh, S. V. and Kumar, S. 2013. *Bharat mein gehunke ratua rog sthiti evam niyantran ranniti. ShodhBulletin sankhya, prashth* (In Hindi), pp. 6-31. Directorate of Wheat Research, Regional Station, Flowerdale, Shimla, Himachal Pradesh, India.

Grote, D., Olmos, A., Kofoet, A., Tuset, J. J., Bertolini, E. and Cambra, M. 2002. Specific and sensitive detection of *Phytophthora nicotianae* by simple and nested-PCR. *European Journal of Plant Pathology*, 108: 197–207.

Gupta, N., Batra,N. and Bhardwaj, S. C. 2017. Wheat rust research – Status, efforts and way ahead. *Journal of Wheat Research,* 9(2): 72-86.

Gupta, V., Ahanger, R. A., Razdan, V. K., Sharma, B. C., Singh, I. and Kaur, K. 2013 Prevalence and distribution in different agro-ecologies and identification of resistance source for wheat stripe rust Journal of Agricultural Research 8(25): 3268-3275.

Hardwick, N. V. 1998. Disease forecasting. Pp. 207-230. In: *The Epidemiology of Plant Diseases*. D. G. Jones eds. Kluwer Academic, Boston, MA.

Hassebrauk, K. 1965. Nomenklatur, geographische verbreitung und wirtsbereich des gelbrostes, *Puccinia striiformis* West. Mitteilungen aus der Biologischen Bundesanstalt fur Land- und Forstwirtschaft. *Berlin-Dahlem*, 116:1-75.

Hibbett, D. S., Binder, M., Bischoff, J. F., Blackwell, M. and Cannon, P. F. 2007. A higher-level phylogenetic classification of the fungi. *Mycological. Research*, 111: 509–47.

Hirst, J., and Hurst, G. 1967. *Long-distance spore transport*. Symposium of the Society for General Microbiology, 17, 307- 344.

Hovmoller, M. S., Walter, S., Bayles, R. A, Hubbard, A., Flath, K., Sommerfeldt, N. and Thach, T. 2016. Replacement of the European wheat yellow rust population by new races from the centre of diversity in the near- Himalayan region. *Plant Pathology*, 65(3): 402-411.

Hussain, M., Kirmani, M.A.S., Ehsal-ul-Haque. 2004. Pathotypes and man guided evolution of *Puccinia striiformis* f. sp. *tritici* in Pakistan. *In: Abstracts:*

Second regional yellow rust conference for Central and West Asia and North Africa, 22–26 March, pp. 21. Islamabad, Pakistan.

Ippolito, A., Schena, L. and Nigro, F. 2002. Detection of *Phytophthora nicotianae* and *P. citrophthora* in citrus roots and soils by nested PCR. *European Journal of Plant Pathology*, 108: 855–868.

James, W. C. 1974. Assessment of plant disease and losses. *Annual Review of Phytopathology*, 12:27-48.

Jiao, M., Tan, C., Wang, L., Guo, J., Zhang, H., Kang, Z. And Guo, Jun. 2017. Basidiospores of *Puccinia striiformis* f. sp. *tritici* succeed to infect barberry, while Urediniospores are blocked by non-host resistance. *Protoplasma*, 254: 2237–2246.

Jin, Y., Szabo, L. J. and Carson, M. 2010. Century-old mystery of *Puccinia striiformis* life history solvedwith the identification of *Berberis* as an alternate host. *Phytopathology*, 100(5): 432–435.

Jindal, M. M., Sharma, I. And Bains, N. S. 2012. Losses due to stripe rust caused by *Puccinia striiformis* in different varieties of wheat. *Journal ofWheat Research*, 4:33–36.

Jindal, M. M., Sharma, I. and Bains, N. S. 2012. Losses due to stripe rust caused by *Puccinia striiformis* in different varieties of wheat. *Journal of Wheat Research*, 4: 33–36.

Joshi, L. M. 1976. Recent contributions towards epidemiology of wheat rusts in India. *Indian Phytopathology*, 29: 1-16.

Kang, Z., Huang, L. and Buchenauer, H. 2002. Ultrastructural changes and localization of lignin and callose in compatible and incompatible interactions between wheat and *Puccinia striiformis*. *Journal of Plant Disease Protection*, 109: 25–37

Kaundal, R., Kapoor, A. S. and Raghava, G. P. S. 2006. Machine learning techniques in disease forecasting: a case study on rice blast prediction. *BMC Bioinformatics*, 7:485.

Khan, M.A. and Mumtaz, H. 2004. Combining yellow rust resistance with high yield in grain wheat. *In: Abstracts: Second regional yellow rust conference for Central and West Asia and North Africa, 22–26 March 2004, pp. 28*. Islamabad, Pakistan.

Khanfri, S., Boulif, M. and Lahlali, R. 2018. Yellow Rust (*Puccinia striiformis*): a Serious Threat to Wheat Production Worldwide. *Notulae Scientia Biologicae*, 10(3): 410-423.

Khanfri, S., Boulif, M. and Lahlali, R. 2018. Yellow Rust (*Puccinia striiformis*): a Serious Threat to Wheat Production Worldwide. *Notulae Scientia Biologicae*, 10(3): 410-423.

Lacourt, I. and Duncan, J. M. 1997. Specific detection of *Phytophthora nicotianae* using the polymerase chain reaction and primers based on the DNA sequences of its elicitin gene ParaA1. *European Journal of Plant Pathology*, 103: 73–83.

Line, R. F. 2002. Stripe rust of wheat and barley in North America: a retrospective historical review. *Annual Review Phytopathology*, 40:75-118.

Line, R. F. 2002. Stripe rust of wheat and barley in North America: a retrospective historical review. *Annual Review in Phytopathology*, 40: 75-118.

Line, R. F. 2002. Stripe rust of wheat and barley in North America: a retrospective historical review. *Annual Review Phytopathology*, 40: 75-118.

Line, R. F. 2002. Stripe rust of wheat and barley in North America: a retrospective historical review. *Annual Review Phytopathology*, 40: 75-118.

Line, R. F. 2002. Stripe rust of wheat and barley in North America: a retrospective historical review. *Annual Review Phytopathology*, 40: 75-118.

Liu, M. and Hambleton, S. 2010. Taxonomic study of stripe rust, *Puccinia striiformis* sensu lato, based on molecular and morphological evidence. *Fungal Biology*, 114: 881–99.

Luo, Y., Ma, Z., Reyes, H. C., Morgan, D. and Michailides, T. J. 2007. Quantification of airborne spores of *Monilia fructicola* in stone fruit orchards of California using realtime PCR. *European Journal of Plant Pathology*, 118: 145–154.

Ma, Q. and Shang, H. 2009. Ultrastructure of stripe rust (*Puccinia striiformis* f. sp.*tritici*) interacting with slow-rusting, highly resistant, and susceptible wheat cultivars. *Journal of Plant Pathology*, 1: 597-606.

Madden, L. V., Hughes, G., and van den Bosch, F. 2007. In: *The Study of Plant Disease Epidemics*. Pp. 40-360. The American Phytopathological Society, St. Paul, MN.

Mahajan, S., Gupta, V., Razdan, VK., Fatima, K. and Sharma, S. 2017. Weather Based Forewarning Model for Yellow Rust of Wheat in Scarcity Zone of Jammu & Kashmir. *Indian Phytopathology*, 70 (2): 200-205 2017.

Malicdem, A. R. and Fernandez, P. L. 2015. Rice Blast Disease Forecasting for Northern Philippines. *WSEAS Transactions on Information Science and Applications*, 12: 2224-3402.

Mamluk OF, El Naimi M, HakimMS. 1996. Host preference in *Puccinia striiformis f. sp. tritici*. In: Proc. Eur. Mediterr. Cereal Rusts Powdery Mildews Conf. 9th. p. 86–88.

Markell, S. and Milus, E. 2008. Emergence of a novel population of *Puccinia striiformis* f. sp. *tritici* in eastern United States. *Phytopathology*, 98(6):632-639.

McCartney, A., and West, J. 2007. Dispersal of fungal spores through the air. In J. Dijksterhuis and R. A. Samson (Eds.). *Food Mycology*. pp 65–87. A Multifaceted Approach to Fungi and Food. Boca Raton, Taylor & Francis group.

McCartney, H., and Fitt, B. 1998. Dispersal of foliar fungal plant pathogens. pp 138 - 160. Mechanisms, gradients and spatial patterns. In D. G. Jones (eds.). *The epidemiology of plant diseases*. Dordrecht: Kluwer.

McIntosh, R. A. 1980. Chromosome location and linkage studies involving the wheat stem rust resistance gene Sr14. *Cereal Research Communications*, 8: 315-320.

Mehta, K. C. 1950. Control of rust epidemics of wheat in India- a national emergency. *Scientific Culture*, 15(7): 263-270.

Mert, Z., Nazari, K., Karagoz, E., Akan, K., Ozturk, İ. and Tulek, A. 2016. First incursion of the warrior race of wheat stripe rust (*Puccinia striiformis*f. sp. *tritici*) to Turkey in 2014. *Plant Diseases*, 100(2): 528.

Morgounov, A., Tufan, H. A. and Sharma, R. 2012. Global incidence of wheat rusts and powdery mildew during1969-2010 and durability of resistance of winter wheat variety Bezostaya. *European Journal of Plant Pathology*, 132: 323–340.

Morgounov, A., Yessimbekova, M., Rsaliev, S., Baboev, S., Mumindjanov, H. and Djunusova, M. 2004. High-yielding winter wheat varieties resistant to yellow and leaf rust in Central Asia. *Paper presented at the Proceedings of the 11th International Cereal Rusts and Powdery Mildews Conference.*

Nagarajan, S. and Joshi, L. M. 1975. A historical account of wheat rust epidemics in India and their significance. *Cereal Rusts and Powdery Mildew Bulletin*, 3: 29-33.

Nagrajan, S., Bahadur, P. and Nayar, S. K. 1982. Occurrence of new virulence 47S102 of *Puccinia striiformis* West in

India during crop year. *Cereal Rusts Bulletin*, 27: 28-31.

Nayar, S. K., Prashar, M. and Bhardwaj, S. C. 1997. *Manual of current techniques in wheat rust.* Research Bulletin No.2: Regional Station, Directorate of Wheat research, Flowerdale, Shimla-171002, India, pp. 32.

Nazari, K., Wellings, C. R. and Park, R. F. 2008. Characterisation of seedling resistance to rust diseases in wheat cultivars from Central Asia and the Caucasus. *International Journal of Plant Breeding*, 2:52–63.

O'Brien, L., Brown, J. S., Young, R. M., and Pascoe, I. 1980. Occurrence and distribution of wheat stripe rust in Victoria and susceptibility of commercial wheat cultivars. *Australasian Plant Pathology*, 9:14.

Pan, J. J., Luo, Y., Huang, C., Sun, Z. Y., Zhao, L., Yan, J. H., and Ma, Z. H. 2010. Quantification of latent infections of wheat stripe rust by using real-time PCR. *Acta Phytopathologica Sinica*, 40: 504-510.

Pretorius, Z. 2004. The impact of wheat stripe rust in South Africa. *Paper presented at the Proceedings of the 11th International Cereal Rusts and Powdery Mildews Conference.*

Rapilly F. 1979. Yellow rust epidemiology. *Annual Review of Phytopathology*, 17:59–73.

Roelfs, A. and Martell, L. 1984. Uredospore dispersal from a point source within a wheat canopy. *Phytopathology*, 74: 1262–1267.

Roelfs, A. P. 1978. Estimated losses caused by rust in small grain cereals in the United States 1918-1976. *Miscellaneous Publication USDA*, 1363: 1-85.

Roelfs, A.P., Huerta-Espino, J. and Marshall, D.1992. Barley stripe rust in Texas. *Plant Disease*, 76: 538.

Rogers, S. L., Atkins, S. D. and West, J. S. 2009. Detection and quantification of airborne inoculum of *Sclerotinia sclerotiorum* using quantitative PCR. *Plant Pathology*, 58: 324– 331.

Saari, E.E and Prescott, J. 1985. World distribution in relation to economic losses. Pp. 259-298. In: Diseases, Distribution, Epidemiology, and Control.

Sanders, R. 2018. Strategies to reduce the emerging wheat stripe rust disease

Schwessinger, B. 2017. Fundamental wheat stripe rust research in the 21st century. *New Phytologist*, 213(4):1625-1631.

Sharma, R. C., Rajaram, S. and Alikulov, S. 2013. Improved winter wheat germplasm for Central and West Asia. *Euphytica*, 190: 19–31.

Sharma, R.C., Amanov, A., Ziyadullaev, Z. 2014. Status of stripe rust resistant winter wheat varieties in Central Asia and the Caucasus. *In: Abstracts, Second International Wheat Stripe Rust Symposium*, pp 73. Regional Rust Research Center. ICARDA, Izmir, Turkey.

Sharp, E. L. 1965. Preparation and post-penetration environment and development of *Puccinia striiformis* on wheat. *Phytopathology*, 55:198–203.

Singh, R, Mahmoudpour, A, Rajkumar, M and Narayana, R. 2017. A review on stripe rust of wheat, its spread, identification and management at field level. *Research on Crops*, 18(3): 528-533.

Singh, R. P., Huerta-Espino, J. and Roelfs, A. P. 2002. The wheat rusts. In: pp: 317-330. Curtis, B.C., Rajaram, S., Gomez Macpherson, H. (eds.). *Bread wheat: improvement and production*. Plant Production and Protection Series no. 30. FAO, Rome.

Singh, R. P., William, H. M., Huerta-Espino, J. and Rosewarne, G. 2004. Wheat rust in Asia: meeting the challenges with old and new technologies. In: New Directions for a Diverse Planet: *4th International Crop Science Congress*, Brisbane, Australia. (Abstracts).

Solh, M., Nazari, K., Tadesse, W. and Wellings, C. 2012. The growing threat of stripe rust worldwide. *Paper presented at the Proceedings, Borlaug Global Rust Initiative, Technical Workshop, September 1-4*. Beijing, China.

Sorensen, C. K. 2012. Infection biology and aggressiveness of *Puccinia striiformis* on resistant and susceptible wheat. PhD Thesis. University of Aarhus, Denmark.

Srivastava, K. D., Joshi, L. M. and Singh, D. V. 1984.Losses in yield components of certain cultivars due to leaf rust of wheat. *Indian Phytopathology*, 37: 96-99.

Stubbs, R. W. 1985. *Stripe rust*. In: Roelfs, A. P., Bushnell, W. R., editors. The cereal rusts II: diseases, distribution, epidemiology, and control. *New York: Academic Press*, 61–101.

Stubbs, R. W. 1985. *Stripe rust*. In: Roelfs, A. P., Bushnell, W. R., editors. The cereal rusts II: diseases, distribution, epidemiology, and control. *New York: Academic Press*, 61–101.

Thach, T., Ali, S., de Vallavieille-Pope, C., Justesen, A. F. and Hovmoller, M. S. 2016. Worldwide population structure of the wheat rust fungus *Puccinia striiformis* in the past. *Fungal Genetics and Biology*, 87:1-8.

Tollenaar, H. and Houston, B. R. 1966. In vitro germination of uredospores of *Puccinia graminis* and *P. striiformis* at low spore densities. *Phytopathology*, 56:1036–1039.

V Gupta, S Mahajan, VK Razdan, K Fatima, S Sharma, 2018. Characterisation of wheat germplasm for slow rust resistance against *Puccinia striiformis*. *Archives of Phytopathology and Plant Protection*, 51 (3-4): 207-216.

Vander, M. M., Ericson, L., Walker, J., Thrall, P. H. and Burdon, J. J. 2007. Evolutionary relationships among species of *Puccinia* and *Uromyces* (Pucciniaceae, Uredinales) inferred from partial protein coding gene phylogenies. *Mycological. Research*, 111:163–75.

Viljanen-Rollinson, S. L. H. and Cromey, M. G. 2002. Pathways of entry and spread of rust pathogens: implications for New Zealand's biosecurity. *New Zealand Plant Protection*, 55:42-48.

Voegele R. T., Hahn M. and Mendgen K. 2009. The Uredinales: cytology, biochemistry, and molecular biology. In *The Mycota*, ed. HB Deising, 5: 69–98. Berlin: Springer/Heidelberg

Voegele, R. T., Struck, C., Hahn, M. and Mendgen, K. 2001. The role of haustoriain sugar supply during infection of broad bean by the rust fungus *Uromyces fabae*. *Proceedings of the National Academy of Sciences of USA*, 98: 81338138.

Wan, A., Zhao, Z., Chen, X., He, Z., Jin, S., Jia, Q. and Li, G. 2004. Wheat stripe rustepidemic and virulence of *Puccinia striiformis* f. sp. *tritici* in China in2002. *Plant Disease*, 88(8): 896-904.

Wang, C. F., Huang, L. L., Zhang, H. C., Han, Q. M., Buchenauer, H. and Kang, Z. S. 2010. Cytochemical localization of reactive oxygen species (O^{2-} and H_2O_2) and peroxidase in the incompatible and compatible interaction of wheat–*Puccinia striiformis* f. sp. *tritici*. *Physiological and Molecular Plant Pathology*, 74: 221–229.

Wang, M. N. and Chen, X. First report of Oregon grape (*Mahonia aquifolium*) as an alternate host for the wheat stripe rust pathogen (*Puccinia striiformis* f. sp. *tritici*) under artificial inoculation. *Plant Disease*, 2013; 97(6): 839-839

Waqar, A., Khattak, S. H., Begum, S., Rehman, T.,Rabia., Shehzad, A., Ajmal, W., Zia,S. S., Siddiqi,I.and Ali, G. M. 2018. Stripe Rust: A Review of the Disease, Yr Genes and its Molecular Markers. *Sarhad Journal of Agriculture*, 34(1): 188-201.

Waqar, A., Khattak, S. H., Begum, S., Rehman, T., Rabia., Shehzad, A., Ajmal, W., Zia, S. S., Siddiqi, I. and Ali, G. M. 2018. Stripe Rust: A Review of the Disease, Yr Genes and its Molecular Markers. *Sarhad Journal of Agriculture*, 34(1): 188-201.

Wellings, C., McIntosh, R. and Walker, J. 1987. *Puccinia striiformis* f. sp. *tritici* in Eastern Australia possible means of entry and implications for plant quarantine. *Plant Pathology*, 36(3): 239-241.

Wellings, C.R., and Kandel, K.R. 2004. Pathogen dynamics associated with historic stripe (yellow) rust epidemics in Australia in 2002 and 2003. *In* Proceedings of the 11th International Cereal Rusts and Powdery Mildews Conference. 22–27 August 2004, John Innes Centre, Norwich, UK. European and Mediterranean Cereal Rust Foundation, Wageningen, Netherlands. Cereal Rusts and Powdery Mildews Bulletin, Abstract. A2: 74.

Wieczorek, T. and Jørgensen, L. 2013. Early detection of sugarbeet pathogen *Ramularia beticola* in leaf and air samples using qPCR. *European Journal of Plant Pathology*, 138: 775–785.

Xu, X. M. 1999. Modeling and forecasting epidemics of apple powdery mildew (*Podosphaera leucotricha*). *Plant Pathology*, 48: 462-471.

Yahyaoui, A. and Rajaram, S. 2012. Meeting the challenge of yellow rust in cereal crops. *Proceedings of the 2nd, 3rd and 4th Regional Conferences on Yellow Rust in theCentral and West Asia and North Africa (CWANA) Region*, pp. 175. ICARDA, Aleppo, Syria.

Yan, J., Luo, Y., Chen, T., Huang, C. and Ma, Z. 2012. Field distribution of wheat stripe rust latent infection using real-time PCR. *Plant Disease*, 96: 544-551.

Zadoks, J. C. 1961. Yellow rust on wheat, studies in epidemiology and physiologic specialization. *Tijdschrift over Plantenziekten*, 67: 69-256.

Zadoks, J. C. 1984. A quarter century of disease warning, 1958–1983.*Plant Disease*, 68:352-355.

Zhang, H., Wang, C., Cheng, Y., Chen, X., Han, Q., Huang, L., Wei, G. and Kang, Z. 2012. Histological and cytological characterization of adult plant resistance to wheat stripe rust. *Plant Cell Reports*, 31: 2121–2137.

Zhang, X., Zhang, T., Young, A. A. and Li, X. 2014. Applications and comparisons of four time series models in epidemiological surveillance data. *PLoS ONE*, 9(2):e88075.

Ziyaev, Z. M., Sharma, R. C., Nazari, K., Morgounov, A. I., Amanov, A. A., Ziyadullaev, Z. F., Khalikulov, Z. I. and Alikulov, S. M. 2011. Improving wheat stripe rust resistance in Central Asia and the Caucasus. *Euphytica*, 179: 197–207.

How to cite this article:

Sheikh Saima Khushboo, Vishal Gupta, Devanshi Pandit, Sonali Abrol, Dechan Choskit, Saima Farooq and Rafakat Hussain. 2021. Epidemiology of Stripe Rust of Wheat: A Review. *Int.J.Curr.Microbiol.App.Sci.* 10(01): 1158-1172.
doi: https://doi.org/10.20546/ijcmas.2021.1001.140