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Vigna Unguiculata (Cowpea) As a Functional Food: Genetic Diversity, Nutraceutical Composition, Bioactive Compounds and Human Health Effects

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Abstract

Cowpea (Vigna unguiculata (L.) Walp.) is a genetically diverse, nutritionally versatile legume with high potential for use as a functional food. In addition to being an inexpensive source of plant protein, it provides carbohydrates, fibre, minerals, vitamins and a range of phytochemicals, such as phenolic acids, flavonoids, anthocyanins, tannins, saponins, phytosterols, carotenoids, tocopherols and bioactive peptides. The present review aims to highlight the impact of genetic variability, nutritional and phytochemical composition, the presence of antinutritional factors, processing, bioavailability, molecular mechanisms and health outcomes of cowpea consumption. The review underlines the complexity of the relationships between cowpea genetic resources and their nutritional and phytochemical profiles, as well as the potential of cowpea phytochemicals for the prevention and management of chronic diseases, including diabetes, cardiovascular diseases and cancer. A considerable amount of evidence supports the role of cowpea phytochemicals in the modulation of oxidative stress, Nrf2/ARE, NF-κB and MAPK signalling pathways, glucose-metabolizing enzymes, ACE activity and cell survival. It does demonstrate that cowpea intake modulates cardiometabolic and inflammatory biomarkers, the gut microbiota, appetite control, and metabolic health. Moreover, there is evidence for the role of cowpea in glycaemic control, gastrointestinal function, and the brain–gut axis, but further clinical trials are needed to determine the relevance of these effects.

Keywords: Vigna unguiculata; Nutritional compositions; Bioactive compounds; Phytochemicals; Functional food; Nutraceuticals.

1. Introduction

1.1 Overview of Vigna unguiculata

Vigna unguiculata (L.) Walp, generally known as cowpea, as an important grain legume belonging to the family Fabaceae and is widely cultured in tropical and subtropical regions, particularly across sub-Saharan Africa, South and Southeast Asia and parts of Latin America, where it represents a major source of dietary protein [1]. Cowpea is consumed in diverse forms, including mature dry seeds, immature green seeds, pods, leaves and processed products. It plays very important role in biological nitrogen fixation and enhances the agricultural importance, meanwhile the cowpea has relatively shorty life cycle and adaptable to high temperature and water deficient environments [2]. Nutritionally, cowpea provides considerable amounts of protein, carbohydrates, dietary fibre, vitamins and essential minerals. Its cheap plant-derived protein makes it exclusively valuable in populations, where the access of animal protein is limited. Subsequently, cowpea pays noticeably to household nutrition, dietary diversification, food security and sustainable agricultural systems [3].

1.2 Functional Food Potential of Cowpea

Due to the abundance storage of biologically active constituents, the importance of cowpea beyond its conventional use. The dietary value mainly accompanied with macro and micronutrients including proteins, carbohydrates, dietary fibre, vitamins and minerals, they help in maintaining normal physiological functions and complete nutritional competence. While, the nutraceutical values are largely attributed from its phytochemicals and other bioactive constituents that employ biological properties beyond basic nutrient supply [4]. Cowpea contains polyphenols, flavonoids, anthocyanins, phytosterols, bioactive peptides and other secondary metabolites that have been associated with antioxidant, anti-inflammatory, antidiabetic, antihypertensive, hypolipidemic and other potentially health-promoting activities [5]. The composition and concentration may may greatly affected by genotype, geographical area, environmental conditions, cultivation and processing methods. Henceforth, cowpea can be considered a promising functional food in which nutritional adequacy and bioactive potential are closely interconnected [6].

Figure 1. Vigna unguiculata (cowpea) plants, pods and seeds.

1.3 Purpose and Scope of the Review

Understanding the nutraceutical value of cowpea demands the knowledge of geographical, genetic, agronomic and technological factors, as both the growing environment and technological processing contribute to its nutritional and phytochemical composition, which can strongly differ depending on the studied variety and growing conditions. Thus, it is essential to evaluate the nutritional characteristics of cowpea produced under different environmental conditions and agricultural practices to identify the key elements associated with its beneficial effects [7]. The cowpea gene pool is extensive and the variations in seed composition and nutritional traits are highly dependent on genetic characteristics, which also determine the differences in the phytochemical profiles of various cowpea types. Moreover, variations in processing, food matrix and digestion conditions, as well as the levels of antinutritional factors, can affect the bioavailability of numerous phytochemicals and nutrients in cowpeas, as well as their physiological effects [8]. Therefore, the present review aims to assess the nutritional, nutraceutical and functional-food value of cowpeas. The review provides an insight into the genetic, agronomic and technological factors associated with the nutritional and phytochemical composition of cowpea, as well as its biological potential. Moreover, the present review analyses the mechanisms of the biological activities of various cowpea components and evaluates the current knowledge of the health benefits of cowpea consumption and its usage in functional food and medicine. The review highlights the conversant and emerging uses of cowpea and its components as functional foods, as well as the technological strategies for the improvement of people's nutrition and health status through dietary interventions.

2. Genetic Diversity and Variation of Vigna unguiculata

2.1 Genetic Origin and Diversity

Vigna unguiculata exhibits substantial genetic diversity resulting from its evolutionary history, domestication, geographic distribution and adaptation to diverse agroecological environments [9]. The species is generally considered to have originated in Africa, followed by domestication and subsequent dissemination to other tropical and subtropical regions. The cultivated species encompasses considerable diversity, including different cultivated groups, landraces, improved cultivars and closely related wild and weedy forms [10]. Landraces maintained by farmers represent an especially valuable source of genetic variation because they have undergone long-term selection under local environmental conditions and may possess desirable traits such as drought tolerance, early maturity, disease resistance and adaptation to marginal soils. Therefore, international and national germplasm collections create important resources for conserving this diversity and identifying genotypes with superior nutritional, nutraceutical and agronomic characteristics [11]. Vigna unguiculata may exhibits diverse scale of genetic variability, which are brought through several process such as evolution, domestication, geographical dispersal and adaptation in varied environments. The plant species is recognized to have originated in Africa before undergoing the course of domestication and being dispersed into other tropical and subtropical regions [12]. Cultivated varieties include many varieties such as those under cultivation, the landraces, improved varieties and related wild and weedy varieties. The landraces cultivated by farmers form a very rich genetic material since they have been subjected to natural selection for many years and possess desirable properties such as drought resistance, earliness, disease resistance and adaptability to marginal soils. This makes germplasm collections very useful in preserving this genetic diversity and discovering improved genotypes for their nutritional and agronomic traits [13].

2.2 Phenotypic and Molecular Genetic Diversity

Phenotypic variation in the cowpea is an indicator of genetic diversity exhibited by the crop, where there are noticeable differences in the seeds size, shape, texture and color, that ranges from white or cream, to red, brown, purple and even black. There are variations in the pod characters like length, thickness, color, number of seeds in a pod, among others [14]. There is also variability in traits like growth habit, plant architecture, flowering period, maturity period, productivity and response to abiotic stress. Most significant for agricultural purposes are genotypes that exhibit drought and heat tolerance, allowing productivity in changing climatic scenarios. This phenotypic diversity serves as a good basis in the selection of cowpea genotypes suitable for specific environments, as well as possessing desirable nutrient content [15].

The development of genomically diversified V. unguiculata has becomes the significance contribution in the field of molecular genetics. The genetic relations, population structure and diverged diversities are studied using molecular approaches such as simple sequence repeats (SSR), amplified fragment length polymorphism (AFLP) and single-nucleotide polymorphisms (SNPs) [16]. In addition, high throughput technologies, including genotyping-by-sequencing (GBS) and whole-genome sequencing have been employed to provide a more thorough analysis of genomic variation. Genome-wide association studies (GWAS) further help in discovery of genomic regions and candidate genes involved in agronomical, nutritional and stress-related traits [17]. From all these techniques confirm the fact that there is a considerable amount of genomic variation present in cowpea, which can be utilized not only for the improvement of cowpea crop but also to identify genotypes with superior nutritional and nutraceutical qualities [18].

2.3 Genetic Variation in Nutritional Composition

The genetic diversity of cowpea, offers important consequences in variation of nutritional and phytochemical composition. The proteins concentration and amino acids compositions are influenced by genotypes and also differ in nutritional quality from the proteins [19]. There is a variation among carbohydrates fractions such as starch, dietary fibres, which majorly influence the energy accessibility, gastrointestinal properties and glycaemic responses. Likely, the accumulations of essential minerals may also change in among genotypes because of genetic difference in accumulation and utilization [20]. Moreover, the genetic variation not only increases the nutritional values but also increases the bioactive phytochemicals like phenolics, flavonoids and anthocyanins. These bioactive constituents impart antioxidant and other biological activities. Henceforth, the role of cowpea in best nutritional properties, as well as in agronomic will be considered as selective cultivars for functional-food development [21].

Figure 2. Vigna unguiculata representing genetic diversity and variation, including morphological and agronomic traits, diverse seed types, sources of genetic diversity and genetic variation.

3. Nutritional and Nutraceutical Composition

Cowpea (Vigna unguiculata) has a complex nutritional composition despite of traditional legume plant. Cowpea seeds contain high amounts of macronutrients in the form of proteins, carbohydrates, dietary fiber and lipids along with micronutrients and phytochemicals. Nutritional composition of cowpea may widely vary depending on genotype, cultivar, growth environment, maturity, presence of colored seed coat and processing methods [22]. Moreover, nutritional value of cowpea not only include mature seeds but leaves and immature pods of cowpea are also eaten in some traditional diets and thus serve as additional sources of micronutrients and bioactive compounds [23].

3.1 Macronutrient Composition of Cowpea

Cowpea is a nutrient-dense legume containing nutritionally important proteins, carbohydrates, dietary fibre and lipids, with significant variation among genotypes. Protein is a major nutritional characteristic and cowpea provides substantial plant-based protein laterally with essential amino acids, particularly lysine and tryptophan; however, methionine and cysteine are relatively limited [24]. Protein quality influenced by digestibility, which can be reduced by antinutritional factors such as phytate, tannins and protease inhibitors, while processing methods such as soaking, germination, cooking, fermentation and dehulling can enhance protein utilization [25]. Carbohydrates, chiefly starch, constitute a major portion of cowpea seeds and variations in amylose content, starch structure and digestibility influence their metabolic properties. The presence of resistant starch allows the carbohydrate fraction to reach the colon undigested, possibly contribute to slower glucose release and improved postprandial glycaemic control [26]. Cowpea is also a valuable source of dietary fibre, including soluble and insoluble fractions, which support intestinal function, nutrient absorption and metabolic health. Fermentable fibre and resistant starch can be utilized by gut microbiota to produce short-chain fatty acids. Although cowpea is relatively low in fat, its lipid fraction contains nutritionally relevant monounsaturated fatty acids (MUFA) and polyunsaturated fatty

acids (PUFA), particularly linoleic acid (18:2, n-6) and smaller amounts of α-linolenic acid (18:3, n-3), along with minor bioactive constituents such as phytosterols and tocopherols [27].

3.2 Micronutrients

Cowpea is a good source of essential minerals and vitamins. The minerals including iron, zinc, calcium, magnesium, potassium and phosphorus. The extent of these minerals varies depending on genotype, soil conditions, geographical origin and farming practices [27]. The absorption of these minerals can be reduced by antinutritional factors such as phytate and tannins, which bind minerals and decrease their bioavailability [28]. Cowpea also contains important B-group vitamins, particularly folate, which supports DNA synthesis, cell growth and one-carbon metabolism, while other B vitamins contribute to energy production and normal nervous-system function. Additionally, cowpea contains tocopherols (vitamin E) that provide antioxidant protection against oxidative damage [29].

3.3 Nutraceutical Components

Apart from its nutritional compositions, the cowpea possesses diverse range of phytochemicals and bioactive compounds that subsidize to its nutraceutical potential. Phenolic acids, including hydroxybenzoic and hydroxycinnamic acid derivatives, contribute to antioxidant activity, while flavonoids possess important antioxidant and potential anti-inflammatory properties [30]. Anthocyanins, predominantly abundant in pigmented cowpea genotypes, contribute to seed-coat colour and exhibit strong free radical scavenging activity. Tannins, mainly concentrated in the seed coat, that enhance antioxidant activity but can also reduce protein and mineral bioavailability when present at high concentrations [31]. Other bioactive constituents, including saponins, phytosterols, carotenoids and tocopherols, may contribute to antioxidant, lipid modulating and other health-promoting effects. In addition, cowpea proteins release bioactive peptides during digestion, fermentation and enzymatic hydrolysis, with reported antioxidant, angiotensin converting enzyme (ACE)-inhibitory and antidiabetic activities [32].

Major composition	**Important components**	**Nutritional and nutraceutical significance**
Protein	Essential amino acids, bioactive peptides	Supports growth, tissue repair and muscle maintenance
Carbohydrates	Starch, resistant starch	Provides energy and may support glucose regulation
Dietary fibre	Soluble and insoluble fibre	Promotes digestive health and glycaemic control
Lipids	Unsaturated fatty acids, mainly linoleic and oleic acids	Contributes to cardiovascular health
Minerals	Iron, calcium, magnesium, potassium, zinc, phosphorus	Important for blood formation, bone health and metabolic functions
Vitamins	Folate, thiamine, riboflavin, niacin, vitamin B6	Supports energy metabolism and normal cellular functions
Polyphenols	Phenolic acids, tannins	Antioxidant and anti-inflammatory potential
Flavonoids	Quercetin, kaempferol and related compounds	Antioxidant and cellular-protective effects

Anthocyanins	Cyanidin and other pigments, particularly in coloured seeds	Antioxidant and anti-inflammatory potential
Bioactive peptides	Protein-derived peptides	Potential antioxidant, ACE-inhibitory and metabolic-regulating activities
Saponins	Triterpenoid/steroidal saponins	Potential antioxidant and lipid-metabolism effects
Phytosterols	β-Sitosterol and related sterols	May contribute to cholesterol-lowering effects
Other phytochemicals	Carotenoids and other secondary metabolites	Antioxidant and functional-food properties
Antinutritional factors	Phytate, tannins, trypsin inhibitors	May reduce nutrient bioavailability; substantially affected by processing

Table 1. Nutritional and Nutraceutical Composition of Vigna unguiculata (Cowpea)

4. Bioactive Compounds and Their Biological Potential

Besides nutritional values of cowpea, it contains a wide plethora of phytochemicals and plant-derived bioactive compounds that contributes to several functional potential against oxidative stress, inflammation, glucose and lipid metabolism [33]. Phenolic acids, including gallic, protocatechuic, p-hydroxybenzoic, p-coumaric, ferulic and caffeic acids, contribute to antioxidant activity through free-radical scavenging and modulation of cellular antioxidant and inflammatory pathways [34]. Flavonoids, such as quercetin, kaempferol, myricetin, catechin and epicatechin, provide antioxidant, anti-inflammatory, metabolic and vascular effects by regulating redox-sensitive pathways, including NF-κB and MAPK signalling [35]. However, their biological effects depend on absorption, metabolism and tissue availability. Anthocyanins, particularly abundant in pigmented cowpea genotypes, contribute to red, purple, brown and black seed-coat coloration and possess antioxidant besides, potential metabolic, anti-inflammatory and vascular activities [36]. Tannins, mainly concentrated in the seed coat and play a dual role, they might contribute to antioxidant and metabolic activities, but at high concentrations they can reduce protein digestibility and mineral bioavailability through interactions with proteins, enzymes and minerals [37]. Bioactive peptides released from cowpea proteins during digestion, fermentation or enzymatic hydrolysis represent another important functional component and have demonstrated potential antioxidant, ACE-inhibitory, antidiabetic and anti-inflammatory activities in experimental studies [38]. Other constituents, including saponins, phytosterols, carotenoids, and tocopherols, may provide additional biological effects, including cholesterol modulation, antioxidant protection and membrane protection [39].

5. Antinutritional Factors, Processing and Bioavailability

The nutritional and nutraceutical worth of cowpea is influenced by its beneficial constituents and antinutritional factors, as well as by the effects of food processing on nutrient availability and phytochemical stability [40]. Major antinutritional factors are phytic acid, tannins, trypsin inhibitors, lectins, raffinose and stachyose. Phytic acid bind to iron, zinc, calcium and magnesium, reducing their intestinal absorption, while tannins interact with proteins and digestive enzymes, thus affecting protein digestibility and mineral utilization. Trypsin inhibitors can interfere with protein digestion, while lectins may affect intestinal nutrient utilization at high concentrations. The raffinose-family oligosaccharides raffinose and stachyose are poorly digested in the small intestine and are fermented by colonic microbiota,

which may cause gas and gastrointestinal discomfort [41]. Food processing can substantially improve the nutritional quality of cowpea by reducing antinutritional factors and modifying the accessibility of nutrients and bioactive compounds. Soaking can reduce water-soluble phytate, tannins and oligosaccharides; germination improve protein digestibility and enhance the availability of certain phenolic compounds; cooking is particularly effective in reducing heat-sensitive trypsin inhibitors and lectins. Roasting and fermentation can modify the phenolic profile and antioxidant activity [42]. Yet, excessive heating may cause losses of heat-sensitive vitamins, degradation of phenolic compounds and changes in protein quality, highlighting the need to optimize processing conditions [43]. During digestion, the food matrix can influence the release, transformation, absorption and metabolism of nutrients and phytochemicals, with dietary fibre, proteins, phytate, tannins and processing conditions affecting these processes.

Antinutritional factor	Effect	Effective processing	Bioavailability outcome
Phytate	Binds Fe, Zn, Ca and Mg	Soaking, germination, fermentation	Increases mineral absorption
Tannins	Reduces protein and mineral utilization	Soaking, dehulling, cooking	Increases protein and mineral availability
Trypsin inhibitors	Reduces protein digestion	Boiling, pressure cooking	Increases protein digestibility
Lectins	Interferes with nutrient absorption	Cooking, pressure cooking	Reduces lectin activity
Oxalates	Binds calcium and other minerals	Soaking, boiling	Increases mineral availability
Saponins	May reduce palatability and nutrient absorption	Soaking, cooking	Increases nutrient utilization
Oligosaccharides	Causes intestinal gas and discomfort	Soaking, germination, fermentation	Increases digestive tolerance

Table 2. Antinutritional Factors, Processing and Bioavailability of Vigna unguiculata

6. Molecular Mechanisms Underlying Health Effects

The potential health benefits of cowpea arise from the mutual actions of polyphenols, bioactive peptides, dietary fibre, resistant starch and other bioactive constituents, which may interact with cellular pathways involved in oxidative stress, inflammation, glucose regulation, cardiovascular function and cell survival [44]. Antioxidant effects may occur through direct scavenging of reactive oxygen species (ROS) by phenolic compounds and peptides, besides through activation of the Nrf2/ARE pathway, which enhances the expression of endogenous antioxidant and cytoprotective enzymes which reduces oxidative damage to lipids, proteins and nucleic acids [45]. The anti-inflammatory activity of cowpea constituents may involve modulation of NF-κB and MAPK signalling pathways, leading to reduced expression of inflammatory mediators such as COX-2, TNF-α, IL-6, and IL-1β; antioxidant activity further suppress oxidative stress induced inflammatory signalling [46]. Cowpea may also support glucose homeostasis through several mechanisms, including inhibition of α-amylase and α-glucosidase, which can slow carbohydrate digestion and glucose release, while dietary fibre and resistant starch may delay glucose absorption and improve

postprandial glycaemic responses [47]. Polyphenols may additionally protect vascular function by reducing oxidative stress and inflammation. In cancer, cowpea's polyphenols and peptides have showed experimental potential through cell-cycle arrest, apoptosis induction, caspase activation and modulation of Bax and Bcl-2, along with effects on cellular proliferation and survival pathways [48].

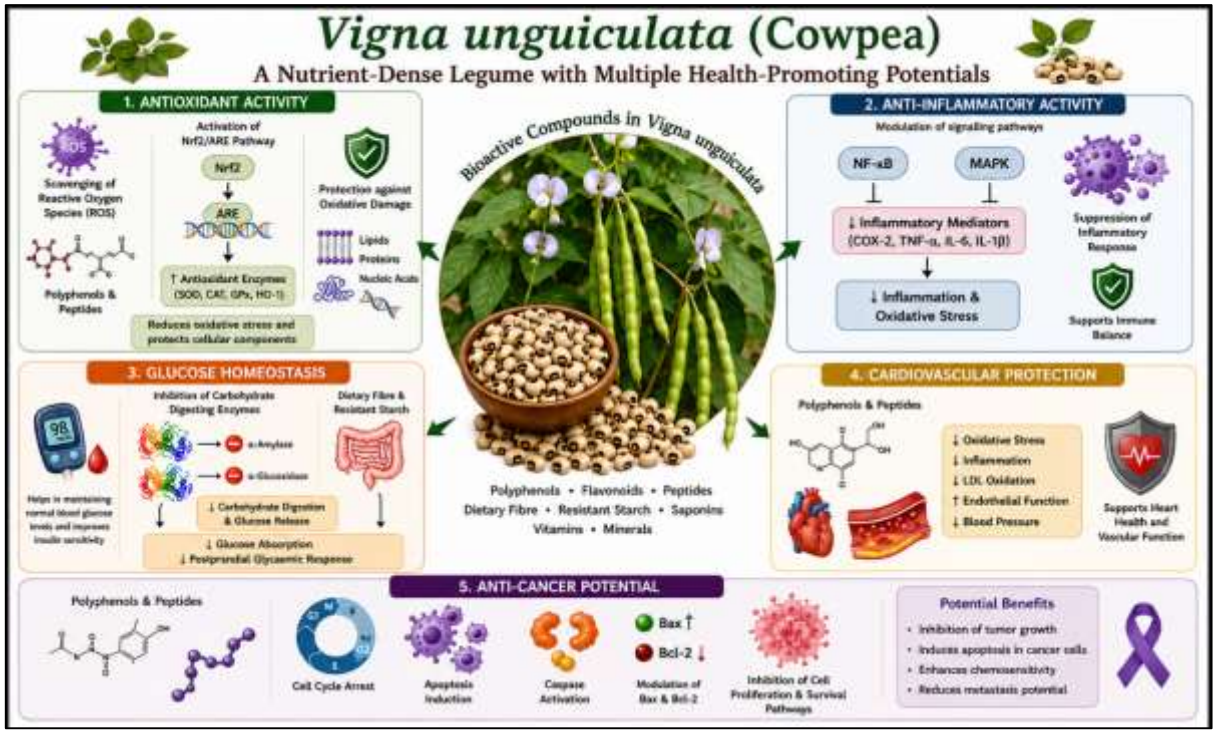

Figure 3. Vigna unguiculata (cowpea): Molecular mechanisms underlying its health-promoting effects.

7. Human Health Effects of Cowpea Consumption

The nutrient concentration and various bioactive composition of cowpea provide a strong source for its potential contribution to human health. Cowpea may support glycaemic control through its combination of protein, dietary fibre, resistant starch and slowly digestible carbohydrates, which can delay carbohydrate digestion and glucose absorption and potentially improve postprandial glucose, insulin responses, glycaemic index and satiety [49]. The proteins, fibre, unsaturated fatty acids, phytosterols and polyphenols may contribute to cardiovascular health by supporting lipid metabolism, blood-pressure regulation, vascular function and reduction of oxidative and inflammatory stress. Cowpea support weight management because its relatively high protein and fibre content, together with resistant starch and slowly digestible carbohydrates, enhance satiety and reduce subsequent food intake [50]. The combination of dietary fibre, resistant starch and fermentable carbohydrates may also advantage gut health by reaching the colon and supporting microbial fermentation and production of short-chain fatty acids (SCFAs), particularly acetate, propionate and butyrate, which may influence intestinal barrier integrity, immune regulation and metabolic signalling [51]. From a nutritional perspective, cowpea provides important protein, iron, zinc, folate and other micronutrients, making it particularly valuable in populations relying heavily on cereal-based diets and therefore contribute to addressing protein and micronutrient deficiencies, although its effectiveness depends on overall dietary intake, digestibility, preparation and nutritional status.

8. Cowpea as a Functional Food

The nutritional density, phytochemical diversity and processing adaptability of Vigna unguiculata provide a strong foundation for its development as a functional food. Cowpea is traditionally consumed as whole cooked seeds, curries, soups, salads and leaf-based foods, providing nutrients within a complex food matrix that combines protein, dietary fibre, resistant starch, minerals and bioactive compounds. The cowpea flour suitable for incorporation into bread, biscuits, pasta, noodles, snacks and other cereal-based products to enhance protein, fibre and micronutrient content [52]. Processing methods such as extrusion can improve the functional and textural properties of cowpea ingredients, while protein concentrates and isolates offer potential for high-protein foods, sports-nutrition products and plant-based meat alternatives. Cowpea proteins can enzymatically hydrolyse to produce bioactive peptides, whereas polyphenol-rich portions may serve as functional ingredients in specialized foods and beverages. The nutritional and nutraceutical traits are largely depending on genetic variation, the selection of targeted genotypes may yield higher level of protein, dietary fibre, resistant starch, iron, zinc, polyphenols, anthocyanins and bioactive-peptide precursors, while reducing undesirable levels of phytate, excessive tannins, trypsin inhibitors, and raffinose-family oligosaccharides to improve nutrient bioavailability and gastrointestinal tolerance [53]. However, breeding targets must be evaluated cooperatively because changes in one trait may influence flavour, colour, digestibility, antinutritional activity, processing properties and consumer acceptance. Therefore, upcoming cowpea development should integrate genomic selection, nutritional composition, bioavailability, processing characteristics, sensory quality and validated human health outcomes.

9. Conclusion

The leguminous species Vigna unguiculata possesses large genetic variability, high nutritive value and rich phytochemical profile, thus providing huge development potential of functional food. The value of cowpea, not only underlying in relatively cheap and rich source of plant protein, its genetic diversity also contributes to variations in protein quality, dietary fibre, starch type, mineral composition, phenols, flavonoids, anthocyanins and other bioactive compounds. Health properties of cowpea mainly attributed by bioactive compounds, but also interactions between genotype of foodstuff, composition of food, processing methods, digestibility, absorption and metabolism, then physiological effects. Soaking, germination, cooking, roasting and fermentation could decrease antinutritional compounds, change accessibility and chemical structure of nutrients and phytochemicals. Therefore, the content of a compound in raw cowpea does not necessarily reflect bioavailability and biological activity of this compound after ingestion. Presented data suggest optimistic health-promoting properties including antioxidant, glycaemic, metabolic, cardioprotective, gastroprotective and others. Recent studies, especially on effect on glycemia control and appetite regulation, suggests that cowpea genotype and composition might affect physiological effects. Thus, future research should focus on genotype-dependent development of functional foods, investigations of bioavailability of compounds, processing and human clinical trials.

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