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A review paper on role of secondary metabolites in imparting biotic and abiotic stress resistance in wheat

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Abstract
Secondary metabolites are natural substances that are used for plants and other lower organisms as defence mechanisms, survival and endure most of the natural biotic and abiotic stresses; these substances are lower in molecular weight and do not impact the primary metabolism of plants. The secondary metabolites can be classified in different classes according to their physical structures and properties, many of these are being synthesized in the wheat crop through many metabolic pathways. Apart from protecting the wheat crop from various biotic and abiotic stresses, the secondary metabolites also help in enhancing the physiological growth of wheat crop passively. Through this paper we have enlighten about secondary metabolites, their classification and the effect of secondary metabolites imparting biotic stresses such as rust, Fusarium wilt and loose smut, effect of secondary metabolites imparting abiotic stresses like salt stress and UV radiation, and effect on wheat crop growth.

Keywords: Secondary, metabolites, biotic, abiotic stress, wheat

Introduction
Secondary metabolites are naturally synthesized products secreted by bacteria, fungus and plants (Mosunova *et al.*, 2021) [1]. With lower molecular weight (Franz Hadacek and Gert Bachmann, 2015) [2], the secondary metabolites are with different chemical structures, the molecules do not necessarily participate in the primary metabolic activities like growth and development but those take part in the defence activities against herbivores, survival of organisms, antioxidant properties which can act as primary line of defence during any stress conditions (Michael Wink, 2008) [3]. These are the end-products of biosynthesis of primary metabolites with not just one function but multiple functions in the plant body. Some of these are used for their allelopathic properties and also positive symbiotic interaction with the pollinator insects and seed distributor animals through their pheromones (Isah T, 2019) [4]. These are produced at the time of interaction of the organisms with the environment, through many secondary metabolic pathways (Rehab A. Hussein and Amira A. El-Anssary, 2018) [5]. The amount and purpose of the production of these secondary metabolites can differ during the growth and developmental stages of the organisms mainly in the plants which undergoes morphological differentiations during the stages. The main purpose of secondary metabolites is to the help the organism to adopt in the changing environment around it (A L Demain and A Fang, 2000) [6]. These are produced in smaller amount, difficult to extract, absence of these may not cause immediate death of the organism but it may lead to poor morphological and physiological activities of the organism eventually be death.

The secondary metabolites can be classified in many classes such as terpenoids, steroids, phenolics, alkaloids, flavonoids, fatty acid-derived substances, polyketides, non-ribosomal polypeptides, enzyme co-factors (McMurry JE, 2015) [7] etc depending on their chemical structures. With their dynamic structures they also differ in their functions distinctly like growth promoters, immunomodulators, enzyme activators and enzyme inhibitors. The term secondary metabolite was given by Albrecht Kossel in the year 1891, he also won Nobel prize in the field of medicine and physiology in the year 1910 (Jones ME, 1953) [9], but now a days these are known as specialised metabolites due to their special functions in the plants, fungus and another lower organism, like helping in eliminating the competition from the external environment (Navarova *et al.*, 2012) [8].

Among the types of secondary metabolites, the terpenoids or terpenes are the largest groups, nearly 3/5th of the total secondary metabolites are being terpenes (Firn R, 2010) [10], which are

basically polymer chains of organic compounds of which the monomer consists of 5 carbons known as isoprene (Jane Buckle, 2015) [11]. Terpenes are lipid structures (Palenzuela *et al.*, 2021) [12] that are synthesized from Acetyl Co-A or from basic intermediate products from glycolysis through mevalonic acid pathway (Luthra *et al.*, 1999) [14]. Terpenoids are modifications of terpenes (Yazaki *et al.*, 2017) [15] after addition or removal of some other functional groups mainly the oxides and oxidised methyl groups in various carbon positions (Bicas *et al.*, 2009) [16]. With the number of carbon atom differs, the structure of isoprene changes giving rise to different types of terpenoids such as monoterpenes, diterpenes, triterpenes, sesquiterpenes, sesterpenes etc. (Perveen, 2018) [17]. The example of terpenes are cardinolides (Agrawal *et al*, 2012) [18], saponins (Hostettmann and Marston, 1995) [19], limonene (Fahlbusch *et al.*, 2003) [20], artemisnin (Brown G, 2006) [21], taxol (Chang *et al.*, 2007) [22] etc. The terpenes present in the plant body can be divided into two types phytoanticipins (Lamothe *et al.*, 2009) [23] and phytoalexins (Glazebrook *et al*., 1994) [24]. The phytoanticipins secrete constantly with or without any stress conditions but the phytoalexins secrete as a response mechanism when there is a stress condition (Silpa P *et al.*, 2018) [25]. The second largest group of the secondary metabolites are the alkaloids which are nitrogen containing organic compounds, primarily found in plants up to 80%, and the rest 20% is present in vascular plants (Manske S, 1965) [26] after the basic structure with carbon, hydrogen and nitrogen, these metabolites differ in the structure by having other elements like boron, chlorine, sulphur in different position of carbon atoms (Rodney *et al.*, 2000) [28]. Phenols are type of aromatic organic substances with one or more benzene ring structures which help to overcome the stress conditions of plants and other organisms, due to the environmental stress conditions (Weber Manfred, 2004) [29]. There are almost 8000 types of phenolic compounds known till now which are produced by shikimic acid metabolism pathway or malonate or acetate pathway. The shikimic acid metabolism is pathway with seven steps found in bacteria, fungus, higher plants which produces aromatic phenolic compounds (Herrmann and Weaver, 1999) [30]. Phenolic acids are heterogeneous groups some of which can be soluble in water but most of which are soluble in organic solvents. Example of phenolic acids are Benzoic acid derivatives, flavones (David Stauth, 2007) [31], caffeic acid (Boerjan *et al*., 2003) [32], lignin (Saake *et al*., 2007) [33] etc. The other types of secondary metabolites also have significant amount of share in amount and function in the plant kingdom as well as in the lower organisms.

Wheat is a crop belonging to the family poaceae, previously known as family graminaceae, it is cultivated in many countries in the world where China, India, Russia, the United States, Canada, Australia, Pakistan, Ukraine, Turkey and Argentina being the top ten countries for the most of the production. It is one of the major staple foods (Shewry and Peter R, 2009) [34] in these countries where it is being consumed throughout the year. Wheat is the food crop that have 55% of carbohydrates and provides 20% of calories consumed daily (Pfeifer *et al.*, 2014) [35]. In financial year 2020-2021, the total worldwide production for wheat was 772.64 million tonnes (USDA, 2021) [36], which is about 1.02 million tonnes less than the previously estimated production. The decline in the actual production of wheat to the estimated production of wheat may be due to many causes like different kinds of biotic and abiotic stresses occurred to the wheat crops. Though from the production of the last year of 763.90 million tonnes to estimates of this year's of 772.64 million tonnes, there can be an increase in production of 8.74 million tonnes which is roughly 1.14% higher (USDA, 2021) [36], the farmers of the developing and lower income countries always remain uncertain about the production as the wheat crops may be damaged by several stresses. Wheat is being attacked by many biotic stresses such as black rust, brown rust, yellow rust, smut, powdery mildew, karnal bunt, leaf blight (Bakala *et al*, 2021) [37] etc and many abiotic stresses like water logging stress, drought stress, mineral stress, cold stress, heat stress (Kumar *et al.*, 2018) [38] which cause significance decrease in potential yield.

To overcome this type of problems, scientists are now investing time in the secondary metabolites for searching a hopeful solution from the wheat crop itself if these can produce a natural defence mechanism against the abiotic and biotic stresses as some of the wheat varieties become resistant to the environmental stresses and some varieties remain susceptible to the stresses. The amounts of secondary metabolites differ from one variety of wheat to other as a result of different kind of interaction between biotic and abiotic stresses with the varieties in different soil types and environmental conditions. These make the variation of resistance and susceptibility between different varieties.

Phenolic Acids in Wheat

There are many phenolic acids being synthesized by wheat crop as vanillic acid, p-hydroxybenzoic acid etc (W. D. Guenzi and T. M. McCalla, 1966) [40]. Flavonoids are one of the most important phenolic compounds that is present in wheat. Quercetin in wheat is known for its antithrombotic effect (Branković *et al.*, 2015) [41]. Up to 93% of the total flavonoids present in wheat are concentrated in the cell wall which is the structural and skeletal entity of the cell, this gives the herbivores a strong repulsion towards the wheat crop making it safe from them (dom, K.K and Liu, R.H, 2002) [42]. 83% of total phenolic content and 79% of total flavonoids content are present in total whole wheat grain flour, this helps in the protection of wheat during storage conditions against storage pests like weevil, saw-toothed grain beetle, lesser grain borer etc (Liu, R.H, 2007) [43].

Secondary Metabolites Imparting on Biotic Stress in Wheat

Biotic stresses are those kinds of stresses which are caused by living beings like pathogens and insects. As mentioned earlier, there are several biotic factors create negative impact on wheat and decrease the production significantly. The flavonoids which have antimicrobial properties help the wheat crop to resist microbial attacks even when there are favourable conditions for microbial interaction (Novotelnov, N.V and Ezhov, 1954) [44]. When there is increase in biosynthesis of flavonoids the resistance mechanism becomes more active (Khlestkina, E.K, 2013) [45].

A) Rust of Wheat

Black rust, also known as stem rust in wheat, is a devastating fungul disease which cause yield loss throughout the world, is caused by *Puccinia graminis tritici.* There are several secondary metabolites which synthesis naturally in wheat crop to act against the fungus and keep the plants safe from it.

Accommodation of lignin in the cell wall is so much slow to make a resistance barrier against stem rust so phenols play a major role in restricting the fungus up to some extent. Leaf rust in wheat is caused by *Puccinia recondita f. sp. tritici* is also a fungal disease. Studies found that accommodation of phenolic acid, ferulic acid, syringic acid, p-coumaric acid can be noticed in the primary leaves of developmental stages of wheat in both bound and unbound forms when those are exposed to leaf rust disease. Two alleles Lr20 and Lr28 are responsible for this phenolic accumulation (Southerton *et al.*, 1990) [46]. The Lr20 allele plays major role in producing p-coumaric acid against the fungal entry in the wheat cell.

B) Fusarium Wilt of Wheat

There are some secondary metabolites mainly flavonoids, phenolic acids, carotenoids, benzoxazinoids and tocopherols which play a significant role in supressing the effect of *Fusarium* wilt in wheat (Penichon *et al.*, 2016) [47]. Tocopherols are types of methylated phenolic compounds that have antioxidant effects. The most common tocopherol present in wheat is beta-tocotrienol. Benzoxazinoids are allelopathic and protective secondary metabolites present in wheat, these are 2,4-dihydroxy-7-methoxy-1,4-benzoxazin-3-one, 2-hydroxy-1,4-benzoxazin-3-one, hydroxamic acids etc (Hanhineva, *et al.*, 2011) [48]. Pathologic interaction can start the biosynthetic pathway of benzoxazinoids which may lead to accumulation of it in the cell wall mainly in the primary cell wall as defence mechanism (Huffaker *et al.*, 2011) [49]. Derivatives of Cinnamic acid like sinapic acid, chlorogenic acid, ferulic acid inhibits the fusarium wilt effectively (Boutigny, *et al.*, 2009) [50]. Phenolic structures taking part in the plant structure development is provides significant actions against fusarium head blight in wheat (Siranidou, *et al.*, 2002) [51]. With these there are another phenolics mainly tyrosine, galactinol, pipecolic acid and phytosterols like adinosines, saccharides are synthesised for acting against fusarium wilt and fusarium head blight (Loskutov, *et al.*, 2019) [52].

C) Loose Smut of Wheat

Loose smut is a seed borne disease which is caused by *Ustilago tritici*, induces the wheat crop to produce different types of phenolic compounds to reduce the biotic stress condition. The amount of phenols changes with different stages of wheat crop (Tehmina *et al.*, 2012) [58]

Secondary Metabolites Imparting on Abiotic Stress in Wheat

A) Impact Against Salt Stress

Benzoxazinoids, primarily cyclic hydroxamic acids help to improve the resistance against soil salinity (Makleit, *et al.*, 2005) [53]. The higher the content of cyclic hydroxamic acid in the wheat, there is more successful resistance to salinity stress in wheat.

B) Impact Against Uv Radiation-

Polyphenolic compounds are effective against the UV radiation at the seedling stage of wheat crop (Gould, *K.S*, 2004) [54].

Secondary Metabolites Imparting on Yield of Wheat Crop Growth

It is always being a main concern for scientists to keep the height of wheat semi-dwarf up to an optimum level for better yield. Benzoxazinoids help wheat in the stem elongation stage for better growth and therefore it passively takes part in the total grain yield (Tzin, *et al*. (2017) [55]. Benzoxazinoids and their derived products impact with the auxin through auxin signalling present in stems and helps in positive phototrophic growth of stem (Zhou *et al.*, 2018) [56]. These are also recently identified as plant growth regulator (Erb, M. and Kliebenstein, D. J., 2020) [57].

Conclusion

Through this review paper we came to know that there are different kinds of secondary metabolites that are reported by various scientists and their uses in the wheat crop imparting biotic and abiotic stress resistance. Synthesis of those different kinds of metabolites helped in imparting stress tolerance against during various biotic and abiotic stresses and also at different physiological growth stages for helping the wheat crop with dealing all the adverse stress conditions. Thorough research has been done on different various biotic and abiotic stresses on wheat crop that can propose a threat against growth and development of wheat crop, there are many different fields of research as smut, leaf rust, salt tolerance, effect of sandy soil, exposure of wheat to rainfall etc where more researches are needed for developing a resistant wheat crop against the particular stresses of wheat, through selection process naturally.

References

1. Olga Mosunova, Jorge CNavarro-Muñoz, Jérôme Collemare. The Biosynthesis of Fungal Secondary Metabolites: From Fundamentals to Biotechnological Applications, Encyclopedia of Mycology. 2021;2:458-476.
2. Franz Hadacek, Gert Bachmann, Low-molecular-weight metabolite systems chemistry, Front. Environ. Sci, 2015 March 04.
3. Michael Wink. Plant Secondary Metabolism: Diversity, Function and its Evolution, Institute of Pharmacy and Molecular Biotechnology. 2008;3(8):1205-1216.
4. Isah T. Stress and defence responses in plant secondary metabolites production. Biol. Res. 2019;52:1-25.
5. Rehab A. Hussein and Amira A. El-Anssary, Plants Secondary Metabolites: The Key Drivers of the Pharmacological Actions of Medicinal Plants, 2018, DOI: 10.5772/intechopen.76139.
6. A L Demain, A Fang. The natural functions of secondary metabolites, Adv Biochem Eng Biotechnol. 2000;69:1-39.
7. McMurry JE. Organic chemistry with biological applications. In: Secondary Metabolites: An Introduction to Natural Products Chemistry. Stamford, USA: Cengage Learning Ltd, 2015, 1016-1046
8. Návarová H, Bernsdorff F, Döring AC, Zeier J. Pipecolic acid, any endogenous mediator of defense amplification and priming, is a critical regulator of inducible plant immunity. Plant Cell. 2012;24(12):5123-41.
9. Jones ME. Albrecht Kossel, a biographical sketch. The Yale Journal of Biology and Medicine. 1953 September26(1):80-97.
10. Firn R. Nature's Chemicals. Oxford: Biology, 2010.
11. Jane Buckle. Basic Plant Taxonomy, Basic Essential Oil Chemistry, Extraction, Biosynthesis, and Analysis, Clinical Aromatherapy (Third Edition), Essential Oils in Healthcare, 2015, 37-72

12. Miguel Palenzuela, David Sánchez-Roa, Jesús Damián. Valentina Sessini Marta E.G. Mosquera, Polymerization of terpenes and terpenoids using metal catalysts, Advances in Organometallic Chemistry. 2021;75:55-93.
13. Bérdy J. Bioactive microbial metabolites. The Journal of Antibiotics. 2005;58(1):1-26.
14. Rajesh Luthra, Pratibha M. Luthra, Sushil Kumar. Redefined role of mevalonate–isoprenoid pathway in terpenoid biosynthesis in higher plants. 1999;76(2):133-135.
15. Kazufumi Yazaki, Gen-ichiro Arimura, Toshiyuki Ohnishi. 'Hidden' Terpenoids in Plants: Their Biosynthesis, Localization and Ecological Roles, Plant and Cell Physiology. 2017 October58(10):1615-1621.
16. Juliano Lemos Bicas, Ana Paula Dionísio, Gláucia Maria Pastore. Bio-oxidation of Terpenes: An Approach for the Flavor Industry. 2009;109(9):4518-4531.
17. Shagufta Perveen. Introductory Chapter to Terpenes and Terpenoids, 2018. DOI: 10.5772/intechopen.79683
18. Agrawal Anurag A, Petschenka Georg, Bingham Robin A, Weber Marjorie G, Rasmann Sergio. Toxic cardenolides: chemical ecology and coevolution of specialized plant-herbivore interactions. The New Phytologist. 2012 April;194(1):28-45.
19. Hostettmann, K. Marston A. Saponins. Cambridge: Cambridge University Press, 1995. 3ff. ISBN 978-0-521-32970-5.
20. Fahlbusch Karl-Georg, Hammerschmidt Franz-Josef, Panten Johannes, Pickenhagen Wilhelm, Schatkowski Dietmar, Bauer Kurt, *et al*. Flavors and Fragrances. Ullmann's Encyclopedia of Industrial Chemistry, 2003. DOI:10.1002/14356007.a11_141
21. Brown G. Artemisinin and a new generation of antimalarial drugs. Education in Chemistry. Royal Society of Chemistry. 2006;43(4):97-9.
22. Chang AE, Ganz PA, Hayes DF, Kinsella T, Pass HI, Schiller JH, *et al*. Oncology: An Evidence-Based Approach. Springer Science & Business Media, 2007, 34.
23. Rocío González-Lamothe, Gabriel Mitchell, Mariza Gattuso, Moussa S, Diarra, François Malouin, Kamal Bouarab. Plant Antimicrobial Agents and Their Effects on Plant and Human Pathogens, Int J Mol Sci. 2009 Aug;10(8):3400-3419.
24. Glazebrook, Ausbel, Ausubel FM. Isolation of phytoalexin-deficient mutants of Arabidopsis thaliana and characterization of their interactions with bacterial pathogens. PNAS. 1994;91(19):8955-8959.
25. Silpa P, Roopa K, Thomas TD. Biotechnological Approaches for Medicinal and Aromatic Plants. Springer Science and Business Media LLC; Cham, Switzerland. Production of Plant Secondary Metabolites: Current Status and Future Prospects, 2018, 3-25.
26. Manske RHF. The Alkaloids. Chemistry and Physiology. Volume VIII. – New York: Academic Press, 1965, 673.
27. Chemical Encyclopedia: alkaloids
28. Rodney C, Toni M, Kutchan N, Lewis G. Biochemistry and molecular biology of plants. In: Buchanan B, Gruissem W, Jones R, editors. Natural Products. Rockville, MD., USA: Wiley, 2000, 1253-1348.
29. Weber Manfred, Weber Markus, Kleine-Boymann Michael. Phenol. Ullmann's Encyclopedia of Industrial Chemistry. 2004. Weinheim: Wiley-VCH. DOI: 10.1002/14356007.a19_299.pub2
30. Herrmann KM, Weaver LM. The Shikimate Pathway. Annual Review of Plant Physiology and Plant Molecular Biology. 1999;50:473-503.
31. David Stauth. Studies force new view on biology of flavonoids. Eurek Alert!; Adapted from a news release issued by Oregon State University, 2007 March 5.
32. Boerjan Wout, Ralph John, Baucher Marie. Lignin biosynthesis. Annual Review of Plant Biology. 2003;54:519-546.
33. Saake Bodo, Lehnen Ralph. Ullmann's Encyclopedia of Industrial Chemistry. 2007. Weinheim: Wiley-VCH. DOI:10.1002/14356007.a15_305.pub3
34. Shewry, Peter R. Wheat, Journal of Experimental Botany. 2009;60(6):1537-53.
35. Pfeifer M, Kugler KG, Sandve SR, Zhan B, Rudi H, Hvidsten TR, *et al*. Genome interplay in the grain transcriptome of hexaploid bread wheat. Science. 2014;345:1250091.
36. World Wheat Production 2020/2021, World Agricultural Production.com, United States Department of Agriculture (USDA), 2021 Jan.
37. Harmeet Singh Bakala, Kamalpreet Singh Mandahal, Ankita, Loveleen Kaur Sarao, Puja Srivastava. Breeding Wheat for Biotic Stress Resistance: Achievements, Challenges and Prospects, 2021. DOI: 10.5772/intechopen.97359
38. Kumar Abhinandan, Logan Skori, Matija Stanic, Neil MN. Hickerson Muhammad Jamshed, Marcus A, *et al*. Abiotic Stress Signaling in Wheat – An Inclusive Overview of Hormonal Interactions During Abiotic Stress Responses in Wheat, 2018. DOI.org/10.3389/fpls.2018.00734
39. Brading PA, Verstappen ECP, Kema GHJ, Brown GHJ. A gene-for-gene relationship between wheat and Mycosphaerella graminicola, the Septoria tritici blotch pathogen. Phytopathology. 2002;92:439-445.
40. Guenzi WD, McCalla TM. Phenolic Acids in Oats, Wheat, Sorghum, and Corn Residues and Their Phytotoxicity, 1966.
41. Branković G, Dragičević V, Dodig D, Zorić M, Knežević D, Žilić S, *et al*. Genotype × environment interaction for antioxidants and phytic acid contents in bread and durum wheat as influenced by climate. Chilean J Agric. Res. 2015;75:139-146.
42. Dom KK, Liu RH. Antioxidant activity of grains. J Agric. Food Chem. 2002;50:6182-6187.
43. Liu RH. Whole grain phytochemicals and health. J. Cereal Sci. 2007;46:207-219.
44. Novotelnov NV, Ezhov IS. About antibiotic and antioxidant properties of grain yellow pigments. Proc. Acad. Sci. USSR. 1954;99:297-300.
45. Khlestkina EK. The adaptive role of flavonoids: Emphasis on cereals. Cereal Res. Commun. 2013;41:185-198
46. Southerton SG, Deveral BJ, Changes in phenolic acid levels in wheat leaves expressing resistance to Puccinia recondita f. sp. tritici, Physiological and Molecular Plant Pathology. 1990, 2020 December37(6):437-450.
47. Atanasova-Penichon V, Barreau C, Richard-Forget F. Antioxidant secondary metabolites in cereals: Potential involvement in resistance to fusarium and mycotoxin accumulation. Front. Microbiol. 2016;7:566.
48. Hanhineva K, Rogachev I, Aura AM, Aharoni A,

Poutanen K, Mykkanen HJ. Agric. Food Chem. 2011;59:921.
49. Huffaker A, Dafoe NJ, Schmelz EA. ZmPep1, an ortholog of Arabidopsis elicitor peptide 1, regulates wheat innate immunity and enhances disease resistance. Plant Physiol. 2011;155:1325-1338.
50. Boutigny A-L, Barreau C, Atanasova-Penichon V, Verdal-Bonnin M-N, Pinson-Gadais L, Richard-Forget F. Ferulic acid, an efficient inhibitor of type B trichothecene biosynthesis and tri gene expression in fusarium liquid cultures. Mycol. Res. 2009;113:746-753.
51. Siranidou E, Kang Z, Buchenauer H. Studies on symptom development, phenolic compounds and morphological defence responses in wheat cultivars differing in resistance to Fusarium Head Blight. J Phytopathol. 2002;150:200-208.
52. Loskutov IG, Shelenga TV, Konarev AV, Khoreva VI, Shavarda AL, Blinova EV, *et al*. Biochemical aspects of interactions between fungi and plants: A case study of Fusarium in oats. Agric. Biol. 2019;54:575-588.
53. Makleit P. Changes in cyclic hydroxamic acid content of various rye varieties for the effect of abiotic stress. Acta Biol. Szeged. 2005;49:103-104.
54. Gould KS. Nature's Swiss army knife: The diverse protective roles of anthocyanins in leaves. J Biomed. Biotech. 2004;5:314-320.
55. Tzin V, Hojo Y, Strickler SR, Bartsch LJ, Archer CM, Ahern KR, *et al*. Rapid defense responses in wheat leaves induced by Spodoptera exigua caterpillar feeding. J Exp. Bot. 2017;68:4709-4723.
56. Zhou S, Richter A, Jander G. Beyond defense: multiple functions of benzoxazinoids in maize metabolism. Plant Cell Physiol. 2018;59:1528-1537.
57. Erb M, Kliebenstein DJ. Plant secondary metabolites as defenses, regulators, and primary metabolites: the blurred functional trichotomy. Plant Physiol. 2020;184:39-52.
58. Tehmina Anjum, Sabin Fatima, Sana Amjad. Physiological changes in wheat during development of loose, Trop. plant pathol. 2012 Apr, 37(2).