CHAPTER 1

Pigmented Wheat: Nutrition Scenario and Health Benefits

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1.1 Introduction

Wheat (*Triticum aestivum*) is a major staple cereal crop that belongs to the grass family *Poaceae (Gramineae)*, and has an important place among crop species, playing a crucial role in the human diet. It is one of the primary sources of nutrition for about 2.5 billion people worldwide, and is used for making various wheat-based food products (pasta, crackers, noodles, pastries, *etc.*). Wheat grain is considered a major source of starch, protein, minerals, B-group vitamins, and dietary fibres.[1] It is believed that wheat was one of the first food crops ever grown. Wheat was first cultivated about 10 000 years ago, as a part of the agricultural revolution (*i.e.*, the shift to agriculture from hunting and gathering). For around 8000 years it has been the prime food source for some of the major civilizations of the world. Currently, wheat is the most commonly grown crop worldwide, with nearly 772 million metric tons being produced in more than 120 countries. Most of the world's wheat

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is produced by two countries: India and China. In India, which ranks second after China, production is estimated between 98 million to 105 million metric tons. It is also the second-most produced cereal behind maize and, in terms of food security, it is one of the dominant crops in India after rice.[2] Generally, amber-colored wheat varieties are consumed on a daily basis around the world. However, attention is increasingly being given to colored wheat varieties that are rich in anthocyanins, carotenoids, phenolic compounds, and other phytochemicals, owing to their numerous health benefits. Pigmented wheat came into existence in the 19th century by crossbreeding interspecies crosses of *Triticum aestivum* with distinct wild wheat species: *Triticum monococcum L. spp. aegilopoides, Thinopyrum ponticum*, and *Th. bessarabicum*.[3] Color variation in the wheat grain is dependent on genetic factors, growing conditions and technology used.

Wheat bran, covering the endosperm, comprises three tissue layers (the pericarp, testa, and aleurone layer), where pigments are localized and provide different colors.[4] Carotenoids (tetraterpenoids) are yellow, orange, and red colored pigments that are responsible for the color of the wheat grain located in the endosperm. Wheat grain contains a wide range of carotenoids, including lutein, β-carotene, β-apocarotenal, antheraxanthin, β-cryptoxanthin, zeaxanthin, triticoxanthin, taraxanthin (lutein 5, 6-epoxide), and flavoxanthin, whereas phlobaphenes (deoxyflavanoids) are responsible for the reddish brown color found in the outer layer of the kernel.[5] Anthocyanins are water-soluble flavonoids that give rise to the blue, black, purple, and red colors in the outer layer of kernel. However, genotype and environmental conditions are also responsible for the pigmentation in the wheat.[6] The purple color is due to anthocyanin accumulated in the pericarp, while the blue color is caused by anthocyanin in the aleurone layer.[7] In black wheat, anthocyanin is localized in both the pericarp and aleurone layers. A category of black wheat called Chinese black wheat contains high levels of polysaccharide and protein. It also contains more dietary fibre and less carbohydrate than conventional wheat. It has also been reported that black wheat (Qinhei No.1) contains more iron, zinc, manganese, copper, selenium, magnesium, potassium, and phosphorus, which are beneficial to health.[6] In purple wheat varieties, some of the anthocyanin present in high amounts include:

- cyanidin-3-glucoside (4 mg g^{-1}),
- peonidin-3-glucoside (2 mg g^{-1}),
- cyanidin-malonyl-glucose (1 mg g^{-1}),
- cyanidin-succinyl-glucose (1 mg g^{-1}),
- peonidin-malonyl-glucose,
- peonidin-succinyl-glucose,
- peonidin-malonyl-succinyl-glucose.

Blue wheat contains five to eight important anthocyanins, with delphinidin 3-rutinoside, delphinidin-3-glucoside and malvidin-3-glucoside the most prevalent pigments.[4] Purple wheat contains a lower level of anthocyanins than black and blue wheat varieties. There is a great variation in anthocyanin levels in pigmented wheat varieties, as is evident from studies, which found that: the total anthocyanin content of purple wheat varies from 10 to 305 mg kg^{-1} dry kernel weight; for blue wheat anthocyanin content ranges between 17 and 211 mg kg^{-1} dry kernel weight; and in black wheat it varies between 56 and 198 mg kg^{-1} dry wheat kernel.[7]

The protein content of pigmented wheat is 11.4–18.17%, which is higher than common wheat.[8] The percentage of total amino acids and essential amino acids present in pigmented wheat is approximately 8.88–18.91% and 7.31–18.13%, respectively.[9] Pigmented wheat varieties contain almost the same amount of fat and dietary fibres as conventional wheat.[3] Moreover, pigmented wheats are abundantly rich in vitamin B, including B1 (thiamine), B2 (riboflavin), B3 (niacin), B6 (pyridoxine), B9 (folate). It also contains (in smaller amounts) provitamin A (β-carotene), vitamin D (calciferol), and vitamin K (phylloquinone). Pigmented wheat also contains a large amount of zinc (108.54–142.68%), magnesium (5.31–40.63%) and iron (8.57–42.86%).[1] It has been found that flour yield is lower in colored wheat because of its lower volumetric weight than common wheat. As levels of anthocyanin is high in bran, bran-rich flour obtained from purple and blue wheat can be used to make food products such as biscuits, bread, *etc.* and in the extraction of natural colorants (dyes and fragrances).[4] The presence of carotenoids, total phenolic compounds (TPCs), total anthocyanin compounds (TACs), total dietary fibres (TDF) in the colored wheat exhibit antioxidant properties that basically helps in extending the shelf life of products and protects against degenerative diseases.[5] Pigmented wheat promotes a healthy lifestyle and helps in the prevention of several long-term diseases such as cardiovascular diseases (CVD), inflammation, cancer, obesity, gallstones, and metabolic syndrome.[10]

1.2 Transformation in the Consumption Patterns of Wheat

Wheat and wheat-based products are a good source of carbohydrates, proteins and other minerals and vitamins that constitute a healthy consumption pattern.[11] However, this crop still needs to be improved for its micronutrients and other functional components. Colored wheat makes up for the lack of certain micro-nutrients and functional compounds of the traditional wheat varieties. By virtue of being rich in bioactive substances such as phenolic acids, flavonoids and anthocyanins, it proves to be a good dietary supplement in the management of diseases such as diabetes, cardiovascular diseases, *etc.*[12] Pigmented wheat therefore quickly found a new place in the wheat world, and began to firmly establish itself as integral to human life. There is always a desire for a truly affordable and proportional diet in a single item in this busy civilization, which is unquestionably significant. While wheat is already considered one of the most cost-effective and essential food sources, and thus the introduction of pigmented wheat essentially began to meet this demand.[1] When compared to conventional wheat types, pigmented wheat is significantly rich in anthocyanins, flavonoids, carotenoids, phenolic acids, other bioactive compounds, and a variety of other necessary nutritive riches, as well as nutrients found in regular wheat, which is present in the bran and also in the flour, can lead to a bad effect on the consumers.[13] As a result, colorful ones enhance both diet and health, and they are being encouraged to be embraced by our society, which is highly crucial.

Over time, it has also been discovered that the natural colorants in colored wheat could take over and replace synthetic colors. These natural additives can be used in a wide range of products, including cosmetics, medicines, treatments, textiles, and several other things. They essentially give a much better texture, color, and other qualities than synthetic colorants, providing improved and appealing versions of foods and other products. Thus, pigmented wheat not only suits daily dietary needs but also facilitates management of health conditions and provision of alternative additives in the food industry. The multifaceted advantage of pigmented wheat would be key in encouraging its uptake among consumers. As a result, these characteristics make pigmented wheat an intriguing topic for food scientists and technologists to investigate, demonstrate, and utilize for the benefit of the world.[1]

Many clinical research and epidemiological studies suggest that regular consumption of pigmented wheat can reduce the risk of chronic diseases comparted with non-pigmented ones.[8] The pigments have antioxidant, anti-inflammatory, anti-microbial, anti-cancer, and anti-aging properties, provide protection to the nervous system and immune system, and provide the body with a wide range of functional assistance.[15] It even has various effects on platelets and blood vessels that reduce the risk of coronary heart diseases,[16] including preventing diseases like type 2 diabetes and obesity.[1] According to Sharma,[12] fruits like blueberries and blackberries are inherently high in anthocyanins, while mangoes are rich in carotenoids and contain high amounts of sugar. Therefore, high doses can pose a fundamentally high risk of high blood sugar. In pigmented wheat, the availability of pigments also provides a variety of essential nutrients, so the adoption of colored ones encourages switching to a low-sugar diet. It also contains some fairly unique properties that promote brain activity and even pigmented wheat like black wheat has a higher capacity than conventional wheat to scavenge free radicals in the colored seeds.[17]

Since colored wheat attracts consumers, it has begun to dominate the food industry. Due to various properties, pigmented wheat has attracted a lot of researchers, breeders, and industrialists to utilize it as commercial, functional, and nutraceutical food. Various innovative and colored products have been developed, such as noodles, bread, tortillas, muffins, and many other innovative foods, with some still under development.[12] Several agro-food companies have started their business, while many farmers have started new lives by filling their land with wheat of a specific color, gaining worldwide popularity.[18] For future and present generations, consumption patterns are shifting to now fixate on a diet that is preventive and nutritive in nature. This naturally has an impact on global consumption and production of pigmented wheat varieties over traditional ones due to their functional characteristics.

1.3 Types and Breeding of Pigmented Wheat

Although purple, blue, and black wheat are produced in small quantities, they show potential to be utilized in food, ornamentations, colorants, and other application. The welcoming of pigmented wheat on a large scale for their production and utilization is necessary because of the antioxidant properties, health benefits, and other features from the pigments providing an extra advantage over conventional wheat. However, these varieties of wheat did not originate from the local or wild crops, rather, they have been developed after much research on breeding and genetics over a long period.[19] The range of pigments generally agrees with the 'The Law of Homologous Series in Hereditary Variability,' which was drawn by N. I. Vavilov in 1920.[5] Although the pigments in wheat grains are quite low, they do influence the qualities of wheat products like bread, cookies, biscuits, pasta, and noodles.[19] The color gene expression of the wheat grain differs with the origin of the seed tissue. Moreover, in this grain, there are four main types of tissue *i.e.*, pericarp, seed coat, embryo, and endosperm.[5] In pigmented wheat, the purple color of wheat is due to the anthocyanins in the diploid pericarp layer while the blue color of the wheat is due to the anthocyanins in the aleurone layer, and black wheat develops with the genetic combination of the purple and the blue wheat.[17] Sometimes, a very dark grain can also emerge due to the genetic collaboration of purple pericarp, blue aleurone, yellow endosperm, and red grain.[5] In common black, blue and purple wheat, only forms of glucoside (mono-glycosylated) and rectinoside (di-glycosylated) were identified in every anthocyanin.[15] Further discussion on pigmented wheat (black, blue, and purple) follows.

1.3.1 Purple Wheat

The emergence of purple wheat has started to attract the scientific world. Purple wheat has been seen in variable shades, as growing and environmental conditions, light intensity and temperature hugely affect the amount of anthocyanins developed in the pericarp of the grain.[16] Ludwig Wittmack first reported purple-colored wheat in 1879. In around 1872/1873, Johann Maria, a famous botanist, collected some grains during a trip to East Asia and afterwards he handed these grains to the Museum of Agriculture, in Berlin. It was introgressed from Ethiopian sources to hexaploid bread wheat.[20] So, the purple wheat was first found in the tetraploid durum (*Triticum dicoccum*), in the regions of East Africa like Ethiopia and was genetically transferred to wheat.[19] Stable purple wheat was originated from the crosses of *Triticum dicoccum* var. *Arraseita percival* × *Triticum aestivum* L., and the color was much deeper. This variety inherited its color from the tetraploid wheat, *Triticum* *aestivum* var. *Arraseita percival* from Abyssinia containing a single dominant gene and hexaploid wheat, *Triticum aestivum* L. contains two incompletely dominant genes, and this led to the formation of purple-colored wheat.[15,19] The purple pigments are located in the diploid pericarp layers and since this pigment is present in the pericarp, its color does not segregate among the wheat kernels inside the spike.[17,21] In addition, due the localization of the purple color, the environmental effect on it is much stronger and the anthocyanins present in it are more prone to these environmental effects. Cyanidin 3-glucoside and peonidin 3-glucoside are the two major components seen in purple wheat, in which cyanidin 3-glucoside is the predominant one.[21] About 22 different types of anthocyanins could be found from purple wheat lines and even show higher peak intensities for the acylated anthocyanins.[15] This purple wheat provides many benefits, *e.g.*, anthocyanins from this wheat can also be utilized and crushed into larger pieces and spread over the surface of multigrain bread.[1]

1.3.2 Blue Wheat

The color of the blue wheat is due to the presence of anthocyanins in the aleurone layer.[16] Blue wheat and its varieties were developed using distant hybridization, and alien chromosomes into the wheat genome.[22] The blue color gene is transferred from three wild wheat species known as *Triticum monococcum* L. *spp. aegilopoids*, *Thinopyrum pouticum* (*Agropyron elongatum*), and *Th. bessarabicum*. However, these are also required for further study to determine the gene control and roles of different genes on the development of blue color in wheat.[17] Blue wheat was formed in the first half of the 20th century by crossing wheat with wheat's relatives. Originally, these crosses were carried out to make the crop disease resistant and for other factors like winter hardness, perennial habit, forage traits, and yield components, but this led to the formation of blue wheat. There is evidence that blue aleurone originates from einkorn wheat, including *Triticum boeoticum* boiss or *Triticum monococcum* L., and other types resulting from the interspecific crosses of *Agropyron* (syn. *thinopyrum*) and other wild wheat varieties.[20] Blue coloration is gene dependent and thus contributes to the different blue shades of wheat grain color.[17] Also, there are all over 22 different anthocyanins identified from blue wheat. The blue color is present in the aleurone layer around the seed, except the embryo. It was also noted that there are either two complementary genes or a single dominant gene to control the blue color of the wheat. The shade and stability of blue wheat is also caused by the different localization of anthocyanins in the wheat grain.[15] Unlike purple wheat, cyanidin 3-glucoside is the second most common in the blue wheat. However, anthocyanin present in maximum concentration still remains undefined for blue wheat.[21] Pelargonidin-3-glucoside was also not seen in the blue wheat.[15] The concentration of the color of blue wheat is also determined by light, temperature, growing, and environmental conditions, as with purple wheat.[21] If there is a lower yield, it is due to the negative impact of the genes linked to the blue aleurone chromosomes from the wheat species.[15] Blue wheat differs from other wheat varieties not in the composition of anthocyanins, but its presence of different layers that can be clearly seen during the cross section of the wheat kernel. Blue wheat contains mainly cyanidin, delphinidin, pelargonidin, malvidin, and petunidin glycosides.[5] This blue wheat also holds promises to develop wheat-based functional foods or natural colorants, based on the concentration of anthocyanins.[21] Since the blue color is present in the outer layers of the pigmented wheat, so wholemeal/bran-enriched flour can be utilized in many colored foods, like bakery products. However, blue wheat is more prone to thermal degradation, thus extra care has to be taken and also further studies are required to overcome this challenge.[5]

1.3.3 Black Wheat

Black wheat is a form of pigmented wheat that is developed by crossing purple and blue varieties of wheat and thus the black color is due to the anthocyanins present in both pericarp and aleurone layer. Black wheat was first originated in the laboratory of the Institute of Crop Genetics, Shanxi Academy of Agricultural Science, after 20 years, beginning in 1970.[17] Blue-grained hexaploid wheat was formed by crossing *Triticum aestivum* with *A. glaucum*, and the 'purple 12-1' was formed by crossing *Triticum aestivum* with *Elymus dasystachys*. Then the 'blue-purple 114' was developed by crossing blue-grained hexaploid wheat with 'purple 12-1'.[19] Then the first black wheat that was developed was named 'Black 76' and, gradually, this variety was formed by crossing 'purple 12-1' as the male parent (associated with the mutation in the pericarp) and 'blue–purple 114' as the female parent (as a result of wild introgression).[17,18] Just like blue wheat, black wheat can also be observed without any genetic disorder or affecting any chromosomes to affect its related yield.[15] Black wheat contains the highest parts per million (ppm) *i.e.*, 140 ppm (or 100–200 ppm), while regular wheat contains only 5 ppm.[23] It has the highest amount of anthocyanins among all the other colored varieties It contains 60% more iron and is thus more nutritious than any common wheat. There are twenty-six different anthocyanins that could be found in black wheat itself. Delphinidin-3-(6″-malonylglucoside) is the only compound that is seen in black wheat lines only. Due to the localization of the pigments in the outer pericarp layer, as in purple wheat, this black wheat also appear darker in color.[15] Among all the varieties of pigmented wheat, black wheat draws the most of the attention due to its high nutritional profile, good sensory attributes, and health-promoting activities. It is also used to produce various functional foods and colorants, and can produce products much better than the ones developed from the common wheat. No research has given a complete overview regarding the breeding line, composition, and functional properties of black wheat.[17] However, studies and experiments are still ongoing with the given information for the improved results, better economic value, nutritional and functional properties, and to make the best utilization of it.[15]

1.4 Nutritional Composition of Pigmented Wheat

Conventional wheat varieties have a protein concentration ranging from 10% to 18% of total dry matter, mainly affected by weather and nitrogen fertilizers.[24] Starch constitutes 60–75% of total dry weight in wheat grains.[25] However, it has been observed that pigmented wheat has 11.74–18.17% higher protein content, 8.88–18.91% higher total amino acids, and 7.31–18.13% higher essential amino acids. Even mineral content such as the amount of zinc, iron, and magnesium is raised by the respective percentages 108.54–142.68%, 8.57–42.86%, and 5.31–40.63% when compared with common wheat varieties.[9] The nutritional composition of pigmented wheat varieties is discussed in detail below (see Figure 1.1).

1.4.1 Protein

Black wheat is an abundant source of total essential amino acids, comprising 96 amino acids and their derivatives. The total amino acid content is 15.74%, while essential amino acid content is around 4.45%. The chief storage proteins of black wheat are constituted by alcohol soluble prolamins, glutenin and gliadin. The gluten index used to determine the end-quality of black wheat flour is 69.74, which is lower than that of conventional wheats with a gluten index of 98–99. However, it still falls in the optimal range

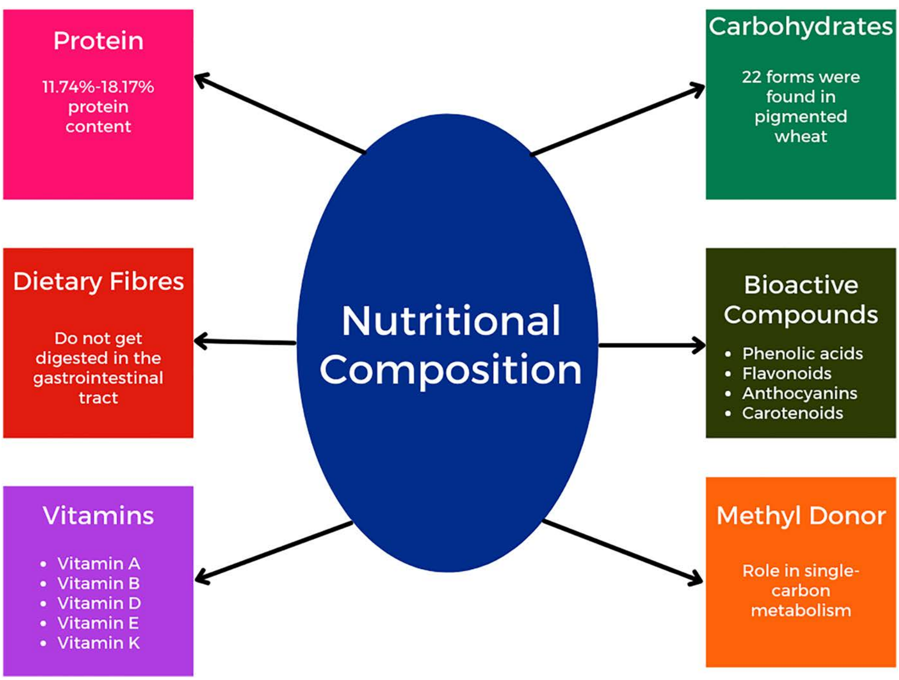

Figure 1.1 Nutritional composition of pigmented wheat.

for application in bread making and can be used to manufacture bread successfully. This paves the way for processing of black wheat to produce low-gluten food products that serve as an alternative for celiac disease patients. It has been suggested that it is critical to investigate wheat accessions in terms of total gluten content. As a result, considerable research, particularly for validation of black wheat's gluten nature, is required.[17] Purple wheat has a protein level that ranges from 29% to 55.37% more than the standard values, but its fat content also ranges from 7.69% to 15.38% higher than the standard values.[26]

1.4.2 Carbohydrates

In wheat, the primary carbohydrate is starch, which is a vital energy-providing component. It is present in the endosperm or flour section of the kernel. Free sugars, such as glucose, fructose, sucrose, raffinose and glucofructans and hemicelluloses are present in a small percentage of 1–2% by weight.[27] In the endosperm of a wheat grain containing a high amount of starch, crystalline and amorphous regions coexist, and there is a formation of semi-crystallized starch due to hydrogen bonding between radially oriented linear and branched macromolecules.[17] Starch is made up of two high-molecular weight polymers – amylopectin and amylose. Linear amylose makes up 20–30% of normal wheat starch, while branched amylopectin makes up 70–80%.[25] The distinctive physiochemical qualities of starch have allowed the production of various food items because of its properties. For the optimal production of bread, the usual amylose:amylopectin ratio present in wheat starch granules is vital.[27]

Twenty-two forms of carbohydrates were found in pigmented wheat varieties of red, blue, purple, and black.[28] More polysaccharides have been found in black wheat than in conventional wheat varieties. Around 75% of carbohydrates in black wheat are concentrated in its endosperm.[17] In the nutritional profiling of white, black, and blue wheat lines and advanced lines made by crossing the white and pigmented wheat varieties (purple, black, and blue), the carbohydrates and sugars are found to be lower in blue and white wheat lines, and higher in black donor and advanced lines.[29]

1.4.3 Dietary Fibres

Specific polysaccharides, such as cellulose, hemicellulose, pectin, *etc.*, are not digested in the gastrointestinal tract. These form the dietary fibre that boosts the volume of the food and thereby decreases the accessibility of starch granules by enzymes present in the digestive tract. In black wheat, total dietary fibres are around 1.15% of the total weight, and insoluble fibre contributes to a more significant fraction. This insoluble fibre offers volume to the body and the faeces, which helps prevent constipation and stimulate the intestinal transit.[17] However, the proportion of dietary fibre has been reported in purple wheat across multiple varieties (ZY4, ZY5, ZY11, ZY17-1, ZY17-2, ZY21 and ZY22) to be 11.30%.[26]

1.4.4 Bioactive Compounds

Bioactive compounds are phytochemicals extracted from natural food sources or their by-products, that can regulate metabolic functions and positively influence the overall health of an individual.[30] Pigmented wheat is abundant in anthocyanin and numerous other phytochemicals such as phenolic acids, flavonoids, carotenoids, *etc.*, thereby increasing their value as an advantageous food for the health-conscious crowd. Pigmented wheat kernels are a rich source of by-products like carotenoid and anthocyanin-rich pericarp (in purple wheat), aleurone layer (in blue wheat), and endosperm (in yellow wheat). Red wheat is a result of its outer layer containing phlobaphene. Black wheat that has been synthesized by crossing purple and blue wheat varieties has increased free radical scavenging quality and phenolic acid content.[5] Bioactive substances such as anthocyanins, phenols, flavonoids, *etc.*, of great value are found in black wheat.[17] Pigmented wheat varieties are abundant sources of vital bioactive compounds such as tannins, polyphenols, carotenoids, and anthocyanins. Thus, the different varieties have proven to fight against chronic diseases such as cardiovascular diseases, diabetes, inflammation, obesity, *etc.* Food manufacturers and researchers are in the process of tapping into this potential of pigmented wheat.[1]

In the red, purple, blue, and black pigmented wheat varieties, metabolite profiling has shown the presence of 174 flavonoids: 118 flavones and derivatives, 25 flavonols, 11 flavanones, 14 anthocyanins, 5 isoflavones, and 1 proanthocyanidin. In particular, tricin, chrysoeriol, apigenin, luteolin, quercetin, and their glycosides are present in greater concentrations.[28] Black, purple, and blue pigmented wheat lines and their antioxidant properties are linked with anthocyanins and phenolic compounds.[31]

1.4.5 Phenolic Acids

Phenolic acids are one of the most extensively found bioactive compounds, protecting plants from biotic (infections, wounds) and abiotic (nutrient deficits or excess, cold, and visible light) challenges. Furthermore, phenolics contribute to various food characteristics like bitterness, astringency, color, flavour, odour, and lipid oxidation resistance. Phenolic acid has anti-inflammatory, anti-bacterial, anti-proliferative, anti-carcinogenic, and antioxidative properties.[32] In common wheat, phenolic acids are present in soluble conjugate and insoluble form. Phenolic acids are sub-divided into hydroxybenzoic acid derivatives and hydroxycinnamic acid derivatives, which possess antioxidant properties. In metabolite profiling of red, yellow, blue, purple, and black pigmented wheat varieties, 53 phenylpropanoids, with 17 distinct phenolic acids and 36 derivatives, were found.

Hydroxycinnamic acids were present in the greatest concentration. The concentration of bound phenolic components is greater than those found in free form. Gentisic acid and protocatechuic acid were the most abundant phenolic acids and were found in higher concentrations in purple and black wheats. 4-methoxycinnamic, two cinnamic acid derivatives and 3,4,5-trimethoxycinnamic acids, have been identified and found to be much higher in yellow and blue wheats.[28]

However, black wheat comprises various phenolic acids like gallic, caffeic, gentisic, syringic, vanillic, *p*-hydroxybenzoic, ferulic acids, *p*-coumaric, and *o*-coumaric acid. Higher phenolic acid concentration is present in the bran than the wholemeal. Ferulic acid is the major phenolic acid present in black wheat. Higher soluble phenolic content is reported in black wheat than in white wheat. On comparing black wheat's phenolic acid with that of purple and common yellow varieties, bound total phenolic acids (TPC) content was 1.6 times higher in black wheat and free TPC was found to be 1.6 and 6 times more in black wheat than purple and yellow varieties, respectively.[17]

Phenolic acids have been detected exclusively in the outer layers of the wheat grain. A strong correlation between the antioxidant properties of phenolic acids – both free form and bound form – and total phenolic content has been depicted. Upon biochemical evaluation of the different bran fractions – outer bran, coarse bran, and shorts – of blue, purple, and black varieties of pigmented wheat, most phenolic acids were in bound form. These bound phenolic acids can be expected to promote health more effectively, since they may circumvent the upper gastrointestinal digestive process and can be absorbed directly into the plasma during intestinal digestion. The bran fractions with a higher concentration of phenolic acids can be obtained in debranning and utilized in the production of functional foods. Unfortunately, it requires changes by adding more bran in flour during processing.

The ferulic acid concentration in blue-pigmented wheat variety decreased gradually from outer bran to coarse bran to shorts. Coarse bran of black pigmented wheat and purple-pigmented wheat contained more ferulic acid than the other fractions. The highest concentration of total phenolic acids was noted in the outer bran of blue wheat, which amounted to 3459 $\mu g\ g^{-1}$, while the shorts of purple wheat have the lowest value of total phenolic acids of 1731 $\mu g\ g^{-1}$.[33]

1.4.6 Flavonoids

Flavonoids are polyphenols with great antioxidant properties and various medical benefits, and are generally found in the bran layer and germ.[1] They are one of the plant secondary metabolites that exhibit antioxidant, anti-inflammatory, anti-mutagenic, and anti-carcinogenic properties, along with the capacity to modulate key cellular enzyme functions. The general structure of flavonoids comprises a 15-carbon skeleton, made up of two phenyl rings A and B and a heterocyclic ring C. Six significant subtypes of flavonoids can be differentiated, although they have an overall structure of C6–C3–C6 carbon skeleton.[34] Depending on the structural distinctions, classification is made into different sub-groups such as flavones, isoflavones, anthocyanidins, chalcones, *etc.* Some of the flavonoids observed in wheat are tricin, quercetin, vitexin, kaempferol, *etc.*[17] Black wheat has been reported to have 174 flavonoids,[28] with the highest total flavonoid content (TFC) of 876 μg g^{-1} dry weight, whereas other wheat's TFC ranges from 694–841.81 μg g^{-1} dry weight.[35] The highest mean flavonoid content of black wheat may be a consequence of various flavonoids such as luteolin and its derivatives, anthocyanins, tricin, apigenin. Tricin derivatives, such as *O*-glucuronic acid with antioxidant properties have been reported to be concentrated in the bran and hull of certain types of black wheat.[17]

1.4.7 Anthocyanins

Anthocyanins are a part of the flavanol subclass of flavonoids and are present in the outermost layers of the wheat kernel. They play a pivotal role in the grain's color development.[17] These pigments are localized in specific kernel sections, which can be extracted to form anthocyanin-rich portions that can serve as either colorants or ingredients in functional foods[31].[28] After quantification of different types of wheat for 14 anthocyanins, black wheat was observed to contain 13 out of the 14 types of the anthocyanins in higher concentration when compared to other wheat varieties. In purple wheat, cyanidin 3-*O*-glucoside and peonidin 3-*O*-glucoside form the anthocyanin fraction and delphinidin 3-*O*-rutinoside and delphinidin 3-*O*-glucoside have been found in blue wheat.[36] The anthocyanin concentration has been found to be highest in black wheat, followed by purple, blue, red, and conventional yellow wheat.[28]

Generally, wheat with pigmented grain contains six anthocyanidins: cyanidin, delphinidin, malvidin, pelargonidin, peonidin, and petunidin. Cyanidin has been noticed to be effective against cardiovascular and liver diseases. It has improved metabolic systems and spatial memory and protected DNA cleavage, inhibition of invasion and mortality of tumor cells. Delphinidin is anti-inflammatory with bone protective and neuroprotective effects. It has an inhibitory effect on platelet activation, thrombosis and human glyoxalase. Malvidin is known to have anti-cancerous and anti-inflammatory activities in endothelial cells. It is known to be cytotoxic to human leukaemia cells and acts as an antioxidant. Pelargonidin is efficient in treating cancer and vascular diseases and has proven to prevent neuro-degenerative disorders. Peonidin has shown to prevent vascular and cardiac disorders and inhibit tumor cell growth with apoptotic effects on human breast cancer cells. Petunidin protects against liver cancer and reduces bone loss.[1]

1.4.8 Carotenoids

Plant pigments that give most fruits and vegetables their color are called fat-soluble carotenoids. Structurally, these compounds are 40-carbon isoprenoids having long conjugated polyene chains. Carotenoids are present in plant photosynthetic tissues, chromoplasts and chloroplasts. The biological activity of carotenoids is said to be affected by temperature and light. In cereals, the germ, bran, and endosperm contain carotenoids. The genotype of the cereal decides whether the carotenoid is present in an esterified or free form. The concentration of carotenoid is a determining factor for the color of wheat products and is used for analysing the quality of durum wheat. Some of the carotenoids in wheat such as alfa-carotene, beta-carotene, gamma carotene, and beta-cryptoxanthin, are converted to retinol, while lutein, lycopene, and zeaxanthin are functionally antioxidants. Other types of carotenoids that might be present in wheat are β-apocarotenal, triticoxanthin, lutein-5, 6-epoxide (taraxanthin), flavoxanthin, and antheraxanthin. Lutein is the most predominant carotenoid, followed by zeaxanthin, antheraxanthin, α-carotene, and β-carotene, with β-cryptoxanthin being a minor carotenoid, which is at the level of being non-detectable. In comparison, wheat flour during storage undergoes oxidation from either enzymatic or non-enzymatic mechanisms and causes carotenoid content to diminish.[17] Black wheat has been reported to show higher average total carotenoid content than red and white wheat varieties.[37] The carotenoid content of black wheat is at levels equivalent to those seen in ordinary wheat and other pigmented wheat such as blue, red, and purple varieties of wheat.[17]

1.4.9 Tocols

Tocols, commonly known as vitamin E (tocopherols and tocotrienols) are monophenols derived from 6-hydroxy-2-methyl-2-phytylchroman, which are used as food additives in the food and pharmaceutical sectors.[38] Tocopherol and tocotrienols are composed of a chromanol ring connected with a phytyl side chain. An unsaturated phytyl side chain distinguishes tocotrienols from tocopherols, which contains three double bonds. Based on the quantity and locations of methyl groups on the chromanol ring, tocopherols and tocotrienol has four isomers. Out of the isomers, α-tocopherol has long been known to be the most biologically active form of vitamin E when it comes to prevention of cell membrane oxidation.[25] Blue and purple-grained spring wheat varieties have an average tocol content of 32.68 mg kg^{-1} dry weight and 30.33 mg kg^{-1} dry weight, respectively. This was equivalent to the tocol levels of white-grained Novosibirskaya 67 spring wheat variety, *i.e.*, 32.00 mg kg^{-1} dry weight and red-grained Bohemia winter wheat variety, *i.e.*, 31.01 mg kg^{-1} dry weight.[5]

1.4.10 Vitamins

In comparison with standard wheat, most pigmented wheat varieties have been shown to have more levels of vitamin B (thiamine, riboflavin, niacin, pyridoxine, folate) and vitamin E (tocopherol/tocotrienol). Apart from this, minor amounts of β-carotene (precursor of vitamin A), vitamin D and vitamin K are also present.[39] Black wheat is an especially rich source of vitamin K. Black wheat has been reported to contain 19 vitamins; significantly, it contains 11.47 mg kg^{-1} of vitamin K in BGW 76 variety, which was 1.6 times greater than the vitamin K content of conventional wheat (Jinchun 9).[31] In black wheat, significant amounts of B3, B5, and E have been found.[9] All of these vitamins have a considerable impact on various bodily functions, which often overlap with each other. Vitamin B3 is concerned with the maintenance of healthy skin, DNA synthesis and energy metabolism. Vitamin E most significantly is concerned with prevention of haemolysis. The development of blood cells, hormone release, gland function, and food conversion to energy are linked to vitamin B5.[17] In terms of vitamin content, purple wheat varieties such as ZY17-1 and ZY22 outperform other wheats. More amounts of α-vitamin E, β + γ -vitamin E and total vitamin E compared with standard values were found in purple wheat.[26]

1.4.11 Methyl Donor

Principal methyl donors are betaine and choline, with wheat being the most abundant source of betaine.[40] Folate and B12 are members of the methyl-donor vitamin family, including choline and betaine. Methyl donors get their name from their role in single-carbon metabolism, which involves transferring methyl groups from amino acids like serine, glycine, and choline to a range of other substances like proteins, RNA, DNA, and intermediate metabolites.[41] Compounds like betaine, choline, dimethylglycine, and trigonelline have the ability to donate a methyl group to another molecule. Whole-wheat products contain increased concentrations of choline and betaine. Choline is required as a precursor of membrane phospholipids and acetylcholine, a neurotransmitter and through betaine. It also involved in donating methyl group to *S*-adenosylmethionine. Methyl donors, which are present as an interchangeable compound in wheat kernels, are present in much higher concentration in whole-wheat flour than refined flour.[42] In an animal model study, during the periods of gestation and early postnatal development, high choline intake showed improved cognitive function in adulthood and prevention of age-linked decline of memory and protection from neuropathological changes connected with Alzheimer's disease, *etc.*[43]

1.4.12 Anti-nutritional Factors

A major aim in nutrition is to diminish anti-nutritional factors, as they have been found to contribute towards micronutrient and mineral inadequacies, which negatively influences the nutritional properties that many cereals and legumes may otherwise offer. Anti-nutritional factors have been found to unfavourably affect the bioavailability of many nutrients.[44] Anti-nutrient factors found in wheat are tannins 1.43–1.84 mg g^{-1} dry basis (db), and phytic acid 7.95–8.00 mg g^{-1} db.[45] Phytic acid chelates with metal ions and decreases the availability of minerals, such as zinc.[44] Mineral bioavailability may also be affected by the elevated amounts of polyphenols.[46] In wheat that is a monocotyledon crop, the phytates present in the bran or aleurone layer can be removed through milling. Soaking the grains has also been an effective way to diminish anti-nutrient phytochemicals, such as phytate and tannins. Consumption of wheat after a period of soaking is recommended to ensure less impact of anti-nutrients.[44] Removal of phytate and other anti-nutritional factors in cereals is done during germination. Wheat flour that has been germinated and fermented shows decreased amounts of anti-nutrients.[46] A vital aim of many wheat-breeding programs to improve grain quality is the reduction of such anti-nutritional compounds. The current outlook on a balanced diet that promotes health, growth, and development comprises a diet that will supply sufficient calories, micronutrients, proteins, and low anti-nutritional constituents.[47]

1.5 Health Benefits of Pigmented Wheat

Pigmented wheat contains numerous phytochemicals, including various medical and health benefits like obesity, cardiovascular diseases, type 2 diabetes, cancer, *etc.* (see Figure 1.2).

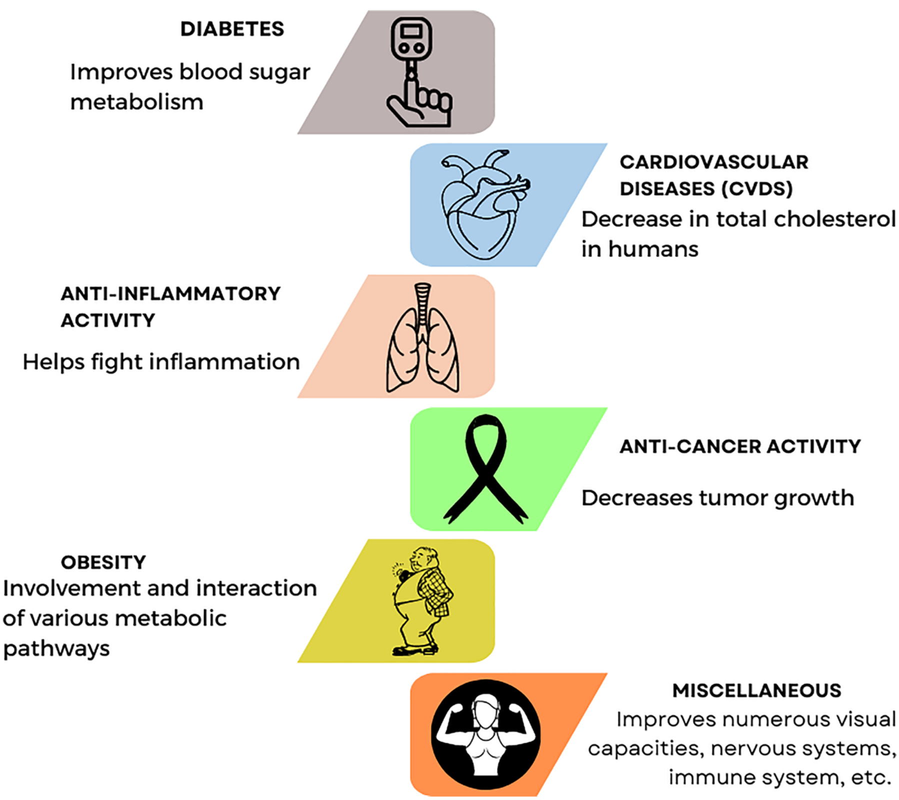

Figure 1.2 Health benefits of pigmented wheat.

1.5.1 Diabetes

Diabetes is a chronic disease that occurs when the pancreas does not produce enough insulin or when the body cannot effectively use the insulin it produces. Hyperglycemia, or raised blood sugar, is a common form of diabetes and may seriously damage the body's various systems, especially the nerves and blood vessels. In studies, the extended intake of wholewheat was associated with a decreased risk and mortality from type 2 diabetes.[1] According to findings from Tyl and Bunzel,[48] blue wheat has been found to possess properties that decrease amylase-catalyzed starch absorption related to postprandial blood glucose levels, and is effective in curbing diabetes. The presence of high anthocyanin content in black wheat improves cholesterol levels and blood sugar metabolism in diabetic patients.[23] Compounds such as phenolic acids, tocopherol, and carotenoids are present in significant quantities across pigmented wheat varieties, which offer anti-diabetic effects. α-Tocopherol and β-carotene rich meals are also linked with decreased risk of type 2 diabetes and are consumed on a large scale by health-conscious people. Moreover, studies on rodents have shown that the presence of phenolic acids like gallic acid, syringic acid, ferulic acid, caffeic acid, and sinapic acid exhibit anti-diabetic properties.[1]

1.5.2 Cardiovascular Diseases (CVDs)

Cardiovascular diseases are a group of heart and blood vessels disorders, which should be treated as early as possible. Globally, these also are the leading cause of death. The major causes that lead to CVDs are tobacco use, unhealthy diets, obesity, physical inactivity, and excessive use of alcohol. Some of the CVDs are heart attack, coronary artery disease (*i.e.* narrowing of the arteries), heart muscle disease (cardiomyopathy), heart failure, congenital heart disease, abnormal heart rhythms, or arrhythmias, aorta disease and manfan syndrome.

Pigmented wheat contains a significant quantity of anthocyanin and carotenoids that are principally situated in the external aleurone layers. There is considerable proof that if wholegrain-based breakfast in the form of cereal is consumed for three weeks, then there is a significant decrease in total serum cholesterol up to 21.4%.[49] Whole bran of pigmented wheat contains arabinoxylan, which can be utilized to bring down the plasma, LDL-C fixations levels and total cholesterol.[50] In a study, after a mean 12-year follow up, people who consumed larger amounts of flavonoids have been proven to have lower risk of CVDs and reduced risk of any non-fatal cardiovascular events.[51] Phenolic compounds present in pigmented wheat have also been shown to suppress doxorubicin-induced cardiotoxicity due to inhibition of oxidative stress in the myocardial cells of rodent.[17]

1.5.3 Anti-inflammatory Activity

Anti-inflammation action is much displayed by flavonoids as their significant properties. Proanthocyanidins, anthocyanin, γ-oryzanol, and other bioactive mixtures have similarly been connected to anti-inflammatory activities. It has been reported that pigmented concentrates of wheat are quite convincing in reducing irritation, oxidative tension, and atherosclerotic wounds or injuries. In addition, the advancement of weight-related insulin barriers is mostly caused by inflammatory aggravations. Utilizing whole-wheat-based bread and fibre could chop down fundamental exacerbation among diabetic women as per clinical experts. Entire wheat grain usage can increase liver and inflammatory resilience in overweight and obese subjects with raised plasma cholesterol. The significant content of anthocyanin in black wheat varieties functionally acts as a safe-guard from lifestyle diseases.[1] Total anthocyanin content of wheat flour ranges from 6.61–95.04 mg kg^{-1} and follows in the order black > blue > purple > white. All colored wheat varieties had significantly higher TAC content, which helps to fight with inflammatory diseases.[52] Some bioactive compounds like proanthocyanins, anthocyanin, gamma-oryzanol *etc.*, are also beneficial for anti-inflammatory activities. Pigmented portions of wheat that offer antioxidant properties indicate a decrease in inflammation and oxidative pressure.[53] Wholewheat grain utilization can also improve liver and inflammatory resilience in overweight and fat subjects with raised plasma cholesterol.[54]

1.5.4 Anti-cancer Activity

Cancer is a disease in which some of the body's cells grow uncontrollably and spread to other parts of the body. Cancer can start almost anywhere in the human body, which is made up of trillions of cells. Usually, human cells grow and multiply (through a process called cell division) to form new cells as the body needs them. When cells grow old or become damaged, they die and new cells take their place. Sometimes this orderly process breaks down, and abnormal or damaged cells grow and multiply when they should not. These cells may form tumors, which are lumps of tissue. Moreover, cancer is one of the most common causes of death all around the globe.

The presence of naturally dynamic phytochemicals substantiate the role of pigmented wheat grain in probable prevention of breast cancer, colon cancer, liver cancer, ovarian cancer, and prostate cancer as upheld by epidemiological investigation of wholegrains.[1] Black wheat has also made an appearance and acts as a better option in the form of food supplements for all those suffering from this disease.[23]

1.5.5 Obesity

A disorder involving excessive body fat increases the risk of health problems. One of the primary casual factors of obesity is chronic intake of energy-dense or high-calorie foods. Obesity may cause insulin resistance, dyslipidemia, and hyperglycemia.[1] Recent studies have indicated that commonly consumed polyphenols and anthocyanin-rich diets suppressed co-morbidities. Whole grains are calorie deficit and give a feeling of satiety, accounting their role in body weight regulation. Many observational studies have shown an inverse linkage between whole grain intake and the risk of obesity.[12] The presence of naturally occurring antioxidants that develop in the grain help in filling the gap and therefore enriches pigmented wheat, especially black wheat with high nutritional value, highlighting its significant health benefits.[23]

1.5.6 Miscellaneous

According to the analysis of Tsuda,[55] an anthocyanin-rich eating regimen helps improve numerous visual capacities, for instance, decreasing eye exhaustion, improving nearsightedness, and upgrading the retinal bloodstream to lessen glaucoma. Black wheat is the solution to all the problems related to eyes among adults. Further, it was stated that it helps in the normal function of the cerebrums by decreasing age-related neurodegeneration and psychological decay. Black wheat contains anthocyanins and antioxidants than regular wheat, which controls antibodies and free radicals in our bodies that also boosts our immunity. Black wheat can also help in diminishing malnutrition.[23] Purple wheat containing anthocyanins have also been investigated for their antioxidant and anti-aging potential on *Caenorhabditis elegans* nematode experimental model.[56] Extracted anthocyanins from purple wheat were able to extend the life span of wild and oxidative stress mutants because of the ability to reduce oxidative stress.[12] Black wheat also significantly reduces fat pad and restricts body weight gain.[23] Pigmented wheat and its varieties contain diverse combinations of phytochemicals and are the main components known to impart protective and beneficiary effects to human body.[1]

1.6 Consumer Perceptions of Pigmented Wheat

Conventional wheat provides a sufficient amount of nutritional content to the consumer but nowadays, consumers are more concerned about their health and thus are looking for more nutrient-rich sources rather than only energy-giving foods. Pigmented wheat is getting more and more popular due to its amazing health benefits. Although pigmented wheat is produced in lesser yields than conventional wheat, it under higher demands for various purposes in the food industry.[4] There are many health claims for foods having sufficient dietary fibres in developed countries, and actually, it benefits humans for various health reasons. Pigmented wheat rich in dietary fibres help in lowering serum cholesterol level, insulin response and postprandial blood glucose.[17] Purple wheat noodles provide three-times more antioxidants than red grapes, and helps in lowering blood pressure and cholesterol, improving eyesight and prevent liver disease.[57] In bread wheat, commonly, white and red wheat are used, but purple and blue colored wheat is rare.[31] In terms of consumption-related traits, pigmented wheat does not contain any bitter compounds and enhances grain palatability for humans. Through the means of human sensory panels or highly reproducible, robust, and sensitive model systems or other "consumption" trials the consumption preference between or acceptance of pigmented wheat and conventional wheat varieties can be determined.[17] Currently, blue and purple corn are used for production of naturally colored blue tortillas.[58] In research studies, biscuit-making trials were performed from wholemeal flour and purple wheat flour; analysis was conducted on the basis of quality of characteristics purple flour consist of higher gluten index than that conventional flour. Higher TAC levels in purple wheat were detected, whereas in conventional wheat, no TAC level was observed, but somehow anthocyanin reduction was also observed. TPC level were slightly higher in purple than conventional wheat but on the other hand TYP level were less rich in purple than conventional wholemeal flour.[36] Some of the drawbacks were that TPC (Total phenolic compounds) present in flour gets degraded during dough mixing; this shows that flour contains higher antioxidant compounds compared with noodles and bread.[59] Blue wheat released in Australia has 25% less yield than the check cultivators.[15] Regular wheat has a 5 ppm concentration of anthocyanin, whereas black wheat grain is observed to have approximately 100–200 ppm of anthocyanin.[17] This attracts the consumer towards it usage, as it is a wiser and a healthier option. Black wheat is also more digestible than conventional wheat and poses many other health benefits; knowing about all these factors nowadays is attracting consumers.

1.7 Product Development From Pigmented Wheat

Pigmented wheat grains have varied processing qualities depending on their color, whether they are red, purple, or black, and the pigments (carotene, xanthophylls, anthocyanin, and phenolic compounds) contained in their seed coat.[17] Different structural compositions of pigmented wheat are given in Figure 1.1. Pigmented wheat has increased nutritional benefits, higher antioxidant activity and similar processing characteristics to regular wheat; it may be marketed to manufacture a variety of functional meals. Flours, breads, noodles, and pasta have been successfully formulated using pigmented wheat varieties. However, to overcome any shortcomings and to retain its original palatability, it is necessary to adopt effective processing technology for biologically active wheat cultivars.[16] The process parameters and circumstances must be optimized before they can be used in a commercial application.[3] The highest crude protein content has been found in flour produced from black grained wheat compared with flours produced from bread wheats. The protein and dough quality of purple and blue wheat has to be assessed prior to their utilization in bread making. Investigating the chemical changes occurring in bioactive compounds such as phenolic acids and anthocyanins during baking is vital.[31] Compared with known varieties used in bread-making such as Glenlea, black wheat has a higher crude protein content but similar HMW-glutenin subunits to those of Glenlea, black wheat can potentially be utilized in making bread. The antioxidant properties of purple wheat has been found to be the greatest, followed by the antioxidant property of whole grain bread and white bread.[31] However, before the production of bread, it is vital to determine the quality of wheat flour, as bread is the most common staple food, consumed globally.[16] Biscuits are consumed daily and are popular snack choices across countries. As one of the bakery items with a long shelf life, biscuits can be transformed by the addition of functional ingredients that are beneficial to health. Wholemeal flour made from purple wheat has been used to create biscuits, in which, although the anthocyanin profile decreased post-processing, it was similar to the values found in the assessment of wholemeal flour made from purple wheat (which is higher than conventional wheat). Structural differences due to higher gluten strength do act as a deterrent towards its popularity, but the creation of healthy products offering antioxidant properties is possible through purple wheat.[36] Indian unleavened flatbread has also been prepared using blue, purple and black wheat in which blue wheat had low dough extensibility, though the high nutritional content is present in the aleurone (outer pericarp) layer. Purple and black wheat were found to have sensory scores similar to conventional variety and are hard grained hence will form acceptable end products.[60] According to reports, black wheat possesses comparatively good properties and sensory characteristics, with substantial cooking losses and thus, black wheat flour can be used to make noodles. Noodles made from pigmented wheat flour have lower gumminess, hardness and chewiness, irrespective of milling method.[17] Chinese black grained wheat is suitable for noodle production after its combination with strong flours, as the gluten content present is heat-stable. The gluten content can be improved by breeding.[61] To achieve better health results, whole-wheat flour and partially debranned grain flour of black wheat can also be used for human consumption. There is a need for research to test the acceptability of noodles from pigmented wheat. Other products can also be developed, such as vinegar, breakfast cereals, muffin (including bran), antho-beer, soy sauce, and food colors using pigmented wheat. The use of bran fractions of pigmented wheat flour along with other cereal flours can improve the nutritional content with the formulation of various functional foods, but further studies are still required to understand consumer acceptance regarding palatability and the acceptability.[16]

1.7.1 Roasting of Pigmented Wheat Flour

When it comes to product development, we see continuous attempts to increase the efficacy of pigmented wheat processing lines. In order to do this, it becomes vital to study the properties and changes occurring in them by different processing methods. In a study conducted to examine the impact of roasting of pigmented wheat by three methods – sand roasting, pan roasting, and microwave roasting – significant variations in the functional properties, color and pasting properties were observed in the case of microwave roasting. Roasting affects the antioxidant content significantly and hence unroasted grains would be preferred over roasted grains when it comes to this aspect. To summarize a few of the findings, sand roasting has exhibited greatest reduction in total phenol content for black and yellow (conventional) wheat and greatest reduction in total phenol content for purple wheat was exhibited by microwave roasting. The lowest impact on total phenol content for yellow and purple wheat was seen in the case of pan roasting and microwave roasting for black wheat. Post-roasting, emulsifying capacity was also altered, and a reduction in the emulsifying capacity of black wheat (2–5.9%), purple wheat (4.52–6.86%), and conventional yellow wheat was observed (3.2–7.38%). Microwave roasting showed the most significant reduction, and sand roasting method the lowest reduction in the emulsifying capacity. The density of all flours was reduced considerably – lowest in the case of sand roasting and highest in case of microwave roasting – by all methods of roasting, due to moisture removal and void space creation in the cellular matrix or loss of integrity of the matrix. Percentage reduction in density for yellow wheat was 17.19–21.66%, purple wheat was 2.9–3.4%, and black wheat was 1.8–2.9%. Amylose content was boosted and amylopectin content saw a decline post roasting. The outlook for the future of pigmented wheat processing is the optimization of roasting such that we can retain the nutritive value of the pigmented wheat flour.[17]

1.8 Future Prospects

It has been proved that pigmented wheat is more nutritious than conventional wheat. The quantity and quality of proteins, minerals, dietary fibres, phytochemicals, and other bioactive compounds in pigmented wheats is far better than in conventional wheat varieties.[1] Although pigments have many beneficial features, their availability to most people is limited due to the low yield and high cost. Both farmers and researchers are trying to discover innovations as their consumption is not widely promoted.[17] Colored wheat is one of the underutilized crop due to its content, composition, dynamics, genotypic variation, and the products developed from it.[62] It is known that pigments can be more easily absorbed from cereals than any other food group.[21] In addition, colored grains can be easily stored and have a comparatively longer shelf life due to the stability in processed food products. So, it is necessary to consume in moderation and thus, the transfer of rich color pigmentation in wheat germplasm is done using breeding techniques in the hope of secured color, good yield, and some horticulture characters. Further studies are still required to analyze various activities related to the compounds from pigmented wheat.

As pigmented wheat contains higher concentrations of pigments and other nutrients, so the nutritional and health benefits can be easily acquired if added into different products.[22] However, it is necessary to find new processing technology that can keep the original attributes of pigments. This is because the conventional method damages them. Thus, the pearling process is encouraged but scientists still looking for more yield and better performance expecting to have in further generations, as it is known that different pigments have different processing technologies because of the different genetic backgrounds, and thus the results clash with each other.[8]

Further, significant progress has been noticed regarding identifying the gene responsible for the colored varieties. Most likely, RNA sequencing and SNP mapping will help identify and map the colored traits in the wheat kernel quickly.[22] It has been suggested that combining pigmented wheat with biofortification breeding could also play an important role in supplying additional nutrients left by it to form a complete diet in one food.[26] Even though the functional properties are limited, with the help of nutrient-controlling genes, modern breeding technologies, and genetic engineering, studies are continuously conducted to complete the demand for profit-oriented food products, providing promising tests for analysis.[17]

Farmers have an inadequate number of seeds, limited knowledge, and are unaware of the right processing methods, and are thus unable to facilitate the supply and demand of these pigmented varieties. Hence, their production cost is high, while the yield is low and that's the reason the general public cannot meet the expenses despite numerous advantages when compared with the regular ones.[18] At the same time, many people are unaware of how much nutrition these varieties contain. It is a great supplement to malnutrition as it is abundant in zinc, iron, manganese, copper, selenium, magnesium, potassium, phosphorous, and many amino acids (specifically black wheat)[26] but, ironically, poor people are unable to afford them as it costs twice, thrice, or more than the common varieties depending on the country. Thus, it is necessary to popularize these products with better research work into achieving a higher yield and the formation of better-performing products. There is also an expectation that the government will try to include pigmented wheat as a supplement in the mid-day meals by procuring it at a higher minimum support price (MSP).[18]

Colored wheat has attracted the attention of many, but the low yield is becoming the dragging point; hence, it is essential to provide a satisfactory yield along with the regional adaptation to the world.[29] Investigations are required to check the insects, pests, and disease resistance and the flexibility with the environment and the consumers. This is because the pigments degrade with heat (thermal processing techniques affect the anthocyanins content and thus the thermal stability of anthocyanins in foods is limited), change in pH, and several other environmental and chemical factors, which is a major challenge of applications of pigmented wheat in the food industry.[22] The research regarding these provides an expectation for the food industry to use colored wheat grains to develop better wheat and wheat-based products, enhancing their nutritive values.[1] Studies are still done as they can formulate into highly nutritive foods. These crops have huge sell prospects because of the potential for product development aside from the beneficial properties.[63]

1.9 Conclusions

Pigmented wheat is usually a rich source of pigments and bioactive compounds with better nutritional and functional properties. The health benefits of colored wheats are known because of their richness in dietary fibres, carbohydrates, proteins, phytochemicals, and other micronutrients present in the outer layer, compared with white ones. However, these characteristics mainly depend on the genotypes, crop processing method, storage conditions, and environment. It acts as a food and medicine because it reduces the risk of chronic diseases. It shows that colored wheat, in all senses and purposes, is a much better food source than the normal ones. Colored wheat is much healthier, as it increases the nutritional content, such as the developed products' anthocyanin content, than white one. A careful selection of appropriate fractionation processes is required, as most of the potent nutrients are present in the bran and germ layer. Thus, it depends on the processing method for the quality of the flour and the products developed from it. Although the pearling process is preferred over that of the roller-milling process for retaining the anthocyanins in the refined flour, further investigation is still needed. Pigmented wheat contains several nutrients and micronutrients and thus has the potential to tackle the issue of malnutrition persisting in the world. It can also benefit farmers by providing higher prices for higher yields, rather than giving higher production costs. So, there is a need to properly develop and utilize pigmented wheat and its products. Pigmented wheat has huge market potential and provides many additional features needed for commercial product development, laying the foundation for industrial use. However, research would be necessary to build out the supply chains, small- and large-scale tests could be modeled to evaluate the potential applications of pigmented wheat and whether it would compete with the normal varieties in terms of yields, function, and quality performance.

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