Journal of Environmental Sciences and Sustainability

ISSN: 3106-7883 | 3106-7875
Volume 2, Issue 4, 2025

STRENGTHENING GLOBAL NUTRITION THROUGH OILSEED CROP BIOFORTIFICATION

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Keywords
Biofortification, Oilseed Crops, Nutritional Security, Genetic Modification

Article History
Received: 10 October 2025
Accepted: 15 December 2025
Published: 31 December 2025

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Abstract

Malnutrition resulting from deficiencies in essential vitamins and minerals remains a major global public health concern. Biofortification—the process of enhancing the nutritional quality of crops through genetic engineering, conventional breeding, and agronomic interventions—offers a sustainable and long-term strategy to combat this challenge.

Oilseed crops such as soybean, canola, sunflower, olive, safflower, and sesame play a central role in human nutrition, providing fats, proteins, and essential micronutrients. Enhancing the nutritional profiles of these crops presents significant opportunities to alleviate deficiencies in iron, zinc, omega-3 fatty acids, and vitamins A, D, and E. Recent progress includes the development of canola varieties enriched with lysine, carotenoids, and omega-3 fatty acids, transgenic safflower with elevated omega-9 content, and selenium-enriched olive oil.

Emerging approaches, including nutrient priming and gene-editing technologies, have facilitated the production of cultivars with improved micronutrient composition, thereby enhancing their dietary and health benefits. The adoption of biofortified oilseed crops can substantially improve nutrient intake and help reduce malnutrition, particularly in resource-limited settings. Moreover, integrating biofortification with precision agriculture and advanced technologies can further strengthen food security and public health outcomes. Overall, biofortification represents a forward-looking and sustainable pathway toward ensuring a more nutritious and resilient global food system.

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INTRODUCTION

Malnutrition occurs when the body receives an imbalance of nutrients, leading to adverse health effects (Ofori et al., 2022). This condition arises when the body does not receive adequate amounts of essential nutrients, such as vitamins and minerals, leading to adverse health effects. Malnutrition manifests in various forms, including underweight (low weight for age), wasting (low weight for height) and stunting (low height for age) (Dwivedi et al., 2023).

Micronutrient deficiencies, such as inadequate intake of zinc, iron, vitamin A, and iodine, not only have severe health consequences but also impose significant economic burdens. These deficiencies can lead to productivity losses amounting to approximately 0.8% to 2.5% of a nation's gross domestic product (GDP). Specifically, iron deficiency anemia ranks among the top five causes of years lived with disability globally and is the leading cause among women (Fullman et al., 2018).

Iron deficiency anemia affects a substantial portion of the global population, impacting approximately 30% of individuals worldwide. Thiscondition is particularly prevalent among pregnant women, withan estimated 36.5% affected, and non-pregnant women of reproductive age, with a prevalence of 29.6%. According to WHO Children under five years of age are also significantly affected, with an estimated 269 million children experiencing anemia globally notably, anemia is responsible for

ISSN: 3106-7883 | 3106-7875
Volume 2, Issue 4, 2025

approximately 20% of maternal deaths, underscoring its severe impact on maternal health. Zinc deficiency is another critical nutritional concern, affecting both men and women across various age groups. Globally, an estimated 17.3% of the population is at risk of inadequate zinc intake. The prevalence of zinc deficiency varies significantly across regions, with higher rates observed in South and Southeast Asia, Sub-Saharan Africa, and Central America. This deficiency can lead to a range of health issues, including impaired immune function, growth retardation, and increased susceptibility to infections (Dfid & Ukaid, 2012).

Vitamin A deficiency (VAD) poses a significant public health challenge, particularly among pregnant women in various regions. In the Middle East and North Africa (MENA) region, the age-standardized prevalence rate of VAD was 5,249.9 per 100,000 population in 2019, indicating a substantial number of cases (Safari et al., 2024). Similarly, South Asian countries report high VAD prevalence, leading to increased morbidity and mortality among infants, children, and pregnant women (Akhtar et al., 2013). Iodine deficiency is another critical concern, affecting approximately 30% of the global population. During pregnancy, insufficient iodine intake can lead to maternal and fetal hypothyroidism, impairing neurological development of the fetus and resulting in conditions such as cretinism, characterized by profound mental retardation (Skeaff, 2011).

Pregnant women are also susceptible to deficiencies in other essential nutrients, including vitamin D, calcium, and folates. These deficiencies can lead to adverse health outcomes for both the expectant mother and the developing child, emphasizing the need for adequate nutritional intake during pregnancy (Oh et al., 2020). Addressing these micronutrient deficiencies is crucial for improving maternal and child health outcomes globally (Dhaliwal et al., 2022). Over the past decade, Pakistan has faced persistently high and detrimental rates of malnutrition. Approximately 25% of the population in this low- to middle-income country, the world's fifth most populous nation, cannot afford the daily intake of 2,350 calories recommended for adults. Malnutrition is a widespread issue, with 38% of children under five experiencing stunting, indicating chronic malnutrition. The under-five mortality rate stands at 61 deaths per 1,000 live births, with malnutrition contributing to approximately 35% of these fatalities. (Asim & Nawaz, 2018). The 2011 National Nutrition Survey (NNS) revealed that 58% of Pakistani households experienced food insecurity, marking a deterioration from the 51% reported in 2007 (NNS, 2011). Notably, 9.8% of these households faced severe hunger (Khan et al., 2015). This escalating food insecurity has likely precipitated various social and economic challenges for the country, compounding the immediate hardships of hunger (NNS, 2011).

Micronutrient deficiencies among Pakistani children are alarmingly high, posing significant public health challenges. According to the 2018 National Nutrition Survey (NNS), more than half (53.7%) of children under five are anemic, with 28.6% suffering from iron deficiency anemia. Vitamin A deficiency affects 51.5% of these children, while 62.7% are deficient in vitamin D. Zinc deficiency is also prevalent, impacting 18.6% of children under five (Pakistan, 2018).

A study focusing on preschool and school-aged children in flood-affected areas revealed even higher deficiency rates: 90.8% were calcium deficient, 88.3% were zinc deficient, 26.7% were iron deficient, and 53.5% were vitamin A deficient (Haq IU et al., 2021). These deficiencies have profound implications for children's growth, cognitive development, and overall health, underscoring the urgent need for targeted nutritional interventions and policies to address this critical issue (Tanweer et al., 2015).

Journal of Environmental Sciences and Sustainability
ISSN: 3106-7883 | 3106-7875
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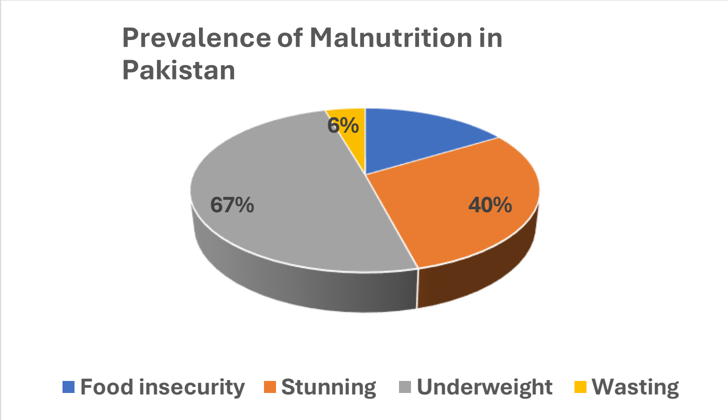

Figure 1. Prevalence of Malnutrition in Pakistan (Soofi *et al.,* 2023)

Biofortification is a method for improving crop yield and an agricultural approach to deal with the problems of nutritional security (Dhaliwal *et al.*, 2022). His approach involves increasing the concentration of essential micronutrients, such as vitamins and minerals within staple crops through methods like conventional plant breeding, agronomic practices, or modern biotechnological techniques. The goal is to develop micronutrient-dense cultivars that retain desirable agronomic traits and consumer preferences, thereby addressing nutrient deficiencies in populations reliant on these staples. Globally, there is a growing recognition of biofortification as a sustainable solution to combat micronutrient deficiencies, often referred to as "hidden hunger." Notable examples include:

- **Golden Rice** Genetically engineered to produce β-carotene, a precursor of vitamin A, Golden Rice aims to alleviate vitamin A deficiency prevalent in regions where rice is a dietary staple.
- **High-Iron Beans** Developed to contain higher iron content, these beans address iron deficiency, particularly in areas where beans are a primary protein source.

These biofortified crops have demonstrated efficacy in reducing deficiencies of vital micronutrients such as iron, vitamin A, and zinc, thereby positively impacting public health outcomes.(Meenakshi, 2009). The efficacy of biofortification is exemplified by successful developments such as Golden Rice and High-Iron Beans. Golden Rice has been genetically modified to biosynthesize β-carotene, a precursor of vitamin A, in the rice endosperm, effectively addressing vitamin A deficiency in populations that rely heavily on rice as a dietary staple (*Tang et al.*, 2009, Akata *et al.*, 2013).

Similarly, High-Iron Beans have been bred to contain elevated levels of iron, targeting iron deficiency prevalent in regions where beans are a primary protein source. These biofortified crops have demonstrated significant potential in mitigating deficiencies of essential micronutrients, thereby enhancing public health outcomes. (Ashoka P. *et al.*, 2023).

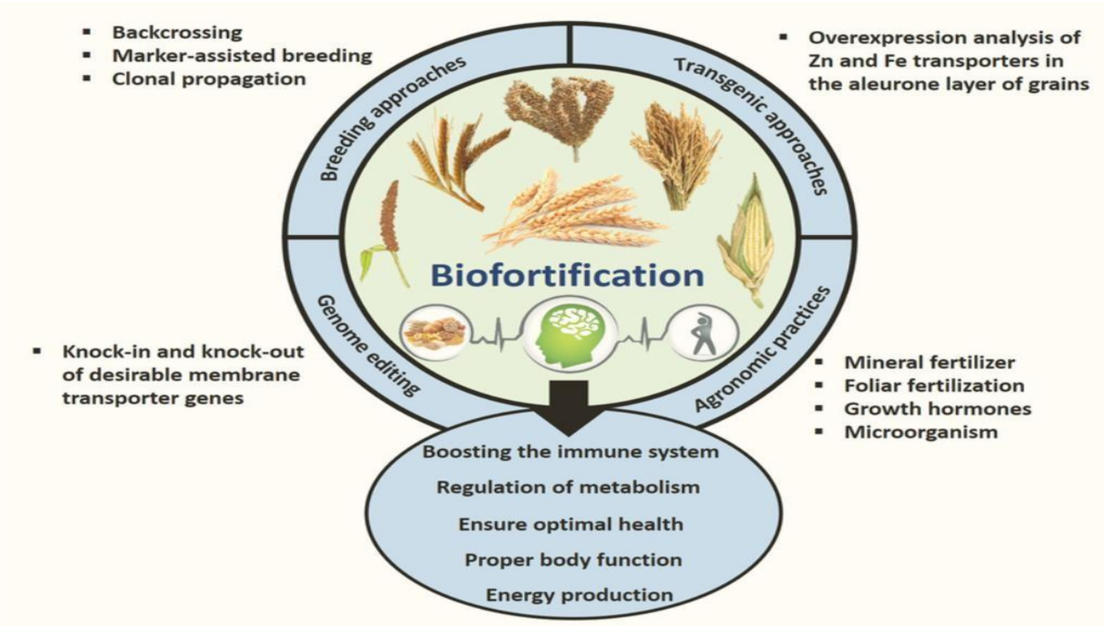

Figure 2. The Role of Membrane Transporters in the Biofortification of Zinc and Iron in Plants

The primary oilseed crops, soybean, olive, safflower, canola, maize, peanut, and sunflower are cultivated for their oil content. The composition of these oils varies, particularly in the ratios of monounsaturated to saturated fats and the concentrations of omega-6 (n6) linoleic acid (LA, 18:2) and omega-3 (n3) alpha-linolenic acid (ALA, 18:3) fatty acids. A deficiency in omega-3 fatty acids is a prevalent dietary concern worldwide. The essential n3 polyunsaturated fatty acid, alpha-linolenic acid (ALA), has been associated with a reduced risk of coronary heart disease (CHD) through several physiological mechanisms, including anti-inflammatory effects, modulation of platelet function, regulation of arterial compliance, antiarrhythmic properties, and enhancement of endothelial cell function. (Colombo et al., 2018). Dietary intake of omega-6 fatty acids has been associated with several health benefits, including reducing low-density lipoprotein (LDL) cholesterol levels, which may lower the risk of heart disease. Additionally, omega-6 fatty acids play a role in stimulating skin and hair growth, maintaining bone health, regulating metabolism, and supporting reproductive system functions (Maciej Serda et al., 2013).

Omega-9 fatty acids, such as oleic acid, are monounsaturated fats shown to exhibit anti-inflammatory properties. These fatty acids can modulate the production of inflammatory mediators, potentially reducing inflammation in various pathological and physiological conditions, including wound healing and eye inflammation. Incorporating omega-6 and omega-9 fatty acids into the diet, while maintaining a proper balance with omega-3 fatty acids, is essential for optimal health outcomes.(Farag & Gad, 2022).

Table 1. Biofortification Strategy to combat Malnutrition

Oilseed Crops	Biofortification Strategy	Targeted Nutrients	Impact on Malnutrition	Impact on Public Health	Typical Regional Deficiencies	Notes
Canola	Genetic Modification & Soil Fortification	Iron, Vitamin A	Enhances iron and vitamin A levels,	Reduces iron deficiency anemia	Common in developing countries	Effective in areas with low iron levels

			combating deficiencies			
Olive	Soil Fortification	Iron, Calcium	Addresses deficiencies in iron and calcium	Helps combat osteoporosis	Calcium deficiency in elderly	Also improves oil quality
Soybean	Genetic Modification	Iron, Zinc	Significant improvement in iron and zinc levels	Reduces zinc deficiency, boosts immunity	Common in low-income regions	Boosts overall nutritional value
Safflower	Foliar Spraying & Genetic Modification	Vitamin E, Iron	Increases vitamin E and iron content, addressing deficiencies	Improves antioxidant levels	Vitamin E deficiency in various populations	Suitable for regions with vitamin E and iron deficiencies
Sunflower	Soil Fortification	Zinc, Vitamin A	Addresses zinc and vitamin A deficiencies	Addresses zinc deficiency in diets	Zinc deficiency in vulnerable populations	Effective in zinc-poor soils
Sesame	Genetic Modification & Foliar Spraying	Calcium, Iron	Enhances calcium and iron content, combating deficiencies	Improves bone health and metabolism	Calcium deficiency in rural areas	Combines both approaches for effectiveness

BIOFORTIFICATION IN OILSEED CROPS

Canola

Canola (*Brassica napus*) is a globally significant oilseed crop, renowned for the high-quality oil extracted from its seeds. This oil is notably low in saturated fats, comprising approximately 7% of its total fatty acid content, which is lower than that of many other common cooking oils (Facts *et al.*, 2006). Canola oil is also a rich source of essential nutrients, particularly vitamins E and K. Vitamin E functions as an antioxidant, safeguarding cells from oxidative damage, while vitamin K plays a crucial role in blood clotting and bone metabolism. The fatty acid profile of canola oil is characterized by a favorable balance of unsaturated fats. It contains approximately 62% monounsaturated fats, primarily oleic acid, and significant amounts of polyunsaturated fats, including about 19% omega-6 (linoleic acid) and 9% omega-3 (alpha-linolenic acid) fatty acids. This 2:1 ratio of omega-6 to omega-3 fatty acids is considered nutritionally ideal, contributing to heart health and reducing inflammation (Aftab *et al.*, 2021). These attributes make canola oil a versatile and health-promoting option for culinary applications, aligning with dietary recommendations for healthy fat consumption. (Canada, 2015). Canola oil is characterized by its low saturated fat content, comprising approximately 7% of its total fat composition. It is rich in monounsaturated fats (approximately 64%) and polyunsaturated fats (about 28%), including essential fatty acids such as alpha-linolenic acid (ALA), an omega-3 fatty acid, and linoleic acid, an omega-6 fatty acid (Kerr & Dunford, 2018).

Nutritionally, a one-tablespoon serving of canola oil provides approximately 2.4 milligrams of vitamin E, accounting for about 16% of the Daily Value (DV), and 17 micrograms of vitamin K, contributing approximately 14% of the DV. These nutritional attributes make canola oil a healthful option for culinary applications, offering a favorable fatty acid

ISSN: 3106-7883 | 3106-7875
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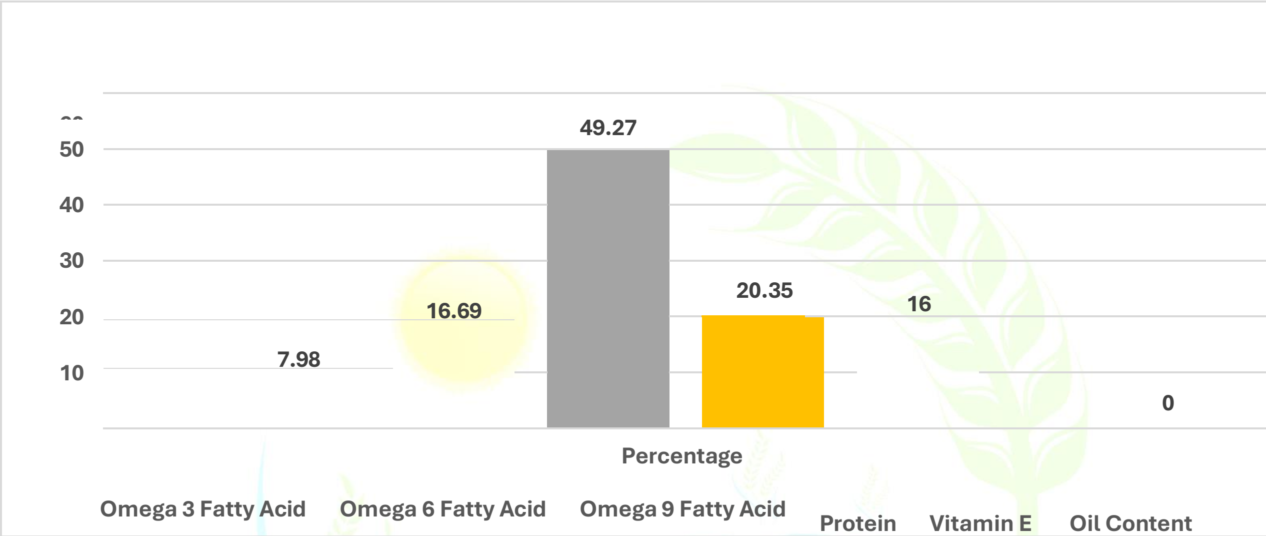
profile and contributing to the intake of essential vitamins (Kubala, 2019). To enhance the nutritional profile of canola oil, fortification strategies can target increasing levels of vitamins D and A, as well as minerals like iron and calcium, which are often deficient in many diets. Fortifying edible oils with vitamins A and D has been implemented in various countries to address micronutrient deficiencies. For instance, a systematic review indicated that such fortification can effectively improve vitamin intake and ameliorate deficiency states in the general population (Szabó et al., 2023). Specifically, fortifying canola oil with vitamin D has demonstrated efficacy in enhancing serum 25-hydroxyvitamin D concentrations. Randomized controlled trials have shown that consuming vitamin D-fortified canola oil resulted in significant increases in these serum levels over a three-month period (Alnafisah *et al.*, 2024). Additionally, products like Land O'Lakes' Butter with Canola Oil Plus Calcium and Vitamin D exemplify successful fortification efforts, providing consumers with enhanced nutritional options. While fortifying canola oil with vitamins A and D is feasible and has been practiced, incorporating minerals such as iron and calcium presents more complex challenges due to potential interactions affecting bioavailability and stability. Nonetheless, ongoing research aims to develop effective fortification methods to address these hallenges and improve the nutritional quality of edible oils (Fairweather-Tait et al. 2002). Implementing such fortification strategies in canola oil could play a significant role in mitigating micronutrient deficiencies and promoting public health (Nichols DG., 1988).



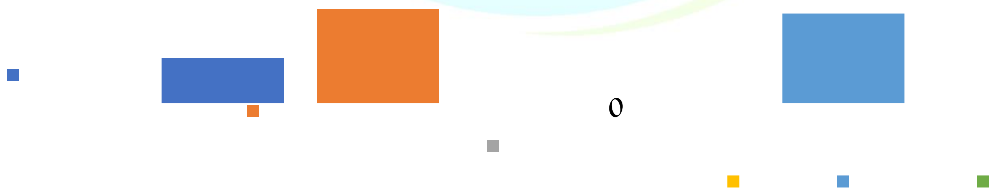


Figure 3. Nutrient Composition of Canola (Batista *et al.,* 2015)

To further enhance the health benefits of canola oil, several genetic modifications have been implemented:

1. **Carotenoid Enhancement**: Overexpressing bacterial phytoene synthase (PSY) in plants has been shown to increase carotenoid content, predominantly α-carotene and β- carotene (Ampomah-Dwamena *et al.*, 2022).
2. **Gamma-Linolenic Acid (GLA) Production**: Canola naturally lacks Δ6-desaturase activity, an enzyme necessary for synthesizing GLA. By

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introducing genes encoding Δ6- desaturase, transgenic canola lines have been developed that accumulate significant levels of GLA, enhancing the oil's nutritional profile (Hong *et al.*, 2002).

3. **Phytic Acid Reduction**: Phytic acid is known to chelate micronutrients, reducing their bioavailability. Transgenic canola varieties, such as Phytaseed™ Canola developed by BASF, express phytase enzymes that degrade phytic acid, thereby increasing the availability of phosphorus and other essential minerals.

These genetic modifications aim to improve the nutritional quality and economic value of canola oil, addressing dietary deficiencies and enhancing public health outcomes (Mandal *et al.*, 2024) .

Biofortified canola has been developed to enhance its lysine content, an essential amino acid often limited in

conventional canola varieties. This advancement has been achieved through genetic engineering techniques that circumvent the normal feedback regulation of key enzymes in the lysine biosynthetic expression of the bacterial phytoene synthase gene (*crtB*). Utilizing a seed-specific promoter to drive *crtB* expression has resulted in a substantial increase in carotenoid levels, predominantly α-carotene and β-carotene, thereby enhancing the nutritional value of canola oil (Shewmaker *et al.*, 1999).

These biotechnological advancements exemplify the potential of genetic engineering to fortify canola with essential nutrients, addressing dietary deficiencies and improving public health outcomes. (Bonet *et al* 2016). Transgenic canola varieties have been engineered to enhance specific nutritional attributes through various genetic modifications:

1. **Carotenoid Enhancement:**

○ **Overexpression of Phytoene Synthase (crtB)**: Introducing the bacterial phytoene synthase gene (*crtB*) into canola seeds has led to a substantial increase in carotenoid content, predominantly α-carotene and β-carotene (Ravanello *et al.*, 2003).

○ **Silencing of Lycopene ε-Cyclase and DET1 Genes**: Suppressing the expression of lycopene ε-cyclase and *DET1* genes has resulted in elevated levels of β-carotene, xanthophylls, and lutein, thereby enhancing the nutritional profile of canola (*Nisar et al.*, 2015).

pathway, leading to increased lysine accumulation in canola seeds (Falco *et al., 1995*).

By addressing dietary lysine deficiencies, particularly in regions where canola is a staple crop, this development has resulted in a significant enhancement of lysine levels, making canola a more nutrient-dense option for both animal feed and human consumption. (Kiani *et al.*, 2017).

Enhancing the nutritional profile of canola has been achieved through targeted genetic modifications:

1. **Lysine Enhancement**: The introduction of bacterial genes encoding Aspartokinase (AK) and dihydrodipicolinate synthase (DHDPS) from *Corynebacterium* and *Escherichia coli*, respectively, has led to a fivefold increase in lysine content. These enzymes play pivotal roles in the lysine biosynthetic pathway, and their overexpression circumvents native feedback inhibition mechanisms, resulting in elevated lysine accumulation (Falco *et al., 1995*).

2. **Carotenoid Biosynthesis**: An innovative approach to augment carotenoid content in canola seeds involves the seed-specific

2. **Lysine Enrichment:**

○ **Expression of Dihydrodipicolinate Synthase (DHDPS) and Aspartokinase (AK)**: By introducing genes encoding DHDPS and AK enzymes, derived from bacterial sources, canola plants have achieved increased lysine content. These enzymes play pivotal roles in the lysine biosynthetic pathway, leading to enhanced lysine accumulation (Shaul & Galili, 1993).

3. **Modification of Fatty Acid Profile:**

○ **Overexpression of Thioesterase Gene (ChFatB2)**: Enhancing the expression of the *ChFatB2* gene has altered the fatty acid composition in canola, potentially improving its nutritional and industrial value.

○ **Expression of Δ12 and Δ6 Desaturases**: Introducing genes encoding Δ12 and Δ6 desaturase enzymes has enabled the biosynthesis of gamma-linolenic acid (GLA) in canola seeds, adding a valuable polyunsaturated fatty acid to its oil content.

4. **Reduction of Phytic Acid**

○ **Phytase Expression**: Incorporating phytase genes into canola has led to the degradation of phytic acid, an anti-nutritional factor that chelates essential minerals. This modification enhances

ISSN: 3106-7883 | 3106-7875
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mineral bioavailability, improving the nutritional quality of canola-based food and feed.

These genetic interventions collectively contribute to the development of canola varieties with improved nutritional profiles, addressing dietary deficiencies and meeting specific health and industrial requirements (Garg *et al.,* 2018).

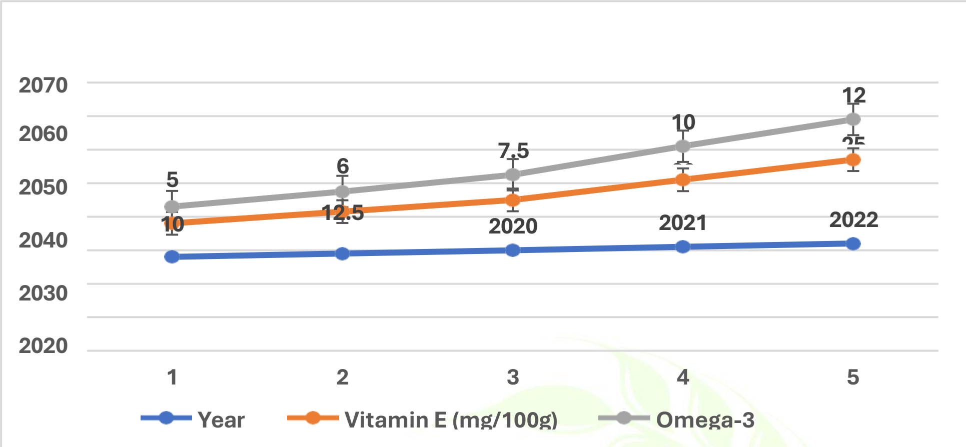


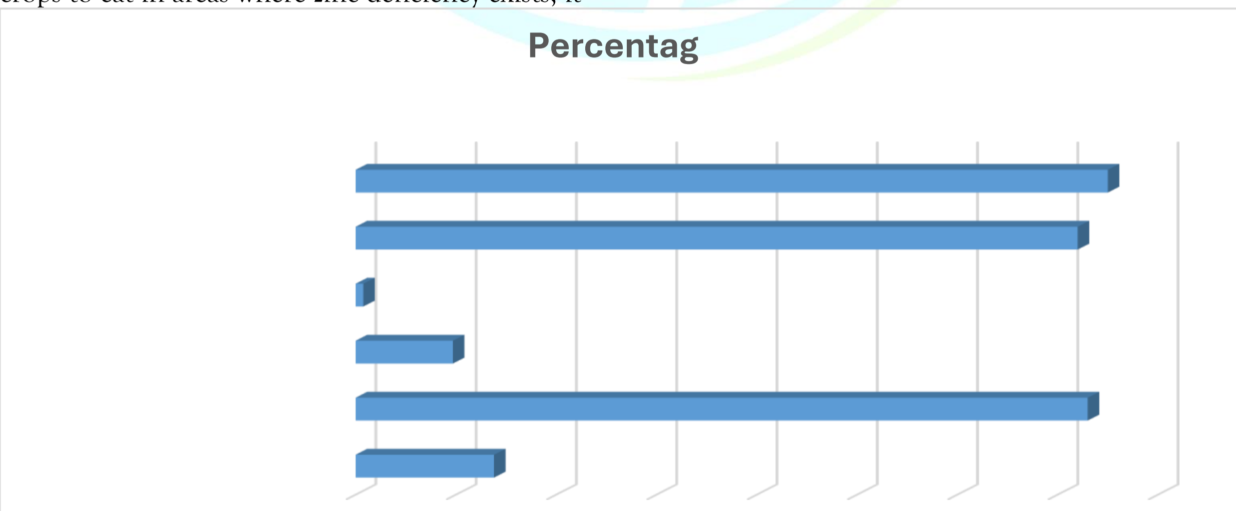
Figure 4. Biofortification in Canola over time (So & Duncan, 2021)

Maize

Maize is a major food crop for over 200 million people worldwide. Almost 15% of the world's protein and 20% of its calories come from maize. Maize is a significant oilseed crop and consumed in areas where zinc deficiency is common, it makes sense to biofortify this crop with zinc. Genetic and agronomic methods might be used to biofortify maize with zinc. Given the significance of zinc for human health, the current study discusses the difficulties in spreading zinc-enriched maize genotypes and focuses on the development of zinc biofortified genotypes to combat

malnutrition. Since maize is one of the most popular crops to eat in areas where zinc deficiency exists, it has been chosen as the targeted crop (Maqbool & Beshir, 2019).

Two necessary amino acids that are involved in the production of proteins and neurotransmitters are tryptophan and lysine. Children should get 35 mg/kg of lysine per day, while adults should get 30 mg/kg. The daily requirements for tryptophan in children and adults are 4.8 and 4 mg/kg body weight, respectively. Reduced appetite, stunted growth, inadequate skeletal development, and abnormal behaviors are the results of these amino acid deficiencies. Therefore, tryptophan and lysine concentrations in Quality



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Protein Maize (QPM) have been increased to about double those of regular maize cultivars (lysine: 0.15–0.20 percent in flour; tryptophan: 0.07–0.08 percent in flour), leading to much greater nutritional quality (Naik *et al.*, 2024).
Conventional breeding has successfully increased carotenoid content in staple foods, resulting in "-carotene-biofortified" maize that are now widely available in nations with malnourished populations and vitamin A deficiencies (Bonet *et al.*, 2016).

Olive
One of the most widely enjoyed foods in terms of nutrition is olives. It is therefore necessary to fortify the plant to satisfy nutritional requirements for olive organic products to meet dietary requirements (Kaur *et al.*, 2020). Olives are a good source of several essential nutrients, including monounsaturated fats. Olives contain 11-15% fat, with 74% being oleic acid, a type of monounsaturated fatty acid, vitamin E and fiber. Olives contain 4-6% carbs, most of which is fiber. Fiber makes up 52-86% of the total carb content. Olives also contain iron, copper, calcium (Rocha *et al.*, 2020). While olives are nutritious, their nutritional profile could be enhanced by fortifying with vitamins A and D, zinc and selenium (Nazario, 2020).

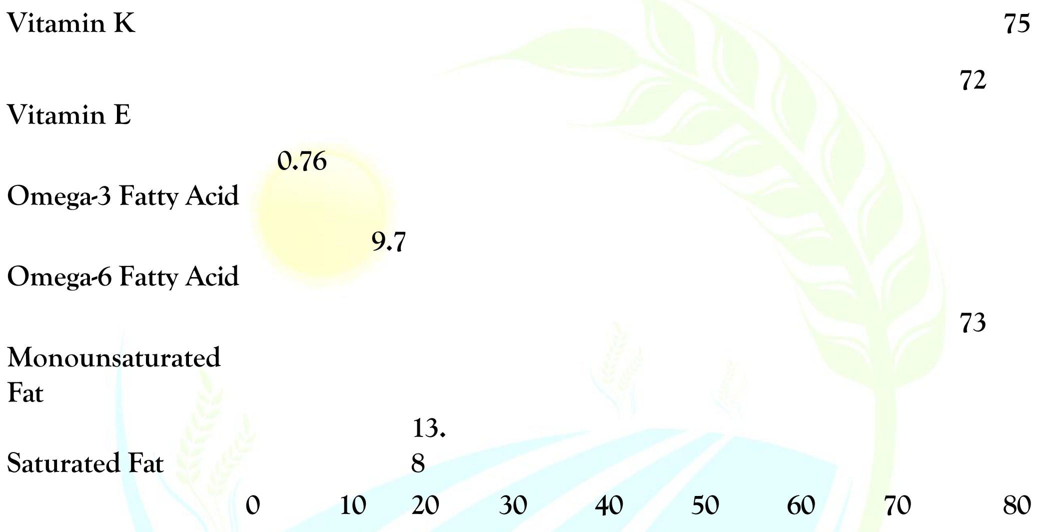

Figure 5. Nutrient Composition of Olive Oil (Rocha *et al.,* 2020)

By fortifying olives with these key nutrients, their overall nutritional value can be improved, making them an even healthier addition to the diet. The process of biofortifying food crops for human consumption is a direct means of increasing selenium (Se) intake through diet. It would be possible to enhance the selenium content of extra virgin olive oil (EVOO) by spraying sodium selenate on the olive tree canopy. When compared to the untreated controls, Se treatments increased the Se content in the EVOO by up to 50 times. All the EVOO samples have Se concentration that can be declared enough to be useful for providing an adequate quantity of Se to the human diet. The Se- enriched EVOO had a considerable increase in phenol and pigment level. The Se treatment had no detrimental effects on the fruit or sensory attributes of EVOO (D'Amato *et al.*, 2014). The addition of selenium to olives enhances their selenium level as well as other nutrient components. For example, phenols, carotenoids, and chlorophyll level have been shown to rise in EVOO treated with selenium, boosting its antioxidant activity and potentially expanding its shelf life (Hossain *et al.*, 2021). Consumption of selenium rich olives can supply at important dose of dietary selenium; a study observed that five olives can supply nearly 29µg, which is significant amount (De Bruno *et al.*, 2020). Additionally, taking selenium supplements has been associated with improved drought tolerance in olive trees, which improves the trees physiological responses to stress. This suggests that in addition to increasing nutritional quality, selenium may help olive harvest large longer. Biofortified selenium in olive is a useful method for boosting the nutritional profile of this significant Mediterranean crop, with implication for both health gains and agricultural resilience (D'Amato *et al.,* 2018).

Soybean

Soybeans are found to include 6.5% protein, 20% fat, considerable proportions of monounsaturated (4.4%) and polyunsaturated (11.3%) lipids, and 9.3% soluble and insoluble fiber. phosphorus, copper, magnesium, folate, vitamin K, and thymine are all prevalent in soybeans (Buckner *et al.,* 2016). Soybeans are nutritious, but the nutritional content might be improved by adding vitamins A and D, zinc, and selenium (Heuzé, V., Tran, G. and Kaushik, 2019).

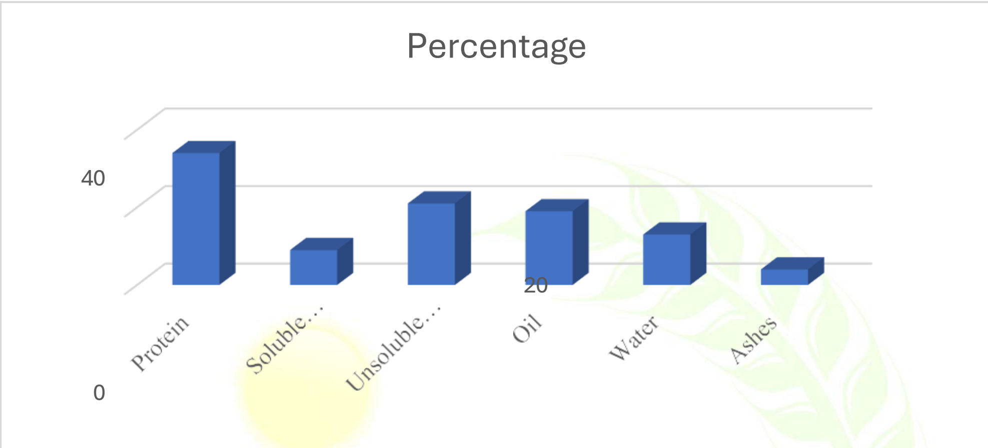

Figure 6. Nutrient Composition of Soybeans (Pekarovicova *et al.,* 2019)

By fortifying soybeans with these key nutrients, their overall nutritional value can be improved, making them an even healthier addition to the diet. As a high-protein food, soybeans (*Glycine max* L.) can be extremely helpful in closing the nutritional gap between what people consume and what their bodies need. Soybeans are regarded as a healthful food that is high in essential amino acids and protein for the human body, which lowers the risk of cancer, heart disease and osteoporosis, among other serious illnesses (Dhaliwal *et al.,* 2022).

To boost micronutrient levels and enhance nutrient bioavailability, soybeans can benefit from the biofortification program. Due to their high protein and oil content, versatility, and potential for biofortification, soybeans are useful tool in the fight to improve nutrition globally. Using methods for sequencing such as the Genotyping Framework for the Genetic Biofortification of Folates in Soybean, accessions can be genotyped to increase the amount of folate in the plant. Using sequencing methods like genotyping by sequencing (GBS), accessions can be phenotyped and genotyped to increase the amount of folate in soybeans (Agyenim-Boateng *et al.,* 2023).

Increasing grain yield from nutrient-rich seeds is the goal of biofortification. Additionally, seed nutri-priming has been presented to increase the bio accessibility and bioavailability of minerals such as Fe and Zn in soybean sprouts. An important point is that soaking the seeds might lower the quantity of antinutrient chemicals, including phytic acid, through leakage during the nutrient priming process (Poudel *et al.,* 2023).

Journal of Environmental Sciences and Sustainability
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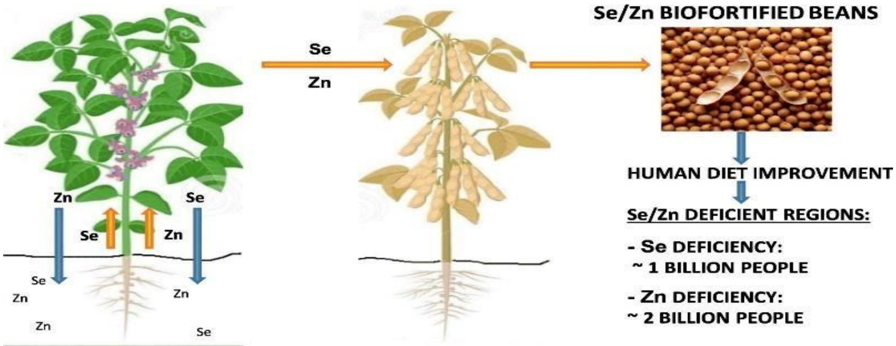

Figure 7. Biofortification of Soybean (*Glycine max* L.)

Enhancing folate content in soybean include identifying soybean germplasm with naturally high folate levels through profiling diverse accessions, elucidating the genetics underlying folate biosynthesis and accumulation in soybean seeds, optimizing growing conditions like temperature and light to maximize folate production and improving folate stability during soybean processing and storage (Science *et al.*, n.d.).

Safflower

Safflower is a commercially important agricultural crop. The main components of safflower seeds contain about 30-45% oil, the unsaturated fatty acids oleic (c18:1) and linoleic (c18:2) and the saturated fatty acids palmitic (c16:0), stearic (c18:0), and oleic (c18:1). The meal from safflower seeds has approximately 24% protein and it is also high in fiber. But safflower plants only naturally generate very little levels of GLA. Therefore, transgenic Safflower plants with seeds that are richer in GLA than what is found naturally would be very useful (Devi *et al.*, 2001).To enhance the nutritional profile of safflower, fortification efforts could focus on vitamins A and D, calcium, iron and zinc (Mosalman *et al.*, 2024).

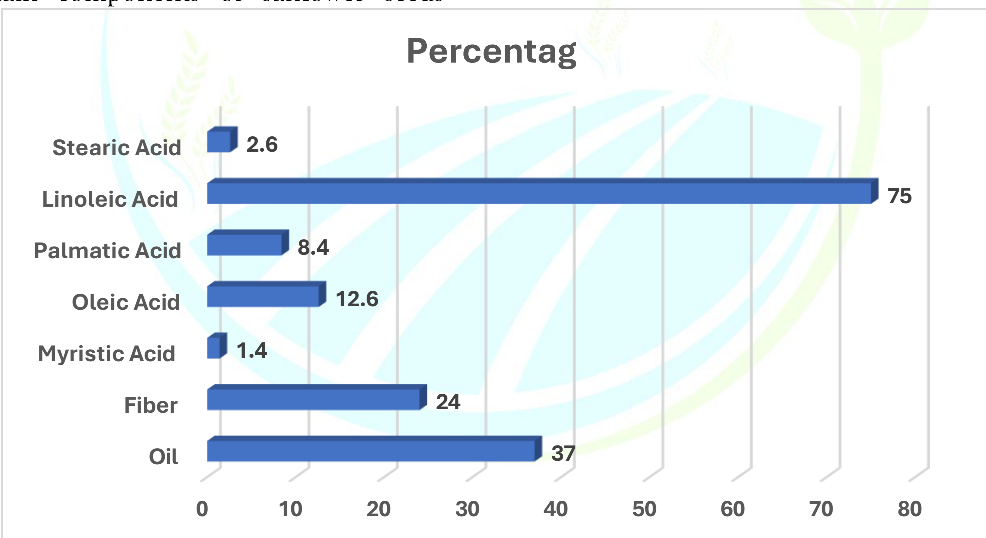

Figure 8. Nutrient Composition of Safflower (Afzal *et al.*, 2017)

The goal of genetic engineering was to boost the amount of ALA. About 78% of total fatty acids are composed of linoleic acid (LA), which is common in safflower seeds and a precursor to ALA. Safflower hypocotyls were successfully altered by researchers to have the delta-15 desaturase (FAD3) gene, which is unique to Arabidopsis and transform LA into ALA. A shorter seed-specific promoter was the driving force behind the alteration, which allowed targeted expression during seed development (Dwivedi *et al.*, 2023).

The biofortification of safflower to raise its alpha-linoleic acid content is an essential field of study for enhancing dietary offers of omega-3 fatty acids. Lack of ALA is linked with ailments caused by an imbalance in the ratio of Omega-6 fatty acid in diets,

ISSN: 3106-7883 | 3106-7875
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and is crucial for human health, particularly among those with inflammatory and cardiac diseases (Ofori *et al.*, 2022).

Transgenic safflower created via biofortification has an inferior LA to ALA ratio and a greater ALA content, both of which enhance health benefits. Safflower oil may be excellent plant-based source of omega-3 fatty acids for those who refrain from eating fish and other aquatic products (Mosalman *et al.*, 2024).

Safflower nourished with ALA and an increased and n6 to n3 ratio supplies additional minerals and health benefits. Transgenic safflower improved with ALA is a potentially beneficial and nutritionally superior novel. It has a lower ratio of LA to ALA, which is required for optimal health (Rani *et al.*, 2018). Plants

have reservoirs of fatty acids that may be transformed from linoleic and alpha-linolenic acid to STA and GLA, respectively, via a process known as delta 6 desaturase. There have been significantly high amounts of GLA in the seeds when the identical delta- 6-desaturase gene has been expressed (Devi *et al.*, 2001).

Sunflower

Sunflower (*Helianthus annuus* L.) is an oilseed crop of enormous importance because of the outstanding quality of the oil derived from its seeds worldwide. Sunflower seeds are highly nutritious, providing a range of essential nutrients that are vitamins, high in vitamin E (an antioxidant) and B-complex vitamins like thiamine (B1) and niacin (B3), protein(20-25%), monosaturated or polysaturated fat, selenium, magnesium, copper, and manganese. To enhance their nutritional profile, sunflower seeds could be fortified with vitamin A, vitamin D, zinc and folate (Petraru *et al.*, 2021).

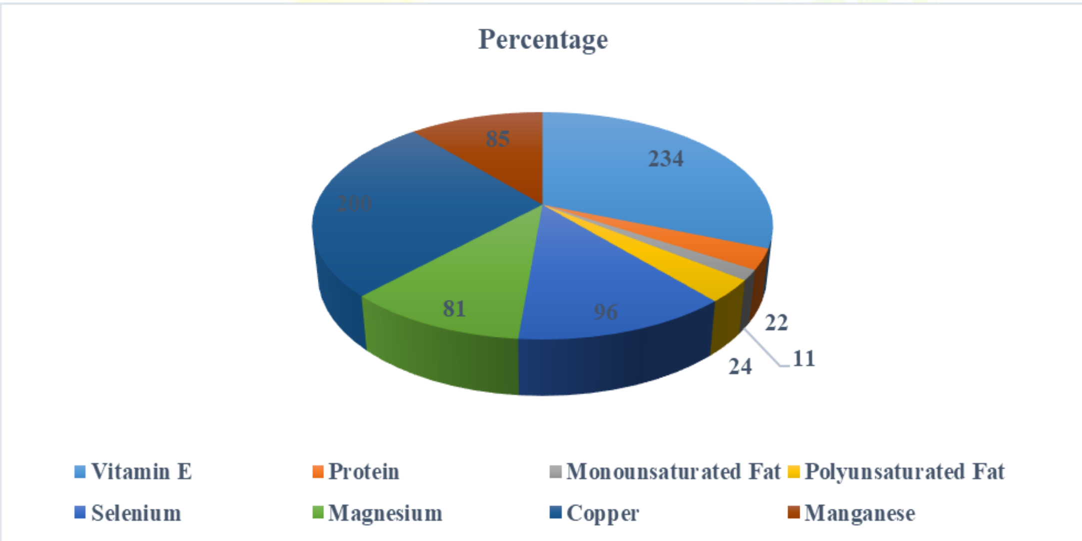

Figure 9. Nutrient Composition of Sunflower (Petraru *et al.*, 2021)

Zinc biofortification through seed nutrient priming is an effective method to increase zinc content in sunflower microgreens. Using zinc oxide (ZnO) and zinc-EDTA as zinc sources resulted in higher levels of chlorophyll and carotenoids in sunflower microgreens compared to using zinc sulfate (ZnSO4). Sunflower, as hyperaccumulator plant, can effectively store zinc in its tissues through mechanisms like compartmentalization in the vacuoles. However, the zinc biofortification did not affect the total phenolic content or antioxidant activity of the sunflower microgreens. Seed nutrient priming with alternative zinc sources is a promising approach for zinc biofortification of sunflower microgreens (Poudel *et al.*, 2023).

Biofortification of sunflower oil through dietary supplementation of selenium, vitamin E, and sunflower oil to dairy cows can increase the antioxidant content of the milk. Feeding dairy cows diets rich in linoleic and linolenic acids from sunflower oil can enhance the conjugated linoleic acid content in the milk. Sunflower oil has functional properties that make it suitable for specialty food applications (Koç & Karayiğit, 2022).

Journal of Environmental Sciences and Sustainability

ISSN: 3106-7883 | 3106-7875

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Soaking sunflower seeds in a zinc sulfate solution was the most efficient in increasing zinc accumulation in the resultant microgreens, with a 229.8% increase over the control (Poudel *et al.*, 2023). Zinc biofortification in sunflowers by seed priming and fertigation is a potential technique for improving the nutritional status of crops. Sunflower microgreens are an essential addition to diets, especially in areas with malnutrition, as these methods can increase zinc levels and boost their health effects (Poudel *et al.*, 2024).

Sesame

With a variety of vital elements, sesame seeds are very nutrient-dense. About 21.9% protein, 61.7% fat (mainly unsaturated), 13.5% carbohydrates, iron, calcium, zinc, magnesium, vitamin E and copper are all found in sesame seeds. Fortification of sesame seeds with vitamin A, vitamin D, and folate can improve their nutritional profile (Wei *et al.*, 2022).

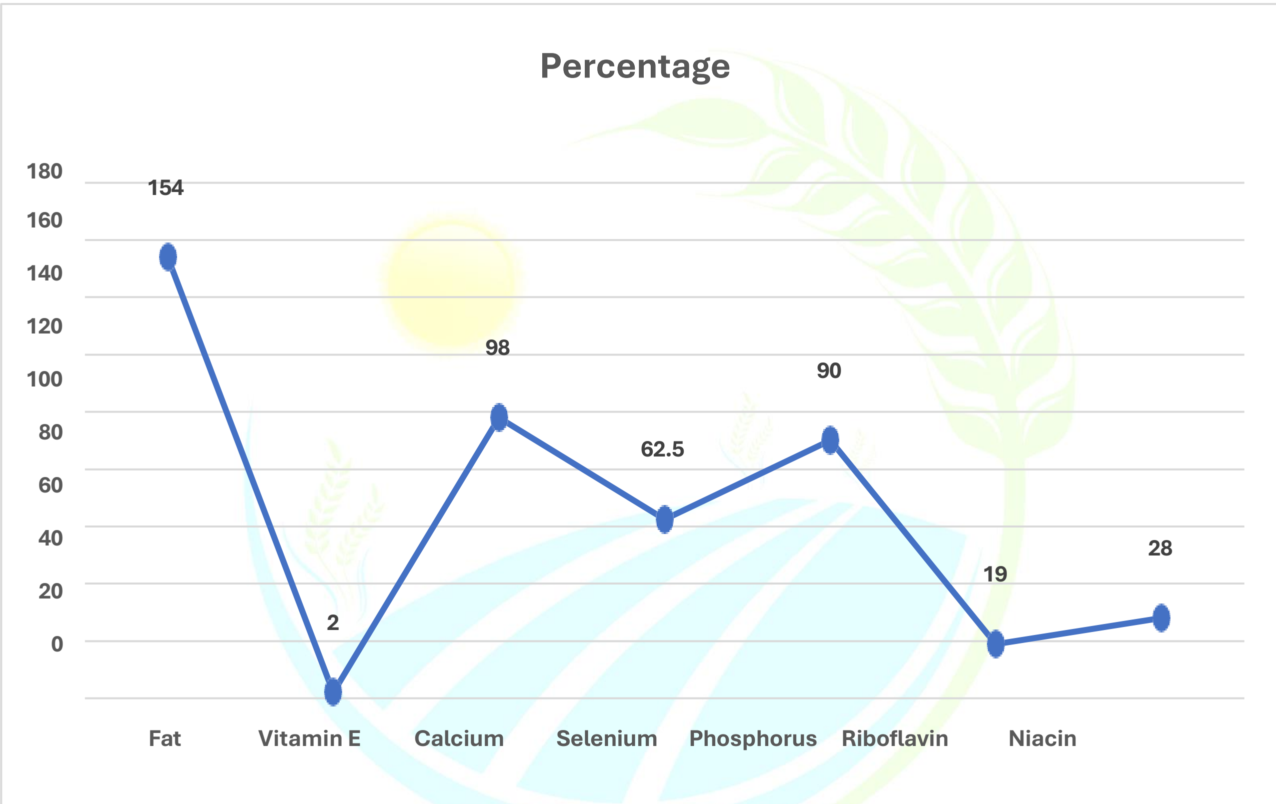

Figure 10. Nutrient Composition of Sesame (Wei *et al.*, 2022)

Sesame seeds are a great food crop that can help solve mineral imbalances through biofortification. Sesame biofortification's main objective is to raise the levels of micronutrients including calcium, iron, and zinc. Anemia and weakened immune system are only two of the health issues that can arise from lack of these essential nutrients (Teboul et al., 2020).

When combined with NPK fertilizer, zinc biofortification of sesame seeds can significantly boost the growth and productivity of sesame plant. In term or mineral nutrient concentrations in seeds, sesame germplasm exhibits a great degree of genetic variation, because of this diversity. Breeding operations can use biofortification to produce sesame cultivars that have higher nutritional value. The sesame line S91 was shown to have a very more mineral/ nutrient content, demonstrating the consumption of sesame's spontaneous genetic variation to identify genotypes with high mineral nutrient content (Eifediyi et al., 2021).

One of the most studied forms of biofortification in sesame is zinc biofortification, the zinc content of sesame seed can be considerably increased by applying zinc through seed treatment or soil amendments. This is particularly crucial since zinc lacking affects immune system performance and general health in many areas out the globe (Kurt et al., 2018).

Sesame yields and growth rise with zinc biofortification. Research indicates that proper zinc treatment can lead to increases biomass, disease resistance, and better seed quality all of which increase agricultural yields. A promising method for improving the nutritional value, of this important crop and treating micronutrient deficiency in human diet, while also boosting agricultural output is zinc biofortification in sesame (Guwela et al., 2024).

Sesame biofortification is a promising method to upgrade the nutritional value of this vital crop, focusing on increasing the levels of critical micronutrients, particularly through strategies like genetic variation, and zinc biofortification, can effectively cure malnutrition. Sesame is crucial in the fight against nutritional deficiencies because this approach benefits consumers while also promoting sustainable agricultural practices (Abbas et al., 2022).

CONCLUSION

Biofortification of oilseed crops presents a sustainable and cost-effective strategy to combat global malnutrition, particularly micronutrient deficiencies that affect billions worldwide. By enhancing the nutrient content of crops through conventional breeding, genetic engineering, and agronomic practices, biofortification improves public health outcomes, especially in regions with limited access to diverse diets. Techniques such as CRISPR gene editing and precision agriculture further enhance the efficacy of biofortification efforts. Developing nutrient-dense, climate-resilient crop varieties is crucial for addressing the challenges posed by climate change and ensuring global food security. Moreover, integrating biofortification with other nutritional interventions, like food fortification and supplementation, offers a comprehensive approach to alleviating malnutrition. As research progresses, biofortification stands as a promising avenue for improving nutrition and health outcomes globally.

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