Review

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J. Agric. Food Chem., **Just Accepted Manuscript** • DOI: 10.1021/acs.jafc.8b02924 • Publication Date (Web): 03 Aug 2018

Downloaded from <http://pubs.acs.org> on August 7, 2018

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Impact of Abiotic Stresses on Grain Composition and Quality in Food Legumes

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ABSTRACT

Grain quality and composition in food legumes are influenced by abiotic stresses. This review discusses the influence of abiotic stresses on grain composition and quality in food grains. Grain protein declines under salt stress due to the restricted absorption of nitrate from the soil solution. Grain phosphorus, nitrogen and potassium contents declined whereas sodium and chloride increased. However, under drought, grain protein increased whereas the oil contents were decreased. For example, among fatty acids, oleic acid content increased, however, linoleic and/or linolenic acids were decreased under drought. Heat stress increased grain oil content whereas grain protein was decreased. Low temperature during late pod-filling reduced starch, protein, soluble sugar, fat and fiber contents. However, an elevated CO₂ level improved omega-3 fatty acid content at the expense of omega-6 fatty acids. Crop management and improvement strategies, next generation sequencing, and gene manipulation can help improve quality of food legumes under abiotic stresses.

Keywords: Dietary significance; Drought; Grain composition; Heat stress; Legumes; Hidden hunger; Salinity

INTRODUCTION

The world population is expected to rise from the current 7.2 billion to 9.6 billion by the middle of the 21st century particularly in developing countries.¹ It is expected that about 70% more food will be needed to feed the rising population.¹ The diversion of food crops to biofuel production is further adding pressure to increase crop production. Also, the large protein gap for the existing global population² is expected to rise linearly with the expected rise in population and with changes in dietary habits (more preference for meat). Legumes can be divided into three distinct

groups: (i) food legumes, (ii) forage legumes and (iii) cover crops. Food legumes, i.e. pulses and oilseeds, are a rich source of proteins^{3,4}, which contribute to fulfilling the protein demands of the existing population. The inclusion of food legumes into cropping systems can help meet the protein requirements of growing population.

Food legumes belong to the *Fabaceae* family (with about 800 genera and 20,000 species)⁵, which is the second most important plant family in the agricultural system after the *Poaceae* family. In terms of world production, food legumes rank third after cereals and oilseeds but have strong impact on the agro-ecosystem and nutrition balances for animals as well as human being.⁶ ⁸ Food legumes improve the soil health through their biological nitrogen fixation ability^{9,10}. Legumes contribute the largest share of protein for livestock feed and the human diet⁷. Legumes have several health benefits, e.g., in the prevention of chronic diseases¹¹⁻¹³, because of their high dietary proteins, fiber, phenolic and oligosaccharide contents. Legumes are a rich source of many essential nutrients such as vitamins, dietary minerals, fibers, antioxidants and other bioactive compounds.¹⁴⁻¹⁶ The food legumes also provide 20–40% of dietary protein requirements especially in the developing world.¹⁷ However, in terms of food provision to humans, legumes are ranked second to cereals worldwide.^{17,18}

Food legumes grow in varying climates ranging from semi-arid to sub-tropical and temperate climates.¹⁹ Factors such as drought, salinity, heavy metals and heat stress can affect legume grain quality. Generally, the protein content in the harvested fraction of food legumes increases or remains unchanged under drought, and decreases under salinity and other environmental stresses.²⁰⁻²³ Under salinity stress, grain protein content declines due to disturbance in nitrogen (N) metabolism and/or decrease in the absorption of nitrate (NO_3^-) from the soil solution²⁴, however, there was a corresponding increase in grain oil content.²⁴⁻²⁵ In contrast, grain oil content tends to decrease under drought stress.²⁶⁻²⁹

Some studies have reported a reduction in protein content under drought³⁰ but different proteins respond in various ways. For instance, proteins such as albumins, globulins and prolamins decreased in faba bean under drought while glutelins increased; yet, the total protein content improved.²⁷ In soybean, under severe drought, a reduction in N uptake may reduce grain protein content.³¹ Among the fatty acids, oleic acid content increased whereas linolenic acid and/or linoleic acid decreased in food legumes under drought^{32,33}. However, protein content was less affected in soybean under abiotic stress due to increased mobilization of amino acids.³⁴

Under heat stress, total oil content tended to increase whereas grain protein content decreased in a variety of food legumes with few exceptions.^{26,35-37} In soybean and peanut, for instance, oil content increased by 37 and 20%, respectively, under heat stress.^{28,39} Heat stress also causes change in the fatty acid composition. For instance, increase in temperature caused significant increase in the oleic acid contents whereas the heat stress caused decrease in the linoleic acid contents.^{40,41} Moreover, the concentrations of N and P in soybean grain increased with temperatures up to 40/30°C (day/night), after which they declined.⁴²

Heavy metal accumulation is a serious issue in areas with more anthropogenic pressure. Higher accrual of heavy metals in arable soils not only pollutes the environment but uptake of these heavy metals by crops including food legumes results in heavy metals entering the food chain and causing human health problems.^{43,44} Moreover, food legumes grown in soils contaminated with heavy metals like cadmium (Cd), lead (Pb), copper (Cu), nickel (Ni) and arsenic (As) may significantly reduce grain protein content due to reduced N uptake and supply to developing grains.^{44,45}

Grain legumes have the potential to serve as an alternative for animal protein. There have been significant improvements in the understanding of the physiology and production of food legumes under abiotic stresses and several approaches have been adapted to improve their

tolerance to different abiotic stresses.⁴⁶⁻⁴⁸ However, the grain quality component is often ignored. As food legumes are mainly consumed for edible proteins or oil, further research on the impact of abiotic stresses on legume grain quality and the development of programs aimed at improving grain quality together with resistance to abiotic stresses are needed.

This review covers the dietary significance and impact of abiotic stresses (salinity, drought, temperature extremes, heavy metals and elevated CO₂) on grain composition and quality in food legumes. Strategies to improve the quality of grain legumes under abiotic stresses are also proposed.

Food Legumes Grain Composition and Dietary Importance

Food legumes are important field crops because of their nutritional quality and distinct ability to fix atmospheric N symbiotically. They are rich sources of complex carbohydrates, protein, vitamins and minerals (Table 1).^{49,50} Food legumes also helps preventing the risk of certain cancer, cardiovascular disease, diabetes mellitus and obesity.^{12,51}

Legumes are recognized as the best source of vegetable proteins.⁵² The main sources of vegetable dietary protein include chickpea (*Cicer arietinum* L.), common bean (*Phaseolus vulgaris* L.), cowpea (*Vigna unguiculata* (L.) Walp.), faba bean (*Vicia faba* L.), grass pea (*Lathyrus sativus* L.), lentil (*Lens culinaris* Medikus), mung bean (*Vigna radiata* (L.) R. Wilczek), pea (*Pisum sativum* L.), pigeon pea (*Cajanus cajan* (L.) Millsp.), soybean (*Glycine max* (L.) Merr.) and urad bean (*Vigna mungo* (L.) Hepper), and are served in various forms as an integral part of the daily diet in many countries. There exists variation in the protein contents of food legumes and can range from 16–28% in chickpea, 26–57% in soybean, 21–29% in common bean, 16–32% in pea, 22–36% in faba bean, 19–32% in lentil, 16–31% in cowpea, 21–31% in mung bean and 16–24% in pigeon pea (Table 1).^{53,54} Crop husbandry practices, species,

genotypic variations within species and environmental conditions can affect grain protein contents.

Globulins and albumins are the major storage proteins present in food legume grains accounting for 70 and 20% of total proteins, respectively, while minor proteins include prolamins and glutelins.^{55,56} Legumin and vicilin are the major types of globulin and albumin proteins. In this regard, vicilin contents are usually higher in food legumes, however, the relative ratio of vicilin and legumin varies with genotype. In addition to highly digestible protein (70–90%),⁵⁷ chickpea grain also contains several essential amino acids including valine, phenylalanine, lysine, leucine, and isoleucine.⁵⁸

Food legume grains, predominantly soybean and peanut (*Arachis hypogaea* L.), contribute more than 35% to the total vegetable oil, of premium quality, in the world.⁵⁹ However, grain oil contents vary in food legumes depending upon the nature of the legumes (pulse or oilseed) (Table 1).

The carbohydrates in the food legumes ranges from 30 to 63% in soybean and chickpea, respectively (Table 1). Although the starch amylose fraction, in food legumes, tends to higher than of cereals, the relative proportion of amylopectin is higher than that of amylose in the legume starch.⁶⁰

Grains of important food legumes are a vital source of minerals such as phosphorus (P), calcium (Ca), potassium (K), nitrogen (N), iron (Fe), magnesium (Mg) and zinc (Zn), and vitamins such as vitamins A, B6, E, K, riboflavin and thiamin (Table 1). Complex carbohydrates are high in these vitamins and minerals which are considered beneficial for several diseases such as cancers and diabetes.^{61,62} Legume grains not only play a vital role in many traditional diets worldwide but are valuable for the food and animal feed industries.^{6,7,13} Legume grains are also a source of minerals essential for human being.⁶³

Some essential fatty acids, including omega-3 and omega-6 fatty acids, cannot be synthesized in the human body, and thus should be taken through food or as supplements. It is reported that mature grains of mung bean picked under high [CO₂] may be a good alternative source of omega-3 fatty acids.⁶⁴

In summary, food legumes are an important source of dietary protein, B-group vitamins, good quality dietary fiber, oil, and macro and micronutrients. Due to their ability to fix atmospheric nitrogen, food legumes play an important role in cropping systems.^{8,65} Food legumes have excellent grain composition with multi-nutritional benefits which may help meet the dietary demands of the rapidly increasing global population. Moreover, the use of these crops is expected to reduce economic losses to the global economy caused by malnutrition.

Influence of Abiotic Stresses on Composition and Quality of Food Grain Legumes

The quality of food legumes is primarily determined by grain composition which includes protein, oil, fatty acids, sugars, dietary fibers, vitamins and mineral contents. Food legumes contain sugars such as monosaccharides (glucose and fructose), disaccharides (sucrose) and oligosaccharides (raffinose and stachyose). Grain legumes may contain the 15 essential nutrients required by the human body in varying concentrations depending on the species and environmental conditions.⁶³ The major minerals in food legumes includes P, K, Ca, Zn, Fe, boron (B) and manganese (Mn), which are essentially required by the human being; any deficiency of these minerals may cause human malnutrition and/or health issues.⁶⁶⁻⁶⁸

Salinity, drought, temperature extremes and heavy metals affect grain protein, starch, fats, vitamins, amino acids and vitamin contents in food legumes, and are discussed in the following sections.

Salt Stress

The presence of soluble salts or exchangeable sodium in the root zone in amounts that affect normal plant function is termed salt stress. Salt stress affects grain quality and limits the spread of plants in their natural habitats.⁶⁹ Salt stress is a concern in arid and semi-arid regions, which constitute about 40% of the earth's land area.⁶⁹ Salt stress inhibits biochemical processes, such as photosynthesis, in food legume crops. The effects on photosynthesis disturb overall plant growth^{70,71} through osmotic effects, specific ion toxicity, nutritional imbalances, and disturbance in the hormonal homeostasis.⁷² Salt stress not only affects plant metabolism and morphology but also influences nutrient uptake and balance⁷³ which affects grain yield and quality.⁷⁴

Grain protein and oil contents in food grain legumes are strongly influenced by salt stress (Table 2).²⁵ The grain protein contents of chickpea and mung bean declined in saline environments (Table 2) due to the disturbance in N metabolism and/or decrease in uptake of nitrate (NO_3^-) from the soil solution.²⁴ In faba bean, a reduction in grain protein contents with increasing salt stress (60 mM, 120 mM and 240 mM) was observed.⁶⁹ Likewise, a reduction in soluble proteins with increasing salt stress in cowpea was also recorded.⁷⁵ Salt stress reduced the nutrient uptake in three grain legumes—teary bean (*Phaseolus acutifolius* A. Gray), cowpea and wild bean “frijolillo” (*Phaseolus jiliformis* Bent)—which reduced the plant growth.⁷⁶ However, increased protein contents with increasing salinity was recorded in black gram⁷⁷ as was at mild levels of salt stress in common beans.⁶⁹ This contradiction may be attributed to the differential extent of tolerance against salt stress between and among grain legume species. Salt stress may influence different metabolic events within plant systems, which may or may not affect the attributes of grain quality in different food legumes. For instance, a reduction in plant N uptake and/or disturbance in N metabolism may influence grain protein assimilation and

166 contents.²⁴ Under non-saline conditions, grain had higher oil and protein contents than those
167 observed under a saline situation.²⁰

168 Salt stress has strong and diverse effects on the quality and composition of legume grains.⁷⁸
169 For instance, gradual decrease in the carbohydrates, polysaccharides, amino acid contents and
170 protein contents was noted in mung bean with increase in the level of salt stress (Table 2). This
171 reduction in carbohydrates and polysaccharides was plausibility due to salinity-induced osmotic
172 stress, nutritional imbalance, specific ion toxicity and reduced photosynthesis.^{21,79,80} However,
173 decrease in the N uptake was responsible for reduction in the total amino acid contents.⁸⁰ N, P
174 and K concentrations declined in mung bean grain with increasing level of salt stress, while Ca,
175 Na, Mg and chlorine (Cl) concentrations increased (Table 2)²¹ N assimilation declined due to C-
176 deamidated reductions in NO_3^- uptake. With increased rhizosphere sodium (Na^+), uptake of Na^+
177 increased while K^+ uptake decreased.⁸¹ Salt stress favors the uptake of certain nutrients, owing to
178 ionic imbalances, at the expense of other certain other nutrients.⁸²

179 In conclusion, salinity significantly reduces the carbohydrates, total amino acid, protein, oil
180 percentage and polysaccharides in food legumes. This reductions in grain polysaccharides and
181 carbohydrates are due to reduced photosynthesis, osmotic stress, specific ion toxicity and
182 nutritional imbalances. Decrease in total amino acids and grain proteins is due to reduced N
183 uptake because of antagonism of Cl^- and NO_3^- . However, in some cases, when N uptake and
184 movement to non-root plant parts was not affected by salt stress, protein contents increased.
185 Nonetheless, salt stress may increase Ca, Na, Mg and Cl^- contents in food legume grains at the
186 expense of N, P and K.

187 **Drought Stress**

188 Drought stress strongly influences grain quality and composition in food legumes (Table

3).⁸³⁻⁸⁵ Drought stress not only limits production potential but affects grain quality attributes in food legumes, i.e. protein, fat and carbohydrate contents (Table 3).^{86,87} Although grain protein contents in food legumes are highly dependent on their genetic makeup, environmental factors, particularly drought, may also influence the total protein yield and grain protein contents. Although drought stress tends to reduce grain yield in the most of food legumes, grain protein contents may increase with increasing water deficit,^{87,88} for example, in faba bean, soybean, mung bean, chickpea and spotted bean - a colour variant of common bean.^{27,89-92} However, total protein yield tends to decline in response to drought as has been observed in mung bean²² and in chickpea.⁸⁶

During flowering, a mild water shortage may favor protein assimilation.⁸³ For instance, mild drought increased grain protein content in mung bean and chickpea by 6–21%. However, in lupins, severe drought decreased grain protein content by 19–35%.³⁰ Drought reduced P, N, Fe, and Zn contents and thus the total proteins in the common bean grains.⁹⁴

Upon exposure to drought during pod filling in white, red and chitti beans, grain N and protein contents significantly decreased.⁹⁵ Drought altered the fatty acid composition in soybean which affected total oil levels, oil stability and oil composition, especially during grain filling.⁹⁶

Severe drought during grain filling reduced the oil content in soybean grains by up to 12.4% with a simultaneous decrease in oleic acid content.²⁶ Deficiency in soil moisture during flowering and pod filling increased the free amino acid pool in cowpea grains, but suppressed the incorporation of amino acids into the protein chain, which lowered the protein–amino acid fraction.⁹⁷

Although the total protein content in faba bean increased under drought, different grain proteins behaved differently in this regard.²⁷ For instance, in 13 faba bean varieties tested under drought, three proteins classes —albumins, globulins and prolamins—decreased while glutelin

contents increased and total protein content improved.²⁷ Similarly, a significant increase in dehydrin abundance proteins in soybean grains under drought conditions was recorded in greenhouse and field conditions.⁹⁸

There are reports of reduced protein contents in some food legumes such as lupins, chickpea and soybean under drought stress (Table 3).^{30,99,100} For instance, protein contents were reduced in soybean seeds as drought levels were increased.⁹⁹ Under severe drought in soybean, reduced N uptake reduced grain protein contents.³¹ Electrophoregrams in chickpea cultivars highlighted no obvious effect on grain protein banding patterns indicating that these are stable and not sensitive to environmental changes.⁸⁶

Carbohydrates are a principal dietary constituent of grains and include starches, sugars and fibers categorized as monosaccharides (glucose, fructose and galactose), disaccharides (sucrose and lactose) or complex carbohydrates (starches), all of which supply energy to their consumers. A water deficit of 75% reduced the carbohydrate content in lupin grain by 30% compared with a 35% water deficit.³⁰ Less than optimum conditions favor protein deposition over carbohydrates as carbohydrate translocation is highly sensitive to environmental stresses. In soybean, soluble sugars decreased in mature grains under drought.⁹⁸ In common beans, starch content decreased under drought stress;¹⁰¹ however, drought resistant and sensitive cultivars behaved differently for grain sucrose contents (Table 3). In drought-sensitive cultivars, the sucrose content declined by 29–47% compared with a 43% increase in the drought-resistant inbred line (Table 3).

The storage and nutritional features of grains depend on the fraction of unsaturated (linoleic, linolenic and oleic) and saturated fatty acids in the oil. A higher fraction of polyunsaturated fatty acids is desirable as it reduces plasma cholesterol and low-density lipoproteins, which help to lower the risk of atherogenesis and coronary heart disease.¹⁰² Furthermore, linoleic and linolenic fatty acids are involved in the oxidation and development of undesirable flavors.¹⁰³ In soybean

and peanut, drought had significant effects on fatty acid composition. In soybean and peanut, an increase in oleic acid led to a corresponding decrease in linoleic or linolenic fatty acids.^{32,33} In faba bean, drought had no effect on fat content.⁹² However, in lupins, grain oil contents declined by 50–55% under drought stress.^{104,105}

Drought has a pronounced effect on grain mineral composition in food legumes. For instance, drought, irrespective of the stress pattern (gradual or sudden), improved the concentrations of P, Ca, molybdenum (Mo), Mn, Cu, and Zn in soybean grain, thus improving P, Ca, Cu, Mo, Mn and Zn contents.⁹⁸ In chickpea, drought substantially reduced grain Na, Ca and K contents, but increased grain proline contents.¹⁰⁶

Tocopherols are well-known antioxidants in vegetable oils which help to prevent the auto-oxidation of lipids.¹⁰⁷ In soybean, drought increased α -tocopherol levels by 2–3-fold.¹⁰⁷

In conclusion, drought strongly influences grain mineral composition, protein, starch and fat contents, the fatty acid profile and antioxidant levels, though different food legumes and genotypes of the same species respond differently. In general, total grain protein contents improve while oil contents decline. Among fatty acids, oleic acid contents increase whereas linoleic and/or linolenic fatty acids decreased in food legumes under drought stress.

Heat Stress

Heat stress is often defined as a condition where temperatures are hot enough for a period of time that they cause irreversible damage to plant function or development. Episodes of heat stress are predicted to occur more frequently due to the predicted climate change. Heat stress strongly affects grain composition (Table 4)^{59,108-112} Heat stress increases air and soil

temperatures, which adversely affect protein content and quality. Protein content declined by 19.6% in peanut at 32/26°C and sharply declined in soybean above 40/30°C.^{38,42} In another study, grain protein content in soybean decreased as temperatures increased from 14°C to 22°C, but then increased up to 28°C.¹¹³

Heat stress has a positive effect on the total oil content in several food legumes (Table 4). For instance, in soybean and peanut, heat stress increased oil content by 37 and 20%, respectively.^{38,39} However, in heat-stressed kidney bean, oil content declined by 23%.³⁶ The effect of optimum and higher daytime soil and air temperatures (28 and 38°C, respectively), was investigated from the start of flowering to maturity, on peanut and it was found that higher soil and air temperatures significantly improved oil content in peanut compared with optimum soil and air temperatures.¹¹⁴

Soybean grains from plants exposed to 35°C during seed filling had 2.6% more oil content than those exposed to 29°C and the ratio of fatty acids changed under elevated temperature.²⁶ For example, oleic acid concentration increased with increasing temperature while that of linoleic acid decreased.^{40,41} Several studies have reported increases in grain oil content and composition in soybean with increasing temperatures ranging from 15/12°C to 40/30°C.^{26,38,40,41,115}

Temperature increases from 28/18°C through 44/34°C had a negative effect on N, P, starch, total oil, fatty acids and total nonstructural carbohydrates in soybean grain.⁴² Moreover, the concentrations of N and P in soybean grains increased with increasing temperature to 40/30°C and subsequently declined. Total nonstructural carbohydrates decreased as temperatures increased while the proportion of soluble sugars to starch decreased in soybean.⁴² Increases in sucrose and oligosaccharides (such as raffinose) and decreases in monosaccharides (such as glucose and fructose) with elevated temperatures have been reported.¹¹⁶

Higher day/night temperatures (32/26°C) reduced total starch and sugar contents in peanut, sucrose content declined by 56%.¹¹⁷ In soybean, CO₂-induced heat stress improved the total amount of nonstructural carbohydrates, with soluble sugars declining more than starch.⁴² High temperature increased the methionine level in soybean but had no effect on other amino acids.³⁸ Heat stress reduced oil content in peanut, but improved oil quality since oleic acid content improved while linolenic and linoleic acid contents declined.^{117,118}

In summary, oil content declines in most food legumes under heat stress, while grain protein and starch contents increase with few exceptions. The ratio of fatty acids in food legume oil changes in grains developed at high temperature. Total nonstructural carbohydrates decrease with increasing temperatures. Among amino acids, only methionine increases under heat stress in soybean.

Low-Temperature Stress

A temperature below the optimum for growth, which may cause injury or irreversible damage, is called low-temperature stress. Under low-temperature stress, grain sugar concentration substantially increased in chickpea but the accumulation of storage proteins, starch and several amino acids decreased; the extent of this effect was strongly influenced by the stage of grain development.¹¹⁹ In another study, cold stress substantially reduced starch, protein, soluble sugars, fat, crude fiber and storage protein fractions in chickpea when applied during late pod-filling compared with early pod-filling stages.¹²⁰

Heavy Metals Stress

The buildup of heavy metals in agricultural soils, to toxic levels, has emerged as an alarming threat. Wastewater can contain various heavy metals including cadmium (Cd), chromium (Cr),

306 lead (Pb), mercury (Hg), Zn and nickel (Ni).¹²¹ Continuous irrigation of agricultural land with
307 industrial wastewater may cause heavy metals to accumulate in soil and the crops grown in that
308 soil.^{121,122} Heavy metal accumulation is a serious issue in areas with more anthropogenic
309 pressure.

310 Presence of the heavy metals in the rhizosphere above the optimum levels not only limits
311 yield and quality—protein and oil contents in particular—in food legumes, but these metals can
312 accumulate in grains causing health concerns (Table 5).^{43,44,123} Heavy metals, particularly Cd, Pb,
313 Cr and As are the main concern. Cd is toxic, causes oxidative stress in plants and is highly toxic
314 to plants, animals and humans.¹²⁴ The toxic effects of Pb rest mainly in its ability to react with
315 functional groups such as sulfhydryl, carboxyl and amine, leading to reduced or loss of activity
316 of many enzymes important for cell function.¹²⁵

317 Soybean has more potential for absorption and accumulation of heavy metals than cereals or
318 other legumes such as common bean and peas.^{123,126} The potential health risks associated with
319 the accumulation of heavy metals, particularly Cd, in soybean cultivated in contaminated areas
320 have been assessed.^{123,127} Beans accumulate heavy metals in grains.¹²⁸ It is reported that pea
321 grains accumulate Fe and Zn while lentil grains have low levels of Pb.¹²³

322 The effects of Cr, Cd and Cu was studied on yield and grain protein content in mung bean,
323 and the effects on grain protein content varied. Grain protein content in green gram improved
324 with Cr application.⁴⁴ Cr application did not affect symbiosis, and thus did not lessen N supply to
325 grains which increased grain protein content.⁴⁴ While other metals (Cd and Cu), used alone or in
326 combination, lowered grain protein content in green gram compared with their respective
327 controls.⁴⁴ Grain protein content decreased gradually with increasing rates of Cd, Cr, Ni, Zn, Pb
328 and Cu except for Cr and Pb in chickpea and mung bean where it increased (Table 5).^{44,129} Grain
329 protein content declined, on average, by 27% with the addition of a mixture of 23 mg Cd + 135

mg Cr + 580.2 mg Ni per kg of soil.¹²⁹ In contrast, heavy metals (Cu, Zn and Mn) present in sewage biosolid increased grain protein ratios and N and P contents in lentil.¹³⁰ In chickpea, Zn application decreased grain protein content (Table 5). In another study, exposure to higher concentrations of heavy metals such as Cd and Hg reduced the oil content in soybean; however, the extent of the reduction was higher with individual rather than combined application of metals which highlights the antagonistic impact of heavy metals on grain oil content.¹³¹ The study also revealed changes in major and minor fatty acids in soybean grain due to heavy metal exposure: oleic (18:1) and linoleic (18:2) acid declined significantly while palmitic (16:0), stearic (18:0) and linolenic (18:3) acid increased markedly.¹³¹ The detrimental effects of Hg on soybean oil content were greater than those of Cd (Table 5).

In summary, food legumes grown in soils contaminated with heavy metals such as Cd, Pb, Cr, Cu, Ni and As had significantly lower grain protein contents with the exception of Cr and Pb which improved this trait in mung bean and chickpea. Grain oil content in food legumes also declined under heavy metal stress and significantly changed the fatty acid profile in soybean grain. Heavy metals may enter the food chain by accumulating in food legume grains grown in soils contaminated with heavy metals and create human health hazards.

Elevated Carbon Dioxide

In general, the elevated [CO₂] do not alter the quality and composition of food legumes.¹¹⁸ For instance, there was no effect of elevated [CO₂] on carbohydrate content, with the exception of glucose, in kidney beans.³⁶ Likewise, grain oil content in common bean, peanut, mung bean and soybean were not changed at high [CO₂].^{36,118} When averaged, the effects of elevated [CO₂]

on wild and domestic legumes had no effect on grain N content.¹³² Nonetheless, the grain composition and quality was altered by elevated [CO₂] in some species and experiments. Omega-3 and omega-6 fatty acids are not synthesized by the body, but are obtained through nutrition or as a supplement, and have a range of beneficial health effects in human beings.¹³³ In mung bean, increased [CO₂] significantly reduced the percentages of palmitic and omega-6 fatty acids in mature grains, but increased omega-3 fatty acids and the relative proportion of omega-3 to omega-6 fatty acids (Table 6).⁶³ Significant reduction in grain protein, by 1.4%, was noted in soybean at elevated [CO₂].¹³⁴ Under elevated [CO₂], soluble protein and reducing sugar contents declined while total soluble sugars and starch increased in mung bean.¹³⁵

Conclusions and Future Research Directions

Food legumes are known for their nutritional and health benefits and their impact on sustainability in agricultural systems. The rapidly increasing population and food consumption/demand trends indicate that global food demand will continue to rise for the coming 4–5 decades. Moreover, the increasing knowledge and curiosity about nutritional quality will increase the demand for quality food.

Potential exists for improving the nutritional quality of food legumes; however, there is limited data on manipulating seed quality as the research has focused on phenotypic and agronomic trait improvement for resistance to abiotic stresses. Future research on food legumes should incorporate ways to improve nutritional quality together with yield enhancement.

The nutritional merits of food legumes have not been fully evaluated. Further research would provide more information on the underlying mechanisms which could increase yield and

improve grain quality. Since few studies have explored the stress-induced effects on grain composition and quality of legumes, it is not yet possible to draw sound conclusions about the changes in grain quality under different types of stresses. Thus, future research should focus on this area. The missing links on the quality aspect of food legumes under abiotic stresses need to be identified using farmer and consumer-based surveys and other possible options.

The large genetic diversity in the germplasm collections of food legumes should be used to focus breeding on genotypes with better yield potential and nutritional quality under less than optimum conditions. This will require concentrated efforts to identify the key traits involved. Model-assisted designs of new ideotypes may help to develop elite genotypes of food legumes with better yields of good quality grains under abiotic stresses. Such improvements will help to lower the increasing global protein gap as well as the economic burden caused by malnutrition.

ACKNOWLEDGMENTS

The authors extend their appreciation to the International Scientific Partnership Program (ISPP) at King Saud University for funding this research work through ISPP# 0085.

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Table 1. Grain Composition of Different Food Legumes

Crop	Chickpea	Mung bean	Lentil	Cowpea	Pigeon pea	Kidney bean	Mothbean	Soybean
Protein (%)	21	24	25	24	22	24	23	37
Total lipids (%)	6	1	1	2	2	1	2	20
Carbohydrate (%)	63	63	63	60	63	60	62	30
Total dietary fiber (%)	12	16	11	11	15	25	–	9
Ca ($\mu\text{g g}^{-1}$)	570	1320	350	850	1300	1430	1500	2770
Fe ($\mu\text{g g}^{-1}$)	43	67	65	100	52	82	109	157
Mg ($\mu\text{g g}^{-1}$)	790	1890	470	3330	1830	1400	3810	2800
K ($\mu\text{g g}^{-1}$)	7180	12460	6770	13750	13920	14060	11910	17970
P ($\mu\text{g g}^{-1}$)	2520	3670	2810	4380	3670	4070	4890	7040
Na ($\mu\text{g g}^{-1}$)	240	150	60	580	170	240	300	20
Zn ($\mu\text{g g}^{-1}$)	28	27	33	61	28	51	19	50
Vitamin B6 ($\mu\text{g g}^{-1}$)	5	4	4	4	3	4	4	4
Thiamin ($\mu\text{g g}^{-1}$)	5	6	9	7	6	5	6	9
Riboflavin ($\mu\text{g g}^{-1}$)	2	2	2	2	2	2	1	9
Vitamin C ($\mu\text{g g}^{-1}$)	40	48	45	15	0	45	40	60
Vitamin E ($\mu\text{g g}^{-1}$)	8	5	5	0	0	2	0	9
Vitamin A (IU)	67	114	39	33	28	0	32	22

Source: ¹³⁶

Table 2. Impact of Salt Stress on Grain Quality and Composition in Food Legumes.

Crop	Salinity imposition	Grain quality indicator	Decrease (–) /increase (+) over control	References
Mung bean	Salinity (4500 ppm)	Protein content	–11%	21
	Salinity (6000 ppm)		–20%	
Mung bean	Salinity (4500 ppm)	Total soluble sugars	–29%	21
	Salinity (6000 ppm)		–32%	
Mung bean	Salinity (4500 ppm)	Total amino acids	–19%	21
	Salinity (6000 ppm)		–21%	
Mung bean	Salinity (4500 ppm)	Nitrogen	+5%	21
	Salinity (6000 ppm)		–24%	
	Salinity (4500 ppm)		–37%	
Mung bean	Salinity (4500 ppm)	Phosphorus	+10%	21
	Salinity (6000 ppm)		–20%	
	Salinity (4500 ppm)		–30%	
Mung bean	Salinity (4500 ppm)	Potassium	+12%	21
	Salinity (6000 ppm)		–8%	
	Salinity (4500 ppm)		–13%	
Soybean	NaCl (3 dS m ^{–1})	Oil content	–27%	24
	NaCl (6 dS m ^{–1})		–57%	
	NaCl (9 dS m ^{–1})		–77%	
Soybean	NaCl (3 dS m ^{–1})	Protein content	–29%	24
	NaCl (6 dS m ^{–1})		–60%	
	NaCl (9 dS m ^{–1})		–79%	
Soybean	NaCl (9 dS m ^{–1})	Oil content	–75%	20
		Protein content	–77%	
Mung bean	Salinity (4500 ppm)	Sodium	+40%	21
	Salinity (6000 ppm)		+106%	
	Salinity (4500 ppm)		+255%	
Chickpea	50 mM	Sodium	+200%	137
	100 mM		+271%	
	50 mM	Potassium	–79.09%	
	100 mM		–72.72%	
	2 dS m ^{–1}	Sodium	+79.80%	

	9 dS m ⁻¹	Potassium	+0.58%	
Faba bean	50 mM	Total carbohydrates	−9.97%	138
	100 mM		−33.40%	
	50 mM	Potassium	−3.30%	
	100 mM		−11.57%	
	50 mM	Sodium	+12.5%	
	100 mM		+62.5%	
	50 mM	Magnesium	−28.57%	
	100 mM		−28.57%	
Chickpea	40 mM NaCl	Sodium	+51.03%	139
	40 mM NaCl	Potassium	+40.31%	
	40 mM NaCl	Chloride	+58.41%	

Table 3. Impact of drought stress on grain quality and composition in food legumes.

Crop	Drought	Experimental conditions	Grain quality indicator	Decrease (–) /increase (+) over control	References
Chickpea	Severe drought vs. well watered	Field trial	Total protein yield of crop	–41%	23
Chickpea	Rainfed vs. irrigated conditions	Field trial	Sodium content	–33%	106
			Potassium content	–25%	
			Calcium content	–7%	
Chickpea	Drought vs. well watered	Field trial	Protein content	–5%	100
Mung bean	Severe drought vs. well watered	Field trial	Protein content	+10%	22
			Total protein yield	–88%	
Spotted bean	Water stress at and reproductive stage	Field trial	Protein content	+6%	29
Mung bean	Drought at reproductive stage	Field trial	Protein content	+8%	28
Mung bean	Drought at vegetative stage			+3%	28
Faba bean	Early-season severe water stress	Field trial	Carbohydrate content	+4%	92
Faba bean	Early-season severe water stress		Fat content	+5%	92
Faba bean	Early-season severe water stress		Protein content	+14%	92
Faba bean	Severe water stress	Field trial	Protein content	+3–9%	27
Lupins	Water stress 75% stress	–	Protein content	–35%	30
Lupins	Water stress 15 days after anthesis	Pot trial	Soluble sugar	–18%	104
			Crude fiber	–11%	
			Starch	–43%	
Common bean	Water stress (30% WHC at early pod-fill stage; drought susceptible cultivar)	Field trial	Sucrose content	–29 to 47%	101
Common bean	Water stress (30% WHC at early pod-fill stage; drought-resistant inbred line)		Sucrose content	+43%	101
Common bean	Water stress (30% WHC at early pod-fill stage)		Starch content	–18 to 20%	101
Soybean	Severe drought at seed filling	Greenhouse	Oil content	–3%	26
Soybean	Severe drought at seed filling	trial	Protein	+5%	26

WHC = waterholding capacity

Table 4. Impact of heat stress on grain quality and composition in food legumes.

Crop	Heat stress	Experimental conditions	Grain quality indicator	Decrease (–) /increase (+) over control	References
Peanut	Sinusoidal temp of 32/26°C; control 20/14°C	Greenhouse trial	Total sugars	–24.5%	117
			Starch	–53%	
			Protein	–19.6%	
Peanut	Sinusoidal temp of 26/20°C; control 20/14°C	Greenhouse trial	Oil content	+20%	117
			Oleic acid	+24%	
Soybean	High temp 40/30°C; control 15/30°C at grain development	Field trial	Oleic acid	+104%	39
			Linolenic acid	–48.6	
Soybean	Sinusoidal temp of 33/28°C; control 18/13°C at grain filling	Phytotron trial	Oil content	+37%	38
			Oleic acid	+196%	
Soybean	Sinusoidal temp of 33/28°C; control 18/13°C at grain filling	Phytotron trial	Sucrose	–56%	38
Chickpea	Elevated temperature	–	Soluble proteins	+20%	35
Chickpea	Temp higher than 32/20°C at grain filling	Field trial	Sucrose content	–9%	37
Kidney bean	Sinusoidal temp of 34/24°C; control 28/18°C	Greenhouse trial	Oil content	–22.7%	36
Soybean	High temp 35°C at grain filling; control 29°C	Greenhouse trial	Oil content	+3%	26
Soybean	High temp 35°C at grain filling; control 29°C		Protein	+4.0%	26

Table 5. Impact of heavy metals stress on grain quality and composition in food legumes.

Crop	Heavy metals	Level (mg kg ⁻¹ of soil)	Grain quality indicator	Increase (+)/decrease (−) over control	References
Chickpea	Cadmium	11.5	Grain protein	−11%	129
		23		−22%	
Greengram		6		−4%	44
		12		−6%	
		24		−8%	
Chickpea	Chromium	67.5		+3%	129
		135		−2%	
Greengram		34		+5%	44
		68		+7%	
		136		+11%	
Chickpea	Copper	66.9		−9%	129
		143.8		−18%	
Greengram		334.5		−4%	44
		669		−5%	
		1388		−6%	
Chickpea	Nickel	290.1		−2%	129
		580.2		−16%	
Chickpea	Lead	195		+3%	129
		390		+6%	
Chickpea	Zinc	4890		+10%	129
		9780		+19%	
Soybean	Cadmium	0.1 mM	Grain oil	−23%	131
		0.5 mM		−28%	
		1.0 mM		−33%	
Soybean	Mercury	0.1 mM		−38%	131
		0.5 mM		−58%	
		1.0 mM		−68%	

Table 6. Impact of elevated CO₂ on grain quality and composition in food legumes.

Crop	Level of CO₂ ($\mu\text{mol mol}^{-1}$)	Grain quality indicator	Increase (+)/ decrease (–) over control	References
Kidney bean	700	Glucose	–27	36
Mung bean	700	Soluble proteins	–9.9	135
		Total soluble sugars	+9.3–15.1	
		Reducing sugars	–8.9 to 9.4	
		Starch content	+15.5	
Mung bean	667	Palmitic acid	–8.56	64
		Omega-6 fatty acids	–21.54	
		Omega-3 fatty acids	+10.04	

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