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Review article

Barriers and levers to enhance end-use functional properties of durum wheat *(Triticum turgidum L.)* grain: An agronomic implication

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ABSTRACT

The current trends in population growth and consumption pattern remain to increase the demand for durum wheat grain. However, multiple biotic and abiotic challenges due to climate change coupled with crop management practices possess major concern to improve durum wheat production and storage proteins. Efforts on developing innovative agronomic and breeding strategies are essential to enhance productivity, and nutritional quality under the changing climate. Nitrogen is an important structural component of protein, and potentially reduce the adverse effect of drought stress through maintaining metabolic activities. Optimum nitrogen fertilization allows durum wheat producing farmers to attain high quality yield, brings economic benefit, and reduces environmental pollution. However, defining an optimum nitrogen fertilizer rate for specific location requires considering yield achievement and quality of the end products. If the producers interest is, geared towards production of high protein content, high nitrogen dose is required. If the interest gears towards grain yield improvement optimization of nitrogen fertilizer rate is important. This indicates that defining product-specific nitrogen application is required for sustainable durum wheat production. Therefore, future challenges of increasing production, productivity, and end-use functional properties of durum wheat will only be achieved through cooperation of multidisciplinary teams who are able to incorporate new technologies.

1. Introduction

Durum wheat ($2n = 28$, AABB, *Triticum turgidum var. durum*) is a commonly cultivated form of allotetraploid wheat, and it contributes to 5% of the world wheat (*Triticum* spp.) production [1]. Its grain is mainly used as industrial raw material to produce pasta, couscous, and bread worldwide. However, the technological properties, and commercial value of the grain is principally determined by the quantity and quality of storage grain proteins [2, 3]. In recent years, the grain protein content of durum wheat received great market attention due to protein premium price paid for durum wheat producing farmers, mainly above 13% that will give about 12% of the protein in the milled semolina [4, 5]. This indicates that lower grain protein content can cause a significant economic loss to durum wheat farmers, as protein content is a decisive quality factor in the market. As far as quality is concerned, all-grain quality appraisals begin with the characteristics of the raw materials, such as acceptable protein content, composition and aggregation levels, grain hardness, and yellow color, which directly affects the dough and other functional properties of the end products.

Improving durum wheat commercial quality traits have become a worldwide principal research area, due to the increase in market demand for acceptable grain quality traits. This aim, however; hampered mainly by the influence of crop agronomic management practices, crop genetic variation, G × E interactions, and intricate divergence in growing environments [6]. Increasing in grain protein content under moisture stress area has been frequently reported [6, 7, 8], probably due to enhanced grain nitrogen accumulation and decreased carbohydrates concentration. Because, under moisture stress conditions, grain starch deposition is decreased and exerts positive influences on protein concentration, as it allows more nitrogen per unit of starch [9]. Furthermore, the daily flow of carbon and nitrogen into the grain increases with increasing temperature and decreases carbon flow per degree-day [10]. However, under sufficient moisture conditions, the grain protein content decreased through dilution of nitrogen with carbohydrates [11]. Therefore,

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agronomic-based intervention is needed to satisfy the current market demand for durum wheat grain.

Tremendous efforts have been made to reduce the negative effect of biotic and abiotic factors, with the primary aim of improving grain yield, and grain storage proteins. The agro-technical measures such as combined application of fertilizers, application of micronutrient containing fertilizers, nitrogen management, and improved crop nutrient use efficiency are widely accepted strategies to improve yield and protein content in wheat [6, 12]. These interventions are also an immediate and effective route to enhance storage protein concentration and associated traits in durum wheat. However, still, there is a need for other intervention as the aforementioned strategies are strongly influenced by varietal difference, habitat conditions, cultivation system, agro-technical measures [6, 13, 14], and negative association between yield and protein content [15]. An increment in grain protein content may mainly come from either improved nitrogen use efficiency of the varieties to accumulate more nitrogen or through the application of high nitrogen dose [12, 16].

A linear increment in grain protein content was observed under high dose of nitrogen application, however, grain yield response to the added high nitrogen rate had shown a diminishing return association [17]. Additionally, the use of nitrogen fertilizer at a higher rate increase the risk of lodging [18], and increase susceptibility of the crop to foliar diseases [19]. In compression with other extraneous factors, the composition of protein fractions is much more affected by nitrogen fertilization and its management [20]. High protein content in the harvested grain could be an indication of whether the crops received adequate amount of nitrogen during the growing period. However, the use of nutrient inefficient varieties will increase the likelihood of soil acidification, if the added nitrogen is not fully up taken by the plant, which in turn costs the farmer to restore the soil pH [12]. Hence, cultivation of durum wheat with acceptable grain protein begins selection of suitable varieties followed by agronomic practices that can increase nitrogen availability at the latter stage.

Knowing the negative relationship existing between grain yield, grain protein content, as well as nitrogen fertilization with biotic and abiotic factors is therefore very important in durum wheat production. Recent advances in our understanding of barriers and strategies to improve end-use functional properties of durum wheat warrant a proper scientific evaluation of nutrient supply, and its impact on grain yield, grain quality, plant growth, and resistance to drought stresses, and other extreme events. Our analysis, therefore, explores durum wheat productivity and nutrient supply, with a universal aim to identify the major production bottlenecks, and agronomic pathways that can enhance grain yield, grain qualitative traits, and a sustainable pattern for the durum wheat cropping system following three key principles such as delivering high quantity yields, acceptable caryopsis quality and the essence of natural environmental health. We provide a thorough analysis of the current state of knowledge and reviews of selected refereed scientific publications related to the capacity of agronomic strategies for optimizing grain yield and caryopsis quality along with genotype, environment, and crop management (G × E × M) interactions.

1.1. Worlds durum wheat production and statistics

Although durum wheat represents 5% of the world wheat production with an annual average volume of 40 million tonnes, it is an economically important "*Triticum*" species due to its unique grain characteristics [21]. Its high protein content and hard grain structure make durum wheat grain suitable and being used for special purposes in pasta and macaroni manufacturers [22]. However, despite its importance, the world durum wheat production is not much higher or proportional to the common wheat. For instance, in the 2020 cropping season, the durum wheat grain represents 5% of the whole wheat production with a cultivated area of 16 million hectares [1]. Additionally, the production volume and cultivated areas are greatly varied from region to region. For instance, Italy (4.95 mt), North America, South America, Asia, Africa, Oceania, and Turkey (3.62 MT) are reported as the main producer of durum wheat grain [1]. Moreover, the EU member countries are also the largest producer of durum wheat grain. Maximum volumes of durum wheat grain are produced in Italy with an average production volume of 4.26 million tonnes in the last decade (1.28 million ha growing area), followed by France with 1.89 million tonnes (0.37 million ha), Greece with 1.07 million tonnes (0.37 million ha) and Spain with 0.98 million tonnes (0.38 million ha) [23].

In the eastern Africa, Ethiopia is the largest producer of durum wheat [24] with approximately 0.6 million ha [25]. However, despite being abundant in genetic diversity for durum wheat [26, 27, 28], the national average wheat production (1.8 t ha^{-1}) is lagged behind the world average wheat production [29]. In addition to its local use, durum wheat grain also plays a significant role as an industrial raw material in making different food staffs such as pasta, macaroni, biscuit, and other end-use products. Over the past decades, the demand for pasta and macaroni has been raised due to the proliferation of population growth, changes in food habit, and expansion of food industries [30]. However, insufficient rheological grain characteristics, and limited production volume complies the food manufacturing sectors to import the required material, although Ethiopia is a center of genetic diversity for durum wheat [30]. Hence, the net annual imported pasta has been estimated about 50,000 t at the cost of approximately €40 million, which in turn influences the country hard currency reserve [31]. This huge gap between demand and supply of durum wheat grain universally justifies a question as to where and by what volume durum wheat production could be improved to satisfy the future durum wheat market in the Ethiopia. Hence, the provision of specific incentives as well as trainings on nutrient management and associated agronomic packages could be important to ensure industrial standard quality durum wheat grain.

1.2. Rheological and functional properties of durum wheat grain

Grain Hardness: Grain hardness is determined by the packing of grain components in the endosperm cells. It is often referred to as the resistance of the grain to an applied fracturing force or to the energy required to reduce the grain sample into fine particles (i.e. semolina, refined flour). In comparison with other wheat spp., durum wheat has a harder endosperm than hard-grained common wheat. This character is mostly associated with the milling properties of wheat [32, 33], water absorption capacity of the semolina, and the baking quality of the resulting dough. The grain hardness is a result of adhesion between starch granules and storage proteins [34].

Storage proteins: In contrast to bread wheat (*Triticum aestivum*), durum wheat (*Triticum turgidum*) is characterized by higher content of grain storage proteins, extreme grain hardness, intense yellow color, high virtuousness milling qualities that are suitable for making pasta, and having good cooking qualities [35]. In durum wheat, grain protein content above 13% (11% moisture basis) that maintains about 12% protein in the milled semolina is important to maintain a good texture in the cooked pasta [36]. It has been observed that dry pasta made from high-protein semolina (<12%) is observed physically stronger and more elastic than pasta made from lower protein semolina [36, 37]. High grain protein composition allows the produce food product to swell when it is cooked, reduces cooking loss, and allows retention of firmness with overcooking and less stickiness [22, 36]. In the bread baking industry wheat flour with high protein content is desired, as loaf volume potential, water absorption, and loaves keeping quality increase with increased storage protein content [38, 39].

Gluten quality and strength: A semolina from extra strong durum grain is thought to produce firmer pasta [36]. In the absence of gluten, a significant effect on both dough rheology and the quality of the final product was observed [40]. Gluten-free dough is characterized by poor cohesiveness and elasticity compared with high gluten wheat dough [41]. Additionally, poor texture, color, and lower specific volume bread was observed at poor gluten semolina [40]. When wheat flour is kneaded with water, gluten proteins enable the formation of cohesive viscoelastic dough that can hold the gases that are produced during proofing, resulting in high-quality, and structured products. The gluten content is mostly found as a remainder of wheat flour after removing the constituents such as non-starchy polysaccharides, starch, and water soluble, consisting of alcohol-insoluble glutenins and alcohol-soluble gliadins [42]. This seems that bread making and the quality of bakery products strongly depend on both the quantity and quality of storage gluten [41].

Semolina yield: Milling industries are principally concerned with the milling yield or percentage of the grain converted to semolina of acceptable purity with minimal flour production, as semolina commands a higher price [36]. High mill extraction rates produce semolina with higher ash (0.9–1.1% dry weight basis) due to contamination with the bran and this reduces semolina's brightness and yellowness [36]. However, when durum wheat is grown in low nitrogen environments, a decrease in kernel protein content, an increase in starchiness, and a decrease in semolina yield were observed. The reduction in semolina yield is possibly related to how quickly the starchy kernels were reduced to fine flour particles [37].

2. Methodology

Several procedures were followed to ensure a high quality review of the literature. First, a comprehensive search of peer reviewed journal articles was completed based on a wide range of key terms. The selected search key terms consisted of durum wheat grain protein content gluten strength, and semolina in combination with the terms drought, nitrogen, and other agronomic based crop management practices including seeding rate, planting date, cropping sequences, break-crops and intercropping. These articles were then screened for relevancy and included in the review when they fulfilled the following three criteria (a) the full text was accessible online, (b) written in English, and most importantly, (c) have primary data on the aforementioned stated terms generated by either quantitative or qualitative research methods. Three data search engines such as, Google® Scholar, PubMed and Scopus, were used one after the other, to generate the published articles around the subject matter for this review. Most of the search results were downloaded through the University license (subscription).

3. Barriers to improve the end-use functional properties of durum wheat grain

3.1. Genetic landscape: a novel sources of variation in grain protein content

Grain protein fractions are quantitative traits mainly controlled by a complex genetic system, agro-technical measures, and environmental factors. Wheat grain has two fundamental storage protein fractions such as gliadins and glutenins. The viscosity of the dough is determined by the gliadin proteins and the glutenin proteins which are mostly responsible for the elasticity of the dough [43]. These are the main protein markers that influence food products made from wheat flour [44]. However, the quality of baking bread is strongly associated with the presence and absence of any classes of allelic variants of high molecular weight (HMW) glutenin subunits [45]. Based on their ploidy levels, differences in development period and stability, wider variation in grain protein content and composition between wheat varieties was observed [46].

Yielding potential of the genetic material also determined the storage grain protein contents. When biological potential was used to evaluate the allometric relationships of grain quality traits, the varieties that contained better protein content are characterized as low yielding potential, while high yielder varieties are accumulated low grain protein content, perhaps due to dilution effect [6, 8, 12, 47, 48]. Indicating that simultaneous improvement of grain yield and protein content could be challenging due to inverse genetic association [6, 8]. This negative consequence could have occurred, if the primary responsible genes that has been improve the grain quality traits intensely correlated with the genes that have a detrimental effect [49]. Hence, care should be taken when choosing durum wheat varieties to consider both grain protein content and yield.

However, the influence of genetic potential on grain nutritional composition is not consistent throughout the previous results. In contrast, high-yielding varieties were unexpectedly found to have high grain protein content, gluten protein, and high molecular weight to low molecular weight gluten subunits ratios [50]. The authors further suggested that high durum wheat productivity might be combined with good quality traits through a suitable breeding approach [50]. Such contradictory and/or inconsistent results are possibly due to divergence in growing locations, varietal response and genotype by environmental interaction. This genetic variation on grain protein content is often explained when modern and old durum wheat varieties are compared [51].

3.2. Avoidance of the old durum wheat varieties in the production system and relay on modern varieties

Following in increasing durum wheat breeding program, ancient wheat genotypes had been disappeared from the human diet and old durum wheat varieties were replaced by high yielder modern varieties grown in high-input agricultural systems [52]. Landraces, old cultivars, and modern durum varieties are differing in certain plant based character that have an important effect on grain quality traits. Even though, old durum wheat varieties are characterized by their low yielding potential [53], they can provide maximum protein and gluten content than the modern ones, even under marginal nitrogen supply [46, 54]. This indicated that the old durum wheat varieties and landraces, which have not been involved in the modern breeding program could have wider genetic diversity in both content and composition of storage proteins. Nazco et al. [55], has been confirmed that the landraces have wider genetic variability much higher than the modern varieties in terms of gluten strength. An intermediate set of cultivars characterized by higher grain protein content, and gluten strength may deserve advanced research, aimed at exploring their full genetic variability for potential grain quality traits [56]. These varieties are proved to be an important source of genetic diversity for further researches to identify potential durum varieties most suitable and being used in the production of good pasta, quality bread, and other associated bakery products [57].

3.3. Shift of grain protein composition under drought and high CO_2 concentration

The ever changing climate bears the risk of recurrent drought stress, and increase atmospheric carbon dioxide. Increment in drought stress and atmospheric CO_2 significantly influences the grain protein content and baking quality. The elevated atmospheric CO_2 concentration has been observed to reduce the grain protein content in wheat [58]. This could be due to alteration of chemical compounds under the increasing atmospheric carbon dioxide, especially a decrease in leaf N concentration and increased the C/N ratio in plants [45]. As nitrogen is the main building block of protein, a decrease in plant tissue nitrogen concentration may affect the concentration of protein in the grain also. However, a number of studies stated about climate change effect on grain yield, but the impacts on the grain nutritional value of wheat have received scanty attention even though this is a critical aspect of food-security [59, 60]. The changing climate is estimated to cause wheat yield loss up to 12.5% [61], and grain nutrition up to 5.5%–10.5% depending on drought tolerance level of the varieties [8].

It has been found that a prolonged scarcity of water can increase amount of protein in the grain [62] (Figure 1). They explained that water stress occurred around the grain filling stage, may increase aggregation level of glutenin subunits which has been reflected in amelioration of the

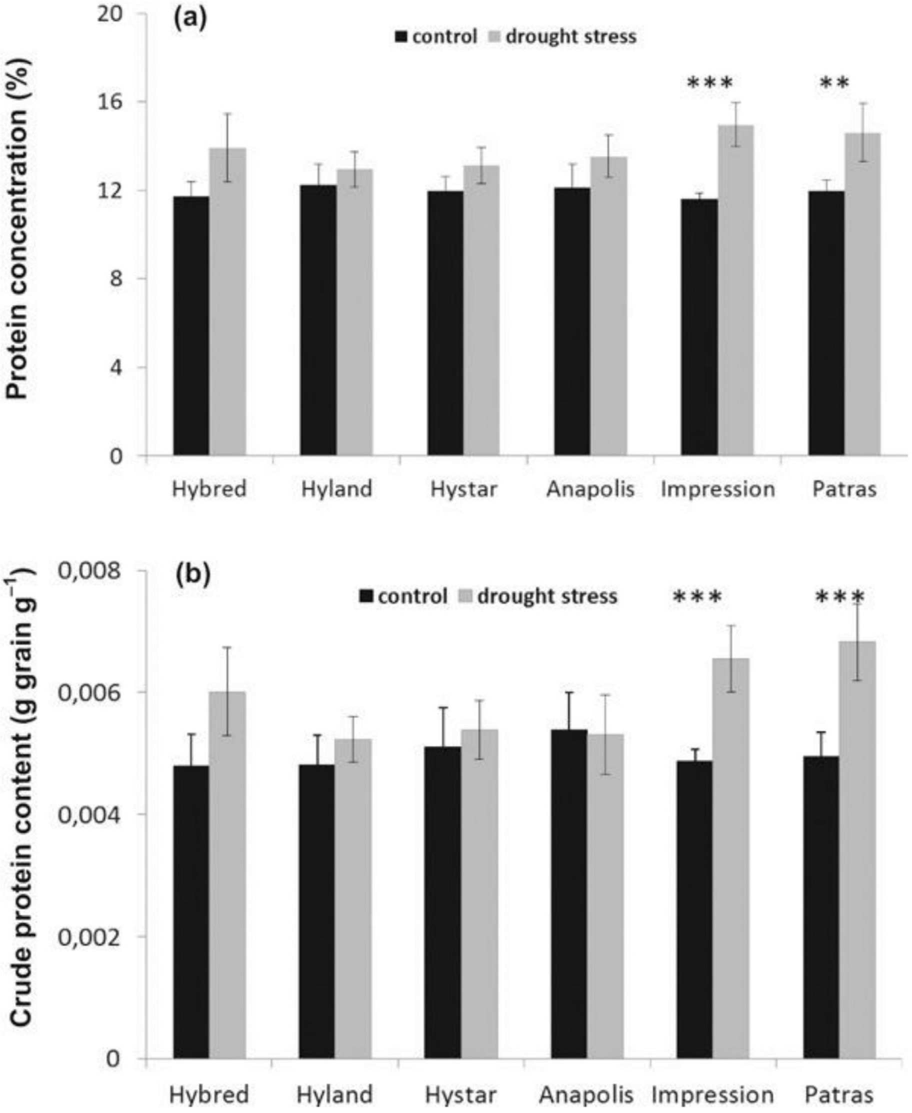

Figure 1. The response of protein content and crude protein content of hybrids in optimum conditions as a contrast to drought stress [69].

end-use functional properties. The grain sample measured at germination to maturation demonstrated that protein content, SDS-sedimentation value, and wet gluten have been increased by about 18.1%, 16.5%, and 21.9%, respectively, under drought stress conditions [63]. Increment in grain protein content under this condition could be due to the reduction in starch accumulation [64]. The decrease in starch accumulation in developing grain is strongly associated with shortening of grain filling stage, since drought fasten early senescence [65]. Additionally, under drought condition, amylose can be decreased, and this might be responsible for the loose packaging of the starch granules [65].

Gene expression of storage proteins such as gliadin and glutenin are strongly influenced by drought stress [66]. Under drought stress condition, some of the storage protein fractions such as α-gliadin and γ-gliadin found to be low [67]. This situation in turn negatively influences the strength of the dough, and dough stability such as loaf volume and valorimetric value [68].

3.4. Planting time and seeding rate

The term seeding rate can be defined as "the amount of seeds which falls into the cultivated land to ensure adequate plant stand establishment and grain yield" [49]. Application of higher or low seeding rate is frequently reported as principal factor for yield and end-use functional properties of durum wheat [6]. Since harvesting high quality grain is controlled by seeding rate, understanding the relationship between grain protein content and seeding rate can be an important factor in durum wheat production. It has been observed that, the protein content and associated quality traits were decreased with increasing the seeding rate [6, 70]. A higher seeding rate stimulates more tiller production, which further intensifies inter-plant competition for fixed resources such as water, nutrient and light, thus a decrease in grain protein content could have occurred when these important resources are inadequate [49]. These effects are more profound when durum wheat producing farmers employed a seeding rate above the optimum level required for adequate stand establishment [6, 71]. However, influence of seeding rate on grain protein content and other grain functional properties strongly dictated by climatic conditions, and soil type of the growing locations [6, 71].

The sole effect of seeding rate, however, altered when seeding rate interacts with planting time, especially on protein subunits. Mikos, and Podolska [72], verified that, the gliadins to glutenins ratio was slightly decreased due to the interaction effect of late planting time and low seeding rate, which points to a shift in the elasticity of gluten proteins. However, it has been observed that sowing crops late in the season offered higher protein content than the early plantings [73, 74, 75]. Higher protein content under late sowing could be due to its determination of extreme events at grain filling stage, as the late sown wheat varieties can flower later in the season, which forces the grain filling period to coincide with terminal drought stress. Increasing protein content under drought stress condition is a frequent phenomenon [62, 65]. This means that, as far as protein content is concerned, the main and interaction effect of agronomic crop management practices should be considered according to a given environment.

3.5. Nature of the growing season

Influence of either absence and presence of rainfall at grain filling stage can affect the grain quality traits. It has been observed that, crude protein content of wheat was decreased by rainfall [76]. Timing, and amount of growing season rainfall often result in poor grain quality [46]. However, this effect is more significant when rainfall is occurred around physiological maturity that might be slow grain drying and promote the germination of wheat grains; thus reducing the falling number [77], and influence the grain color by making black points [78]. These black points are another aspect of wheat grain quality that affects the flour [79]. However, influence of the rate of grain filling period and harvesting season upon grain technological traits of durum wheat and the length of the harvest period during which acceptable grain protein content may be attained has not been well studied.

4. Strategies of improving grain end-use functional properties

4.1. Managing nitrogen fertilization: the two faces of nitrogen application

In the modern agricultural system, the primary concern on the farmers' side is the simultaneous improvement of grain yield and grain technological traits at variable levels of nitrogen fertilization. This concern is principally developed due to an inverse relationship between the grain yield and protein content; as the grain protein content decreased with increasing grain yield because of the dilution effect [12]. Agronomic strategies such as a timely supply of nitrogen fertilizer in a multiple-dose could reduce the negative effect and enhance the grain protein content, gluten, and associated traits [12]. However, as indicated in Figure 2, fertilization amount of nitrogen exerts an immense influence on grain quality traits than grain yield [80, 81, 82]. It means that the total available nitrogen sought to obtain acceptable grain protein content may be significantly higher amount than that has been required simply to improve grain yield and yield-related traits. Additionally, augmenting nitrogen fertilization at a high level was observed to decrease nitrogen use efficiency crops [17], grain yield, and flour quality of wheat [83, 84], probably due to the lodging effect. Lodging reduces the photosynthetic capacity and creating a conducive environment for fungal and leaf disease development as well [85].

Previous studies examining the effects of increases in nitrogen amount showed that nitrogen fertilization at a higher dose can increase the length of basal internodes, which contributed to lodging [87], through influence the lodging resistance of the crop. Although optimization of nitrogen fertilization minimizes the possibility of crop lodging due to the depletion of shoot weight [88], wheat cannot exploit its full genetic potential to accumulate the required protein content [89]. Therefore, the decision to applying further additional nitrogen fertilizer during the season can be based on the product (i.e. yield and quality) interest of durum wheat producing farmers. If the interest gears towards achieving maximum grain yield, optimum nitrogen fertilization is vital, but if the interest is towards the production of high grain protein content, application of nitrogen fertilizer at a higher rate can be recommended [12]. This result indicated that the yield and grain protein content are highly dependent on nitrogen management, to the extent that even the smallest changes in the application dose could cause significant changes in the storage protein content and grain yield as well.

The grain end-use functional properties are strongly associated with the storage protein contents and composition, which can be influenced either by agronomic like technologies [6, 90, 91], and environmental factors [8, 92]. It is a function of total nitrogen uptake and partitioning of nitrogen and dry matter into the grain [93]. Nitrogen fertilization at a right amount and time has been found to increase growth attribute traits i.e. plant height and leaf size due to higher photo absorption concentration, thus increases the dry-matter storage [94]. The change in grain protein content and associated qualitative traits under a high dose of nitrogen fertilization is a frequent phenomenon [89, 95, 96, 97]. This change could be because of the altering effect of nitrogen on the gene expression levels involved in the production of the primary grain storage proteins [89].

Studies reflected that the response of wheat to the increasing nitrogen fertilization dose in the improvement of grain storage proteins is, however, inconsistent. It has been reported that the application of nitrogen fertilizer at a high rate was significantly rather a small effect on gluten content, gluten strength, protein polymerization, and assembly [98, 99, 100]. Inconsistent with these studies, the relative amount of the main storage proteins such as gliadins and glutenins was not affected by an increase in nitrogen fertilization [99, 101]. These inconsistencies in amelioration responses could be a result of the genetic landscape in the allocation of nitrogen to storage protein fractions and due to the sensitive influence of pedoclimatic conditions of the growing locations. In addition to this, Figure 3 illustrates the negative impact of increased leaching at the enhanced nitrogen fertilization. When nutrient use efficiency is calculated as a function of grain yield per estimated nitrogen input, it decreases with the increasing nitrogen input [102].

Like that of its merit to improve the grain quality traits, application of nitrogen fertilizer at higher amount can be a cause for foliar disease development. Therefore, its management is very important to maintain acceptable grain quality. Because, higher dose of nitrogen makes the crop more susceptible to fungal diseases, by creating conducive environment through production of higher biomass [20], and promoting nitrogen like compounds necessary to the growth of disease caused organisms [103]. On the other hand, application of nitrogen fertilizer at enhanced rate increases leaf area index [104]. This increment in turn caused delay in maturity period because of higher radiation interception and use efficiency [104, 105]. These results universally indicate that, if nitrogen is properly managed, it can ensure food security, nutritional security and environmental sustainability.

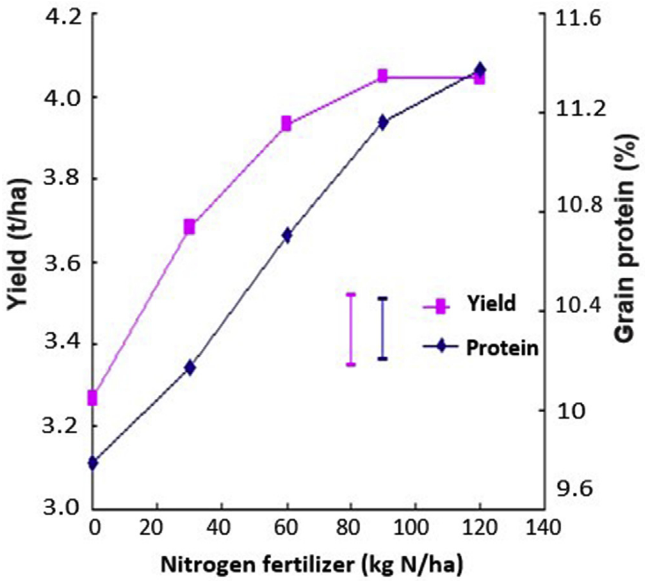

Figure 2. The relationship between grain yield (t ha^{-1}), and protein percentage under variable nitrogen levels (i.e. 30, 60, 90, and 120 kg ha^{-1}) average over 10 wheat varieties [86].

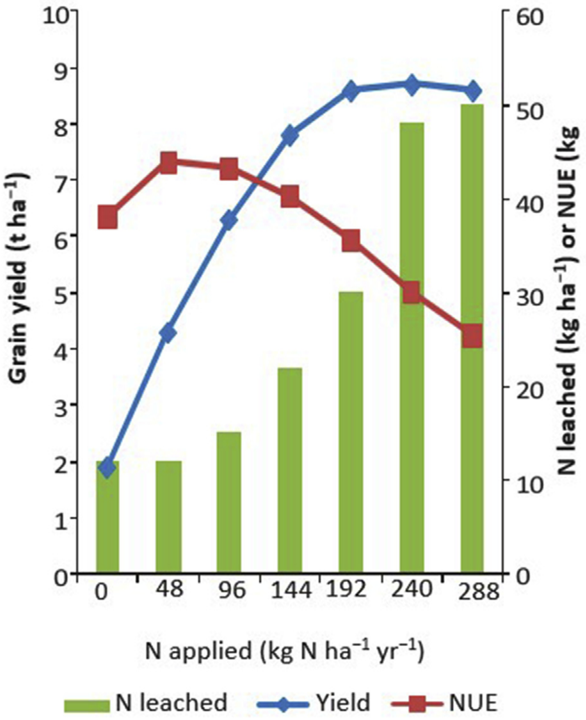

Figure 3. This figure illustrated that the positive benefit of increased yield with increasing nitrogen fertilizer up to around 192 kg ha^{-1} after which there is little apparent increase in yield. In addition to this, it also illustrates the negative impact of increased leaching at the higher nitrogen fertilization. When nutrient use efficiency is calculated as a function of grain yield per estimated nitrogen input, it decreases with the increasing nitrogen input [102].

4.2. Improving nitrogen uptake and remobilization

From the physiological point of view, the storage grain protein formation in wheat grain involves uptake by roots and nitrogen accumulation in vegetative organs, and subsequent remobilization to the seed for protein synthesis. This process is, however, under genetic control in wheat and its expression is fundamentally influenced by growing locations and genotype by environment (G x E) interactions [99]. At the grain-filling stage, the amount of nitrogen uptake is much lower than the demand for nitrogen accumulation in the grain; therefore, this demand could be met by nitrogen remobilized from vegetative organs. The proportion of remobilized nitrogen in the harvested grain is environment-dependent which accounts about 60%–92% of the total grain nitrogen [106]. Nitrogen uptake from the soil prior to heading has been tended to improve grain protein content, if the other resources like water, potassium and phosphorus are not limited [12]. In winter wheat, both nitrogen remobilization and post-anthesis nitrogen uptake contribute to improving grain protein content [107].

Enhanced grain protein content could be achieved through enhancing uptake or remobilization of nutrients. Wang et al. [108], stated that wheat genotypes with enhanced grain protein content were more efficient at nitrogen translocation from the vegetative tissue into the grains. It is also reported that grain protein content in durum wheat cultivars can be increased due to nitrogen remobilization [109]. However, Wang et al. [110] reported that the high-protein cultivar had a higher nitrogen harvest index (i.e. the grain nitrogen content as a proportion of total nitrogen in the plant) than other cultivars having lower protein concentration. The grain protein content is also influenced by the morphological characteristics of durum wheat varieties. Clarke et al. [111], verified that low grain protein concentration was observed in semi-dwarf cultivars than in non-dwarf durum cultivars. Hence, understanding the morphological and physiological basis could allow breeders to develop the simplest breeding approaches to enhance grain both the content and concentration of protein in semi-dwarf durum wheat varieties.

Improvement in nutrient use efficiency of wheat has also a tremendous advantage in increasing grain yield, protein content and reduces environmental pollution as well. Integrated fertilizer management, application time, and proper fertilization rate are observed to enhance nitrogen utilization efficiency. Combined application of nitrogen and sulfur fertilizers during the crop growth period enhances the nutrient use efficiency of wheat [112]. Additionally, the late-season and split application of nitrogen fertilizer showed to improve nitrogen use efficiency resulting in high plant nitrogen uptake and in turn produce better grain protein accumulation [113, 114]. Nitrogen taken up by plants after the booting stage revealed enhanced grain protein accumulation to a greater extent than grain yield [115]. Likewise, splitting of nitrogen fertilization is proved as a crucial production element to improve nutrient use efficiency, grain yield, and grain protein concentration [114]. However, the effectiveness of nutrient use efficiency is observed tremendously influenced by crop developmental stages for protein accumulation in the grain.

4.3. Define proper application time and fertilization method

Nitrogen is a building block of protein components, and its application time is most important in increasing grain protein concentration, particularly when nitrogen is applied late in the season than the approach in which the entire application rate is supplied at sowing [114, 116]. Nitrogen applied before the flowering stage produced maximum grain yield thereby reduces its effectiveness to increase grain protein content [114]. Previous studies demonstrated that nitrogen fertilizer application at heading and anthesis stages were significantly enhanced grain protein concentration [113, 117]. The application of proper fertilization amount at a right time can play an important role to improve grain protein content. Garrido-Lestache et al. [118], verified that a high-dose of nitrogen application at the stem elongation stage was improved the grain protein content. These benefits can be explained through two basic reasons. First, late-season nitrogen application predominantly benefits protein build-up than starch in the grain and prolongs the duration of the grain-filling stage [119]. Second, splitting nitrogen applications into different growth stages fundamentally reduces the nitrogen volatilization from the plant which in turn enables to improve storage grain protein content and composition [106].

The grain end-use functional properties are not only influenced by the developmental stage of durum wheat, but also by nutrient application methods. Foliar-based nitrogen application was found to be more effective than soil-based application at appropriate stages [120, 121]. Because, when nitrogen is augmenting at the flowering stage it will be effectively allocated into the grains, while a spray solution applied to the flag leaf fundamentally allows easy access of nitrogen to grains [122]. Indicating that, enhancing effectiveness of the applied nitrogen must be consistent following the steps of growth, developmental stages and the nutrient uptake capacity of the wheat varieties. Tedone et al. [123], reported that, with a distributed total dose, nitrogen fertilization can be reduced at the very early durum wheat stages (i.e. tillering) in favor of the later growth stages (i.e. stem elongation, earing), which encourages enhanced nutrient absorption and use efficiency of durum wheat.

Nitrogen uptake from foliarly applied nitrogen has two main advantages such as (a) being less dependent on soil moisture status and (b) it is effective when root uptake is impaired in dry soils or at late growth stages when there is decreased root activity [124]. Foliar-based nitrogen application reduces the exorbitant amount of required nutrients, thus decrease photo-toxicity and environmental pollution as well [113, 125]. The low application dose is able to reduce gaseous nitrogen emissions and nitrate leaching [126, 127]. Hence, foliar-based application of nitrogen fertilizer has an agronomic and environmental advantage. However, foliar-based nitrogen application is not yet widely practiced and scanty information is available about its effect on durum wheat grain quality traits and its role in environmental protection. Hence, there is a need of enhancing the efficiency of the applied nitrogen to improve the technologically required traits and reduce the environmental damage caused by high doses of nitrogen.

4.4. Agronomic biofortification

Wheat grain quality traits can be enriched by agronomic biofortification through the application of micronutrients containing fertilizer solutions [126] or genetic biofortification through breeding programs [129]. Agronomic biofortification is a short-term solution, and an important complementary strategy to genetic biofortification, especially when the soil in the target growing location is limited to supply adequate micronutrients [130]. An agronomic biofortification of micronutrients in a sulfate form has been proved to increase the grain protein and gluten content of durum wheat [6]. Universally, studies demonstrated that foliar application of zinc and iron fertilizers have a practical solution to improve grain yield and protein content in wheat [6, 131]. Previous studies confirmed a positive and strong association between grain protein content and micronutrient such as Zinc, and Iron [132, 133]. Additionally, an application of Mn as fertilizer can improve the most important grain quality parameters such as protein content, gluten content, Zeleny sedimentation index, and grain hardness [134]. However, as far as maximum grain protein content and associated traits are concerned, method and doses of application must be considered.

Integrated fertilizer application also found to be an important agronomic practice to improve storage proteins in wheat. An increase in high (38.8%) and low molecular weight (6.7%) glutenins was attained when Zn-containing fertilizers were combined with NPK fertilizers [134]. Another study showed that, split application of nitrogen fertilizer at sowing and stem elongation stages, combined with soil and foliar-based application of zinc and iron-containing fertilizers could be important crop management practices to improve acceptable grain protein content, zinc, and iron concentration in grain [135]. Foliar-based application of nitrogen fertilizer combined with soil plus the foliar application of zinc found to be the best combination to achieve acceptable grain protein content [136].

4.5. Intercropping

In organic-based agriculture, nitrogen application and management are important farming activities to enhance available soil nitrogen and to satisfy the crop requirements. Agro-technical methods such as crop rotation, intercropping, and application of an organic form of nitrogen fertilizer have been found to improve quality, and quantity in wheat. A wheat-legume intercropping has been observed as a promising agronomic measure to enhance grain yield and protein content even under low-input conditions [137]. A significant improvement in grain protein content was reported, when durum wheat was intercropped with faba bean [138], and pea [139]. It has been reported that under cereal-legume intercropping, the grain protein content was much higher than the sole cropping system [140]. Nitrogen remobilization into the grain is much higher due to the high N_2 fixation rate in wheat-legume intercropping than the sole cropping system [138]. This could reduce the influence of high input agricultural system on the environment. Jensen et al. [141], estimated that the increased nitrogen use efficiency in intercropping can decrease synthetic nitrogen fertilizer requirements by about 26% on a worlds scale. Lowering the use of nitrogen fertilizer in the agricultural system will therefore significantly decrease the release of CO_2 and N_2O into the atmosphere [141].

4.6. Proper cropping sequences, and break-crops

Proper cropping sequences allow efficient utilization of the available soil resources by the crop and improve production and grain quality at a system level. Gan et al. [142], summarized that a continuous cereal-based farming system reduced durum grain protein content and grain yield by about 8%–16% and 4%–8%, respectively, as compared with cropping systems that incorporate oilseeds or pulse crops one or two years before the subsequent cropping season. The enhanced protein content under this situation could be due to enhanced nitrogen use efficiency and enhanced grain nitrogen accumulation. Badaruddin and Meyer [143], have found that the total amount of nitrogen concentration by the subsequent wheat crop following legumes was about 9% higher than that following wheat. It can be inferred that, on the basis of the nature of a crop cultivated in the previous year, the availability of the residual water and nutrient status in the soil, required for the subsequent crop growth and development can be significantly influenced.

Additionally, nitrogen use efficiency of wheat following legumes crops was improved up to 32% higher than that for wheat following fallow and up to 21% higher than in continuous wheat [143]. It means that durum wheat can achieve maximum yield with better grain quality, when it grows after any legume species than grown after cereal crops. Therefore, quantifying the grain quality increment level and explaining the principal production factors will help the smallholder farmers to follow proper cropping sequence. These benefits are, however, strongly influenced by cropping season, growing location, variety, and system characteristics dependent nature [144]. However, despite these advantages, information about the cropping sequence effect on grain protein content is very limited.

5. Nitrogen application can reduce drought stress

It has been reported that under drought stress condition, plant water status can be significantly influenced, through declining water potential and relative water content [145]. Nitrogen is an important component of chlorophyll and proteins, and its application in the form of fertilizer is an important agronomic management approach to improve crop productivity [146]. Nitrogen can enhance net photosynthesis rate of the leaf [147]. Studies reported that an application of nitrogen fertilizer at vegetative phase reduces the adverse effect of drought stress through its role in maintaining high leaf water potential, photosynthetic activities, and antioxidative defense mechanism [148]. The combined effect of nitrogen deficiency and drought stress condition could influence, therefore, the strongly correlated physiological functions of wheat [148]. However, nitrogen effect under varying drought stress levels at various phenological periods of wheat are not clearly understood. An investigation conducted on the impact of drought stress under different nitrogen doses on physiological and other attributes can provide important insights to develop drought tolerant wheat varieties [149]. Therefore, an adequate evaluation of the combined effect of nitrogen deficiency and drought stress impact on the morphological, physiological, and grain quality characteristics can provide valuable information, and understanding of durum wheat performance under stress condition.

6. Conclusions

This review has highlighted the significance of selecting an optimal quality improvement strategy, as a function of the desired industrial and local food products. The most promising strategy seem to rely on the correct management of nitrogen fertilization, and choice of nutrient use efficient varieties. An appropriate nitrogen fertilization is an effective route to enhance grain technological traits. Its management contributes to (i) maximum yield production depending on the extent of the applied nitrogen rate, (ii) ameliorates protein content, gluten content, and (iii) enhances dough rheology and other end-use functional properties. However, the total amount of the applied nitrogen sought to obtain acceptable grain protein content is a significantly much higher amount than that has been required simply to improve grain yield and yield associated traits. Hence, defining an optimum nitrogen fertilizer rate for a specific location requires considering grain yield achievement and quality of the end products. Therefore, if the wheat producing farmers interest is geared towards high grain protein content, application of high nitrogen doses is required. However, if the interest gears towards achieving maximum grain yield, a low rate of nitrogen fertilizer is significantly recommended. Additionally, application of nitrogen fertilizer at optimum rate can reduce the negative consequence of drought on yield and quality of wheat. It can be universally inferred that future challenges associated with increasing production, productivity, and technological quality traits of durum wheat could be achieved by the cooperation of multidisciplinary teams who could incorporate and develop new technologies for sustainable durum wheat production and better return.

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Author contribution statement

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