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FACULDADE DE CIÊNCIAS AGRÁRIAS E VETERINÁRIAS
CÂMPUS DE JABOTICABAL

GENOTYPIC VARIABILITY OF COWPEA (*Vigna Unguiculata* (L.) Walp) AND SELENIUM UPTAKE FOR DETERMINING AGRONOMIC BIOFORTIFICATION STRATEGIES TO COMBAT HIDDEN HUNGER

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"Life is not easy for any of us. But what of that? We must have perseverance and above all confidence in ourselves. We must believe that we are gifted for something and that this thing must be attained."

- Marie Curie

Physicist, chemist, and winner of the 1903 and 1911 Nobel Prize in Physics

May 14, 19271, Vassar College, Poughkeepsie, Nova York.

DEDICO

A Deus, por colocar em meu coração sonhos que minhas forças humanas jamais seriam capazes de realizar, e me conceder paciência, sabedoria e resiliência para suportar o processo. *“Porque Dele, por Ele e para Ele são todas as coisas. A Ele a glória por toda a eternidade. Amém!” (Romanos, 11-36).*

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GENOTYPIC VARIABILITY OF COWPEA (*Vigna unguiculata (L.) Walp*) AND SELENIUM UPTAKE FOR DETERMINING AGRONOMIC BIOFORTIFICATION STRATEGIES TO COMBAT HIDDEN HUNGER

RESUMO – O aumento da produtividade de grãos tem apresentado relação inversa como conteúdo nutricional das plantas, ocasionando o aumento da fome oculta. O Feijão-caupi é rico em proteínas, e fonte de alimentação com baixo valor agregado para países emergentes. Em hipótese, a determinação de genótipos mais responsivos de feijão-caupi a aplicação de Se por meio da marcha de absorção de nutrientes proporciona estratégias de biofortificação agronômica. O experimento I foi conduzido com 20 genótipos de feijão-caupi para determinação da variação genotípica nos parâmetros de produção e na eficiência do uso de nitrogênio. No experimento II foram aplicadas via solo e foliar as doses de Se (0, 10, 25, 50, 100 e 150 g ha^{-1}) na fonte selenato de sódio e avaliados as respostas fisiológicas e morfológicas dos tratamentos. No experimento III, o genótipo responsivo do experimento I e dose-resposta do experimento II foram utilizados para determinar a aplicação no feijão-caupi e avaliado a marcha de absorção de Se nos estádios fenológicos da culturas para determinar a curva de acumulo de nutrientes. Ao final dos experimentos, foi avaliado o acúmulo de nutrientes (essenciais, benéficos e antinutrientes) nos grãos de feijão-caupi em resposta a aplicação de Selênio para a alimentação humana. Foram realizadas análises de fotossíntese (A), condutância estomática (GS), clorofila (Cl), concentração interna de CO_2 (E), metabolismo antioxidante (malonaldeído, peroxido de hidrogênio, enzimas antioxidantes), metabolismo do nitrogênio (ureia, urease e nitrato redutase), perfil de açucares e flavonoides (HPLC), proteínas de reserva (albumina, globulina, prolamina e glutelina) e concentração de elementos. Os resultados obtidos nesse estudo poderão gerar contribuições significativas para a seleção de genótipos de feijão-caupi responsivos aos programas de biofortificação agronômica e doses seguras de selênio para o combate das deficiências nutricionais por meio de estratégias agronômicas.

Palavras-chave: Nutrição de Plantas, Fisiologia Vegetal, Feijão-caupi, Marcha De Absorção, Selênio.

GENOTYPIC VARIABILITY OF COWPEA (*Vigna unguiculata (L.) Walp*) AND SELENIUM UPTAKE FOR DETERMINING AGRONOMIC BIOFORTIFICATION STRATEGIES TO COMBAT HIDDEN HUNGER.

ABSTRACT – The increase in grain yield has shown an inverse relationship with the nutritional content of plants, leading to an increase in hidden hunger. Cowpea is rich in proteins and serves as a low-value food source for emerging countries. Hypothetically, determining more responsive cowpea genotypes to selenium (Se) application through nutrient uptake gait provides agronomic biofortification strategies. The experiment I conducted with 20 cowpea genotypes to determine genotypic variation in production parameters and nitrogen use efficiency. In Experiment II, Se doses (0, 10, 25, 50, 100, and 150 g ha-1) were applied via soil and foliar routes using sodium selenate, and the physiological and morphological responses of the treatments will be evaluated. In Experiment III, the responsive genotype from Experiment I and the dose-response from Experiment II were used to determine Se application in cowpea and evaluate Se uptake gait during the phenological stages of the crop to determine the nutrient accumulation curve. At the end of the experiments, the accumulation of nutrients (essential, beneficial, and antinutrients) in cowpea grains in response to Se application for human consumption was evaluated. Analyses of photosynthesis (A), stomatal conductance (GS), chlorophyll (Cl), internal CO_2 concentration (E), antioxidant metabolism (malondialdehyde, hydrogen peroxide, antioxidant enzymes), nitrogen metabolism (urea, urease, and nitrate reductase), sugar and flavonoid profiles (HPLC), storage proteins (albumin, globulin, prolamin, and glutelin), and element concentration were performed. The results obtained from this study may generate significant contributions to the selection of responsive cowpea genotypes for agronomic biofortification programs and safe doses of selenium to combat nutritional deficiencies through agronomic strategies.

Keywords: *Vigna Unguiculata*, Agronomic Biofortification, Hidden Hunger, Absorption March, Selenium.

CHAPTER 1 - SELENIUM BIOFORTIFICATION: IMPROVE HUMAN NUTRITION AND RESILIENCE TO ECONOMIC CRISES

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ABSTRACT

Malnutrition can be caused by hidden hunger, resulting in deficiencies in essential micronutrients such as selenium, iron, zinc, copper, calcium, and magnesium. This study developed a meta-analysis of documents from the Web of Science using the keywords "Biofortification," "Selenium," and "Cowpea" from 1990 to 2024. It analyzed the number of documents, keywords, citations, institutions, and H-index to understand the research landscape in this field. Biofortification is a quick, efficient, and sustainable method to reduce micronutrient deficiencies. Selenium (Se) is an essential micronutrient for human and animal health due to its ability to support antioxidant defense systems. Agronomic selenium biofortification has demonstrated significant success in Finland, where selenium-enriched fertilizers have substantially improved public health by boosting selenium levels in food crops. Its significance became particularly evident during the COVID-19 pandemic, as adequate selenium levels were correlated with reduced infection severity, emphasizing its role in global health crises. Economically, selenium biofortification enhances agricultural sustainability by increasing crop resilience to abiotic stresses such as drought and salinity and reducing phytic acid content, thus improving mineral bioavailability. In plants, Se can regulate the activity of antioxidant enzymes, such as superoxide dismutase (SOD), peroxidase (POX), ascorbate peroxidase (APX), and catalase (CAT), which help neutralize reactive oxygen species (ROS) generated under stress conditions. Furthermore, leveraging genotypic variability ensures that different crops optimally uptake selenium, thereby enhancing their nutritional value. By promoting better human nutrition and more robust agricultural systems, selenium biofortification is vital for achieving the UN Sustainable Development Goals, especially Goal 2 (Zero Hunger), which seeks to end hunger, achieve food security and improved nutrition, and promote sustainable agriculture by 2030.

Keywords: micronutrients, abiotic stress, phytic acid, food safety, hidden hunger, agronomic biofortification, zero hunger, human health.

1. INTRODUCTION

Micronutrient malnutrition, also referred to as hidden hunger, pertains to insufficient essential vitamins and minerals, leading to significant adverse impacts on human health (Bouis and Saltzman 2017a). By enhancing the nutritional quality of food crops, agronomic biofortification contributes to increased food security, which is always defined as the consistent access of all individuals to safe and nutritious food (Simkin 2019).

Hidden hunger affects over two billion individuals globally, with higher prevalence in Africa, South Asia, and Northeast Brazil (Siwela et al. 2020). Approximately 811 million people suffer from chronic malnutrition. (Langyan et al. 2022). Thus, One-third of women of childbearing age are anemic, 22% of children under the age of five suffer from stunted growth, and 50% of the global population of pregnant women experience micronutrient deficiencies. (Alae-Carew et al. 2019; PNUD 2022).

Biofortification can contribute to the achievement of various United Nations Sustainable Development Goals (SDGs), including eradicating hunger, achieving food security, improving nutrition, and promoting sustainable agriculture (Rehman et al. 2021). Additionally, biofortification is regarded as a highly cost-effective strategy to combat micronutrient malnutrition on a global scale, particularly when compared to other interventions such as dietary diversification or micronutrient supplementation. (Wakeel et al. 2018)

Among the critical minerals involved are iron, iodine, zinc, copper, calcium, magnesium, and selenium (Shankar 2020; White et al. 2009). The global deficiency rates for Fe, Zn, I, and Se are approximately 60%, 30%, 30%, and 15%, respectively. Additionally, deficiencies in Zn, Fe, and I, along with vitamin A deficiency, can result in a mortality rate of approximately 20% among children under the age of five. (Imdad et al. 2022; White et al. 2009). Over the past twenty years, global governments have invested more than US$ 15 billion in vitamin A supplementation capsules as a medical strategy (Imdad et al. 2017a).

Biofortification involves the enhancement of micronutrient levels in food crops through agricultural technologies (Garg et al. 2018). This technique is essential in agriculture and food systems, as it has the potential to enhance the nutritional quality of crops and subsequently improve public health, particularly for populations with limited access to diverse diets or other micronutrient interventions (Langyan et al. 2022). This study aims to provide a comprehensive overview of the scientific evolution of agronomic biofortification and its integration into food systems. It highlights various success cases that have reduced regional food insecurities and contributed to the development and health of the global population.

5. CONCLUSION

The agronomic biofortification of cowpeas with Se proves to be an efficient way to increase the grain yield and nutritional quality of grains. Doses up to 50 g ha^{-1} positively increase the grain yield. Foliar Se application is revealed to be the most efficient strategy to increase Se concentration in leaves and grains. Low doses of Se (10 and 25 g ha^{-1}) applied via foliar are sufficient to meet the nutritional needs of a population that consumes cowpeas and meet the requirements established by the *Codex Alimentarius* (60 µg day^{-1}). The application of Se also plays synergistic/antagonistic roles with other nutrients that contribute to plant development, such as photosynthesis. This study presents important information for Se management recommendations in field-grown cowpea plants aiming to increase Se concentration in grains at a safety level to combat malnutrition. And reveals that the agronomic biofortification of cowpeas with Se is a cheap and accessible strategy to increase the quality of staple foods, like cowpea, aiming to combat malnutrition in developing countries.

7. REFERENCES

Abebe BK, Alemayehu MT (2022) A review of the nutritional use of cowpea (Vigna unguiculata L. Walp) for human and animal diets. J Agric Food Res 10:100383. https://doi.org/10.1016/J.JAFR.2022.100383

Adebayo A, Yakubu O, Bakare-Akpata O (2020) Uptake, Metabolism and Toxicity of Selenium in Tropical Plants. In: Importance of Selenium in the Environment and Human Health. IntechOpen

Affrifah NS, Phillips RD, Saalia FK (2022) Cowpeas: Nutritional profile, processing methods and products—A review. Legume Science 4:e131. https://doi.org/10.1002/LEG3.131

Alae-Carew C, Bird FA, Choudhury S, Harris F, Aleksandrowicz L, Milner J, Joy EJ, Agrawal S, Dangour AD, Green R (2019) Future diets in India: A systematic review of food consumption projection studies. Glob Food Sec 23:182–190. https://doi.org/10.1016/J.GFS.2019.05.006

Alexieva V, Sergiev I, Mapelli S, Karanov E (2001) The effect of drought and ultraviolet radiation on growth and stress markers in pea and wheat. Plant Cell Environ 24:1337–1344. https://doi.org/10.1046/j.1365-3040.2001.00778.x

Alfthan G, Aspila P, Ekholm P, Eurola M, Hartikainen H, Hero H, Hietaniemi V, Root T, Salminen P, VenäÏinen ER, Aro A (2010) Nationwide supplementation of sodium selenate to commercial fertilizers: History and 25-year results from the finnish selenium monitoring programme. Combating Micronutrient Deficiencies: Food-based Approaches 312–337. https://doi.org/10.1079/9781845937140.0312

Alves LR, Rossatto DR, Rossi ML, Martinelli AP, Gratão PL (2020) Selenium improves photosynthesis and induces ultrastructural changes but does not alleviate cadmium-stress damages in tomato plants. Protoplasma 257:597–605. https://doi.org/10.1007/S00709-019-01469-W/FIGURES/5

Andrade FR, da Silva GN, Guimarães KC, Barreto HBF, de Souza KRD, Guilherme LRG, Faquin V, Reis AR dos (2018) Selenium protects rice plants from water deficit stress. Ecotoxicol Environ Saf 164:562–570. https://doi.org/10.1016/j.ecoenv.2018.08.022

Antonio C, Santos F (2012) Melhoramento do feijão-caupi para temperaturas moderadas e elevadas no Vale do São Francisco.

Asri-Rezaei S, Nourian A, Shalizar-Jalali A, Najafi G, Nazarizadeh A, Koohestani M, Karimi A (2018) Selenium supplementation in the form of selenium nanoparticles and selenite sodium improves mature male mice reproductive performances. Iran J Basic Med Sci 21:577. https://doi.org/10.22038/IJBMS.2018.26023.6397

Bailey RL, West KP, Black RE (2015) The Epidemiology of Global Micronutrient Deficiencies. Ann Nutr Metab 66:22–33. https://doi.org/10.1159/000371618

Bairu M, Laurie S, Mavengahama S, Mekonnen TW, Shegro Gerrano A, Mbuma NW, Labuschagne MT (2022) Breeding of Vegetable Cowpea for Nutrition and Climate

Resilience in Sub-Saharan Africa: Progress, Opportunities, and Challenges. Plants 2022, Vol 11, Page 1583 11:1583. https://doi.org/10.3390/PLANTS11121583

Bajaj M, Eiche E, Neumann T, Winter J, Gallert C (2011) Hazardous concentrations of selenium in soil and groundwater in North-West India. J Hazard Mater 189:640–646. https://doi.org/10.1016/J.JHAZMAT.2011.01.086

Bao P, Huang H, Hu ZY, Häggblom MM, Zhu YG (2013) Impact of temperature, CO2 fixation and nitrate reduction on selenium reduction, by a paddy soil Clostridium strain. J Appl Microbiol 114:703–712. https://doi.org/10.1111/JAM.12084

Barker A V., Pilbeam DJ (2016) Handbook of plant nutrition

Barros JRA, Guimarães MJM, Silva RM e., Rêgo MTC, de Melo NF, de Melo Chaves AR, Angelotti F (2021) Selection of cowpea cultivars for high temperature tolerance: physiological, biochemical and yield aspects. Physiology and Molecular Biology of Plants 27:29–38. https://doi.org/10.1007/S12298-020-00919-7/METRICS

Bhattacharjee S (2010) Sites of generation and physicochemical basis of formation of reactive oxygen species in plant cell. In: Reactive Oxygen Species and Antioxidants in Higher Plants. CRC Press New York, NY, USA, pp 1–30

Bieleski RL, Turner NA (1966a) Separation and estimation of amino acids in crude plant extracts by thin-layer electrophoresis and chromatography. Anal Biochem 17:278–293. https://doi.org/10.1016/0003-2697(66)90206-5

Bieleski RL, Turner NA (1966b) Separation and estimation of amino acids in crude plant extracts by thin-layer electrophoresis and chromatography. Anal Biochem 17:278–293. https://doi.org/10.1016/0003-2697(66)90206-5

Blamey FPC, Hernandez-Soriano MC, Cheng M, Tang C, Paterson DJ, Lombi E, Wang WH, Scheckel KG, Kopittke PM (2015) Synchrotron-based techniques shed light on mechanisms of plant sensitivity and tolerance to high manganese in the root environment. Plant Physiol 169:2006–2020. https://doi.org/10.1104/pp.15.00726

Bloot APM, Kalschne DL, Amaral JAS, Baraldi IJ, Canan C (2023) A Review of Phytic Acid Sources, Obtention, and Applications. Food Reviews International 39:73–92. https://doi.org/10.1080/87559129.2021.1906697

Bohn L, Meyer AS, Rasmussen SK (2008) Phytate: Impact on environment and human nutrition. A challenge for molecular breeding. J Zhejiang Univ Sci B 9:165–191. https://doi.org/10.1631/jzus.B0710640

Bohrer AS, Kopriva S, Takahashi H (2015) Plastid-cytosol partitioning and integration of metabolic pathways for APS/PAPS biosynthesis in Arabidopsis thaliana. Front Plant Sci 5:1–4. https://doi.org/10.3389/FPLS.2014.00751/BIBTEX

Bouis H, Saltzman A (2017a) Melhorando a nutrição por meio da biofortificação: uma revisão das evidências do HarvestPlus, 2003 a 2016. Segurança alimentar global

Bouis H, Saltzman A, Birol E (2019) Improving Nutrition Through Biofortification. In: Agriculture for improved nutrition: seizing the momentum. pp 47–57

Bouis HE, Hotz C, McClafferty B, Meenakshi J V., Pfeiffer WH (2011) Biofortification: a new tool to reduce micronutrient malnutrition. Food Nutr Bull 32:. https://doi.org/10.1177/15648265110321S105

Bouis HE, Saltzman A (2017b) Improving nutrition through biofortification: A review of evidence from HarvestPlus, 2003 through 2016. Glob Food Sec 12:49–58

Boukar O, Fatokun CA, Roberts PA, Abberton M, Boukar O, Fatokun CA, Roberts PA, Abberton M, Huynh BL, Close TJ, Kyei-Boahen S, Higgins TJ V, Ehlers JD (2015) Caupi. SpringerO Boukar, CA Fatokun, PA Roberts, M Abberton, BL Huynh, TJ Close, S Kyei-Boahen.Leguminosas para grãos, 2015•Springer 219–250. https://doi.org/10.1007/978-1-4939-2797-5_7

Bradford MM (1976) A rapid and sensitive method for the quantitation of microgram quantities of protein utilizing the principle of protein-dye binding. Anal Biochem 72:248–254. https://doi.org/10.1016/0003-2697(76)90527-3

Broadley MR, White PJ, Hammond JP, Zelko I, Lux A (2007) Zinc in plants. New Phytologist 173:677–702. https://doi.org/10.1111/J.1469-8137.2007.01996.X

Cabral Gouveia GC, Galindo FS, Dantas Bereta Lanza MG, Caroline da Rocha Silva A, Pereira de Brito Mateus M, Souza da Silva M, Rimoldi Tavanti RF, Tavanti TR, Lavres J, Reis AR dos (2020) Selenium toxicity stress-induced phenotypical, biochemical and physiological responses in rice plants: Characterization of symptoms and plant metabolic adjustment. Ecotoxicol Environ Saf 202:110916. https://doi.org/10.1016/j.ecoenv.2020.110916

Camaschella C (2019) Iron deficiency. Blood 133:30–39

Campos F, Rodrigues Freire Filho F, Lopes Â, Ribeiro V, Querino R, Rocha M (2000a) Ciclo fenológico em caupi (Vigna unguiculata L.Walp.): uma proposta de escala de desenvolvimento. Rev Cient Rural 5:110–116

Campos FL, Ribeiro VQ, Rocha M (2000b) Ciclo fenológico em caupi (Vigna unguiculata L.Walp.): uma proposta de escala de desenvolvimento Universidade Federal do Delta do Parnaiba

Cantarella H, Van Raij B, Quaggio JA (1998) Soil and plant analyses for lime and fertilizer recommendations in Brazil. In: Communications in Soil Science and Plant Analysis. Marcel Dekker Inc., pp 1691–1706

Cappa JJ, Cappa PJ, El Mehdawi AF, McAleer JM, Simmons MP, Pilon-Smits EAH (2014) Characterization of selenium and sulfur accumulation across the genus Stanleya (Brassicaceae): A field survey and common-garden experiment. Am J Bot 101:830–839. https://doi.org/10.3732/AJB.1400041

Carlquist S (1975) Ecological strategies of xylem evolution

Carvalho AFU, de Sousa NM, Farias DF, da Rocha-Bezerra LCB, da Silva RMP, Viana MP, Gouveia ST, Sampaio SS, de Sousa MB, de Lima GPG, de Morais SM, Barros CC, Filho FRF (2012) Nutritional ranking of 30 Brazilian genotypes of cowpeas including determination of antioxidant capacity and vitamins. Journal of Food Composition and Analysis 26:81–88. https://doi.org/10.1016/J.JFCA.2012.01.005

Carvalho M, Castro I, Moutinho-Pereira J, Correia C, Egea-Cortines M, Matos M, Rosa E, Carnide V, Lino-Neto T (2019) Evaluating stress responses in cowpea under drought stress. J Plant Physiol 241:153001. https://doi.org/10.1016/J.JPLPH.2019.153001

Carvalho M, Lino-Neto T, Rosa E, Carnide V (2017a) Cowpea: a legume crop for a challenging environment. J Sci Food Agric 97:4273–4284. https://doi.org/10.1002/JSFA.8250

Carvalho M, Lino-Neto T, Rosa E, Carnide V (2017b) Cowpea: a legume crop for a challenging environment. J Sci Food Agric 97:4273–4284

Cataldo DA, Haroon MH, Schrader LE, Youngs VL (1975) Rapid colorimetric determination of nitrate in plant tissue by nitration of salicylic acid. Commun Soil Sci Plant Anal 6:71–80. https://doi.org/10.1080/00103627509366547

Chauhan R, Awasthi S, Srivastava S, Dwivedi S, Pilon-Smits EAH, Dhankher OP, Tripathi RD (2019) Understanding selenium metabolism in plants and its role as a beneficial element. Crit Rev Environ Sci Technol 49:1937–1958. https://doi.org/10.1080/10643389.2019.1598240

Chauhan R, Awasthi S, Tripathi P, Mishra S, Dwivedi S, Niranjan A, Mallick S, Tripathi P, Tripathi RD, Chauhan R, Pande V (2017) Selenite modulates the level of phenolics and nutrient element to alleviate the toxicity of arsenite in rice (Oryza sativa L.). Ecotoxicol Environ Saf 138:47–55. https://doi.org/10.1016/j.ecoenv.2016.11.015

Chilimba ADC, Young SD, Black CR, Rogerson KB, Louise Ander E, Watts MJ, Lammel J, Broadley MR (2011a) Maize grain and soil surveys reveal suboptimal dietary selenium intake is widespread in Malawi. Scientific Reports 2011 1:1 1:1–9. https://doi.org/10.1038/srep00072

Chilimba ADC, Young SD, Black CR, Rogerson KB, Louise Ander E, Watts MJ, Lammel J, Broadley MR (2011b) Maize grain and soil surveys reveal suboptimal dietary selenium intake is widespread in Malawi. Sci Rep 1:1–9. https://doi.org/10.1038/srep00072

Combs GF (2001a) Selenium in global food systems. British Journal of Nutrition 85:517–547. https://doi.org/10.1079/bjn2000280

Combs J (2001b) Impact of selenium and cancer-prevention findings on the nutrition-health paradigm. Nutr Cancer 40:6–11

CONAB (2023) Boletim da Safra de Grãos 2023/2024. https://www.conab.gov.br/info-agro/safras/graos/boletim-da-safra-de-graos. Accessed 9 Aug 2024

Crizel RL, Deitos ÊC, Ferreira CD, Ziegler V, Hoffmann JF, Pinto VZ (2023) Role of Proteins in Chickpea and Cowpea Considering Global Food Security, Especially Protein-Based

Diet Security. Chickpea and Cowpea: Nutritional Profile, Processing, Health Prospects and Commercial Uses 195–226. https://doi.org/10.1201/9781003382027-8/ROLE-PROTEINS-CHICKPEA-COWPEA-CONSIDERING-GLOBAL-FOOD-SECURITY-ESPECIALLY-PROTEIN-BASED-DIET-SECURITY-ROSANE-LOPES-CRIZEL-

Cui EJ, Song NY, Shrestha S, Chung IS, Kim JY, Jeong TS, Baek NI (2012) Flavonoid glycosides from cowpea seeds (Vigna sinensis K.) inhibit LDL oxidation. Food Sci Biotechnol 21:619–624. https://doi.org/10.1007/S10068-012-0080-7/METRICS

Dahlen CR, Reynolds LP, Caton JS (2022) Selenium supplementation and pregnancy outcomes. Front Nutr 9:1011850. https://doi.org/10.3389/FNUT.2022.1011850/BIBTEX

Dai H, Wei S, Twardowska I (2020) Biofortification of soybean (Glycine max L.) with Se and Zn, and enhancing its physiological functions by spiking these elements to soil during flowering phase. Science of the Total Environment 740:139648. https://doi.org/10.1016/j.scitotenv.2020.139648

Dakora FD, Belane AK (2019) Evaluation of Protein and Micronutrient Levels in Edible Cowpea (Vigna Unguiculata L. Walp.) Leaves and Seeds. Front Sustain Food Syst 3:70. https://doi.org/10.3389/fsufs.2019.00070

Dall'Acqua S, Ertani A, Pilon-Smits EAH, Fabrega-Prats M, Schiavon M (2019) Selenium Biofortification Differentially Affects Sulfur Metabolism and Accumulation of Phytochemicals in Two Rocket Species (Eruca Sativa Mill. and Diplotaxis Tenuifolia) Grown in Hydroponics. Plants 2019, Vol 8, Page 68 8:68. https://doi.org/10.3390/PLANTS8030068

Dareus R, Acharya JP, Paudel DR, Lopes De Souza CH, Tome Gouveia B, Chase CA, DiGennaro P, Mulvaney MJ, Koenig R, Rios EF (2021) Phenotypic diversity for phenological and agronomic traits in the UC-Riverside cowpea (Vigna unguiculata L. Walp) mini-core collection. Crop Sci 61:3551–3563. https://doi.org/10.1002/CSC2.20544

de Cassia Felix Alvarez R, Taveira AC, de Lima SF, Teodoro LPR, de Oliveira JT, dos Santos A, Rodrigues EV, Ceccon G, Teodoro PE (2021) Genetic Diversity of Cowpea Genotypes Grown in the Brazilian Cerrado. HortScience 56:28–29. https://doi.org/10.21273/HORTSCI15514-20

de Souza Marinho JT, Lessa LS, da Costa CR (2021) Agronomic performance of cowpea genotypes in southwestern Brazilian Amazon. Pesqui Agropecu Bras 56:e02046. https://doi.org/10.1590/S1678-3921.PAB2021.V56.02046

de Valença AW, Bake A, Brouwer ID, Giller KE (2017) Agronomic biofortification of crops to fight hidden hunger in sub-Saharan Africa. Glob Food Sec 12:8–14. https://doi.org/10.1016/J.GFS.2016.12.001

Demidchik V, Cuin TA, Svistunenko D, Smith SJ, Miller AJ, Shabala S, Sokolik A, Yurin V (2010) Arabidopsis root K+-efflux conductance activated by hydroxyl radicals: Single-channel properties, genetic basis and involvement in stress-induced cell death. J Cell Sci 123:1468–1479. https://doi.org/10.1242/jcs.064352

Deshpande SK, Mani BR, Desai SA, Nagarathna TK, Hanchinal RR (2018) Review on Characterization of Cowpea Germplasm in Terms of Distinctness, Uniformity, Stability and Novelty for Morphological, Quality and Yield Attributing Parameters. IntJCurrMicrobiolAppSci 7:1124–1139. https://doi.org/10.20546/ijcmas.2018.706.134

Diao M, Ma L, Wang J, Cui J, Fu A, Liu H ying (2014) Selenium Promotes the Growth and Photosynthesis of Tomato Seedlings Under Salt Stress by Enhancing Chloroplast Antioxidant Defense System. J Plant Growth Regul 33:671–682. https://doi.org/10.1007/s00344-014-9416-2

Dixon NE, Gazzola C, Blakeley RL, Zerner B (1975) Jack Bean Urease (EC 3.5.1.5). A Metalloenzyme. A Simple Biological Role for Nickel? J Am Chem Soc 97:4131–4133. https://doi.org/10.1021/JA00847A045

dos Reis AR, El-Ramady H, Santos EF, Gratão PL, Schomburg L (2017) Overview of Selenium Deficiency and Toxicity Worldwide: Affected Areas, Selenium-Related Health Issues, and Case Studies. 209–230. https://doi.org/10.1007/978-3-319-56249-0_13

Dubois M, Gilles KA, Hamilton JK, Rebers PA, Smith F (1956) Colorimetric Method for Determination of Sugars and Related Substances. Anal Chem 28:350–356. https://doi.org/10.1021/ac60111a017

DuBois Michel, Gilles KA, Hamilton JK, Rebers PA, Smith Fred (1956) Colorimetric Method for Determination of Sugars and Related Substances. Anal Chem 28:350–356. https://doi.org/10.1021/ac60111a017

Duntas LH, Benvenga S (2015) Selenium: an element for life. Endocrine 48:756–775. https://doi.org/10.1007/S12020-014-0477-6/FIGURES/2

Echer FR, Dominato JC, Creste JE (2009) Absorção de nutrientes e distribuição da massa fresca e seca entre órgãos de batata-doce. Hortic Bras 27:176–182. https://doi.org/10.1590/s0102-05362009000200010

Eggersdorfer M, Akobundu U, Bailey RL, et al (2018) Hidden hunger: Solutions for America's aging populations. Nutrients 10:1210

El Mehdawi AF, Jiang Y, Guignardi ZS, Esmat A, Pilon M, Pilon-Smits EAH, Schiavon M (2018) Influence of sulfate supply on selenium uptake dynamics and expression of sulfate/selenate transporters in selenium hyperaccumulator and nonhyperaccumulator Brassicaceae. New Phytologist 217:194–205. https://doi.org/10.1111/NPH.14838

El Mehdawi AF, Pilon-Smits EAH (2012) Ecological aspects of plant selenium hyperaccumulation. Plant Biol 14:1–10

Elkelish AA, Soliman MH, Alhaithloul HA, El-Esawi MA (2019) Selenium protects wheat seedlings against salt stress-mediated oxidative damage by up-regulating antioxidants and osmolytes metabolism. Plant Physiology and Biochemistry 137:144–153. https://doi.org/10.1016/J.PLAPHY.2019.02.004

Eurola M, Alainen T, Berlin T, Ekholm P, Erlund I, Hieta-Niemi V, Mannio J, Mykkänen S, Pulkkinen M, Root T, Seppänen M, Siimes K, Venäläinen E-R, Ylivainio K (2022) Report of the Selenium Working Group 2022

Fairweather-Tait S, Reviews RH-NR, 1996 undefined (1996) Bioavailability of minerals and trace elements: Members of EC flair concerted action no. 10: Measurements of micronutrient absorption and status. cambridge.orgS Fairweather-Tait, RF HurrellNutrition Research Reviews, 1996•cambridge.org 9:295–324. https://doi.org/10.1079/NRR19960016

Fairweather-Tait SJ, Bao Y, Broadley MR, Collings R, Ford D, Hesketh JE, Hurst R (2011a) Selenium in human health and disease. Antioxid Redox Signal 14:1337–1383

Fairweather-Tait SJ, Bao Y, Broadley MR, Collings R, Ford D, Hesketh JE, Hurst R (2011b) Selenium in human health and disease. Antioxid Redox Signal 14:1337–1383

Fanzo J, Hawkes C, Udomkesmalee E, Afshin A (2018) 2018 Global Nutrition Report: Shining a light to spur action on nutrition

FAO (2023) Crops and Livestock Products. https://www.fao.org/faostat/en/#data/QCL. Accessed 9 Aug 2024

FAO (2017) The State of Food Insecurity in the World: Building Resilience for Peace and Food Security. Rome

FAO F and agriculture organization of the UNations (2020a) The State of Food Security and Nutrition in the World 2020

FAO F and agriculture organization of the UNations (2020b) The Global Economy of Pulses

Farias VD da S, Costa DLPC, Souza PJ de OP de, Takaki AY, Lima MJA de (2015) Temperaturas basais e necessidade térmica para o ciclo de desenvolvimento do feijão-caupi. Enciclopédia Biosfera 11:1781

Faye M, Jooste A, … JL-D-SAJ of, 2006 undefined Impact of sucrose contents and cooking time on cowpea prices in Senegal: economics. journals.co.zaMD Faye, A Jooste, J Lowenberg-Deboer, J FultonSouth African Journal of Economic and Management Sciences, 2006•journals.co.za

Feizollahi E, Mirmahdi RS, Zoghi A, Zijlstra RT, Roopesh MS, Vasanthan T (2021) Review of the beneficial and anti-nutritional qualities of phytic acid, and procedures for removing it from food products. Food Research International 143:110284. https://doi.org/10.1016/J.FOODRES.2021.110284

Feng R, Wei C, Tu S (2013) The roles of selenium in protecting plants against abiotic stresses. Environ Exp Bot 87:58–68

Ferreira RLU, Sena-Evangelista KCM, de Azevedo EP, Pinheiro FI, Cobucci RN, Pedrosa LFC (2021) Selenium in Human Health and Gut Microflora: Bioavailability of Selenocompounds and Relationship With Diseases. Front Nutr 8:685317. https://doi.org/10.3389/FNUT.2021.685317/BIBTEX

FILHO FF, FILHO FF (2011) Feijão-caupi no Brasil: produção, melhoramento genético, avanços e desafios.

Fredlund K, Isaksson M, Rossander-Hulthén L, Almgren A, Sandberg AS (2006) Absorption of zinc and retention of calcium: Dose-dependent inhibition by phytate. Journal of Trace Elements in Medicine and Biology 20:49–57. https://doi.org/10.1016/J.JTEMB.2006.01.003

Galindo FS, Teixeira Filho MCM, da Silva EC, Buzetti S, Fernandes GC, Rodrigues WL (2020) Technical and economic viability of cowpea co-inoculated with *Azospirillum brasilense* and *Bradyrhizobium* spp. and nitrogen doses. Revista Brasileira de Engenharia Agrícola e Ambiental 24:304–311. https://doi.org/10.1590/1807-1929/AGRIAMBI.V24N5P304-311

Gammelgaard B, Jackson MI, Gabel-Jensen C (2010a) Surveying selenium speciation from soil to cell—forms and transformations. Analytical and Bioanalytical Chemistry 2010 399:5 399:1743–1763. https://doi.org/10.1007/S00216-010-4212-8

Gammelgaard B, Jackson MI, Gabel-Jensen C (2010b) Surveying selenium speciation from soil to cell—forms and transformations. Analytical and Bioanalytical Chemistry 2010 399:5 399:1743–1763. https://doi.org/10.1007/S00216-010-4212-8

Garg M, Sharma N, Sharma S, Kapoor P, Kumar A, Chunduri V, Arora P (2018) Biofortified Crops Generated by Breeding, Agronomy, and Transgenic Approaches Are Improving Lives of Millions of People around the World. Front Nutr 5:. https://doi.org/10.3389/FNUT.2018.00012/FULL

Gigolashvili T, Kopriva S (2014a) Transporters in plant sulfur metabolism. Front Plant Sci 5:107212. https://doi.org/10.3389/FPLS.2014.00442/BIBTEX

Gigolashvili T, Kopriva S (2014b) Transporters in plant sulfur metabolism. Front Plant Sci 5:442

Gill SS, Tuteja N (2010) Reactive oxygen species and antioxidant machinery in abiotic stress tolerance in crop plants. Plant Physiology and Biochemistry 48:909–930

Gondwe TM, Alamu EO, Mdziniso P, Maziya-Dixon B (2019) Cowpea (Vigna unguiculata (L.) Walp) for food security: an evaluation of end-user traits of improved varieties in Swaziland. Sci Rep 9:1–6. https://doi.org/10.1038/s41598-019-52360-w

Gouveia GCC, Galindo FS, Dantas Bereta Lanza MG, Caroline da Rocha Silva A, Pereira de Brito Mateus M, Souza da Silva M, Rimoldi Tavanti RF, Tavanti TR, Lavres J, Reis AR (2020a) Selenium toxicity stress-induced phenotypical, biochemical and physiological responses in rice plants: Characterization of symptoms and plant metabolic adjustment. Ecotoxicol Environ Saf 202:110916. https://doi.org/10.1016/j.ecoenv.2020.110916

Gouveia GCC, Galindo FS, Lanza MGDB, Silva AC da R, Mateus MP de B, Silva MS da, Tavanti RFR, Tavanti TR, Lavres J, Reis AR dos (2020b) Selenium toxicity stress-induced phenotypical, biochemical and physiological responses in rice plants: Characterization of symptoms and plant metabolic adjustment. Ecotoxicol Environ Saf 202:. https://doi.org/10.1016/j.ecoenv.2020.110916

Guignardi Z, Schiavon M (2017) Biochemistry of Plant Selenium Uptake and Metabolism. 21–34. https://doi.org/10.1007/978-3-319-56249-0_2

Gupta M, Gupta S (2017a) An overview of selenium uptake, metabolism, and toxicity in plants. Front Plant Sci 7:234638. https://doi.org/10.3389/FPLS.2016.02074/BIBTEX

Gupta M, Gupta S (2017b) An overview of selenium uptake, metabolism, and toxicity in plants. Front Plant Sci 7:2074. https://doi.org/10.3389/fpls.2016.02074

Gupta M, Gupta S (2017c) An overview of selenium uptake, metabolism, and toxicity in plants. Front Plant Sci 7:2074. https://doi.org/10.3389/fpls.2016.02074

Gupta PK, Balyan HS, Sharma S, Kumar R (2021) Biofortification and bioavailability of Zn, Fe and Se in wheat: present status and future prospects. Theoretical and Applied Genetics 134:1–35. https://doi.org/10.1007/S00122-020-03709-7/FIGURES/8

Ha HY, Alfulaij N, Berry MJ, Seale LA (2019) From Selenium Absorption to Selenoprotein Degradation. Biological Trace Element Research 2019 192:1 192:26–37. https://doi.org/10.1007/S12011-019-01771-X

Hall AE (2012a) Phenotyping cowpeas for adaptation to drought. Front Physiol 3 MAY: https://doi.org/10.3389/FPHYS.2012.00155/FULL

Hall AE (2012b) Phenotyping cowpeas for adaptation to drought. Front Physiol 3 MAY:155. https://doi.org/10.3389/fphys.2012.00155

Handa N, Kohli SK, Sharma A, Thukral AK, Bhardwaj R, Abd_Allah EF, Alqarawi AA, Ahmad P (2019) Selenium modulates dynamics of antioxidative defence expression, photosynthetic attributes and secondary metabolites to mitigate chromium toxicity in Brassica juncea L. plants. Environ Exp Bot 161:180–192. https://doi.org/10.1016/J.ENVEXPBOT.2018.11.009

Harvestplus (2021) Biofortification: The Nutrition Revolution is Now. In: harvestplus.org. https://www.harvestplus.org/biofortification-nutrition-revolution-now. Accessed 10 Feb 2021

Hawkesford M, Horst W, Kichey T, Lambers H, Schjoerring J, Møller IS, White P (2012) Functions of Macronutrients. In: Petra Marschner (ed) Marschner's Mineral Nutrition of Higher Plants: Third Edition, 3rd edn. Elsevier Inc., pp 135–189

He R, Gao M, Shi R, Song S, Zhang Y, Su W, Liu H (2020) The combination of selenium and LED light quality affects growth and nutritional properties of broccoli sprouts. Molecules 25:4788. https://doi.org/10.3390/molecules25204788

Heath RL, Packer L (1968) Photoperoxidation in isolated chloroplasts. I. Kinetics and stoichiometry of fatty acid peroxidation. Arch Biochem Biophys 125:189–198. https://doi.org/10.1016/0003-9861(68)90654-1

Hossain A, Skalicky M, Brestic M, et al (2021) Selenium Biofortification: Roles, Mechanisms, Responses and Prospects. Molecules 2021, Vol 26, Page 881 26:881. https://doi.org/10.3390/MOLECULES26040881

Huang QQ, Wang Q, Wan YN, Yu Y, Jiang RF, Li HF (2017) Application of X-ray absorption near edge spectroscopy to the study of the effect of sulphur on selenium uptake and assimilation in wheat seedlings. Biol Plant 61:726–732. https://doi.org/10.1007/s10535-016-0698-z

Hummel M, Talsma EF, Taleon V, Londoño L, Brychkova G, Gallego S, Raatz B, Spillane C (2020) Iron, Zinc and Phytic Acid Retention of Biofortified, Low Phytic Acid, and Conventional Bean Varieties When Preparing Common Household Recipes. Nutrients 2020, Vol 12, Page 658 12:658. https://doi.org/10.3390/NU12030658

Imdad A, Mayo-Wilson E, Haykal MR, Regan A, Sidhu J, Smith A, Bhutta ZA (2022) Vitamin A supplementation for preventing morbidity and mortality in children from six months to five years of age. Cochrane Database of Systematic Reviews 2022:. https://doi.org/10.1002/14651858.CD008524.PUB4/MEDIA/CDSR/CD008524/URN:X-WILEY:14651858:MEDIA:CD008524:CD008524-CMP-001.21

Imdad A, Mayo-Wilson E, Herzer K, Bhutta ZA (2017a) Vitamin A supplementation for preventing morbidity and mortality in children from six months to five years of age. Cochrane Database Syst Rev 3:. https://doi.org/10.1002/14651858.CD008524.PUB3

Imdad A, Mayo-Wilson E, Herzer K, Bhutta ZA (2017b) Vitamin A supplementation for preventing morbidity and mortality in children from six months to five years of age. Cochrane Database of Systematic Reviews 2017:. https://doi.org/10.1002/14651858.CD008524.pub3

Irani S, Todd CD (2016) Ureide metabolism under abiotic stress in Arabidopsis thaliana. J Plant Physiol 199:87–95. https://doi.org/10.1016/j.jplph.2016.05.011

Ismael MA, Elyamine AM, Moussa MG, Cai M, Zhao X, Hu C (2019) Cadmium in plants: uptake, toxicity, and its interactions with selenium fertilizers. Metallomics 11:255–277. https://doi.org/10.1039/C8MT00247A

Jafari S, McClements D (2017) Abordagens nanotecnológicas para aumentar a biodisponibilidade de nutrientes. Avanços na pesquisa em alimentos e nutrição

Jang HS, Lee J, Lee HJ, Park EY (2020) Phytate-mediated phosphorylation of maize, rice, and potato starches at different pH conditions. Int J Biol Macromol 165:857–864. https://doi.org/10.1016/J.IJBIOMAC.2020.09.245

Jiang H, Lin W, Jiao H, Liu J, Chan L, Liu X, Wang R, Chen T (2021) Uptake, transport, and metabolism of selenium and its protective effects against toxic metals in plants: a review. Metallomics 13:40. https://doi.org/10.1093/MTOMCS/MFAB040

Jiang Y, Schiavon M, Lima LW, Tripti, Jones RR, El Mehdawi AF, Royer S, Zeng Z, Hu Y, Pilon-Smits EAH, Pilon M (2018) Comparison of ATP sulfurylase 2 from selenium hyperaccumulator Stanleya pinnata and non-accumulator Stanleya elata reveals differential intracellular localization and enzyme activity levels. Biochimica et Biophysica Acta (BBA) - General Subjects 1862:2363–2371. https://doi.org/10.1016/J.BBAGEN.2018.03.014

Jiang Y, Tang X, Zhou B, Sun T, Chen H, Zhao X, Wang Y (2017) The ROS-mediated pathway coupled with the MAPK-p38 signalling pathway and antioxidant system plays roles in the responses of Mytilus edulis haemocytes induced by BDE-47. Aquatic Toxicology 187:55–63. https://doi.org/10.1016/j.aquatox.2017.03.011

Jones GD, Droz B, Greve P, Gottschalk P, Poffet D, McGrath SP, Seneviratne SI, Smith P, Winkel LHE (2017a) Selenium deficiency risk predicted to increase under future climate change. Proc Natl Acad Sci U S A 114:2848–2853. https://doi.org/10.1073/PNAS.1611576114/SUPPL_FILE/PNAS.201611576SI.PDF

Jones GD, Droz B, Greve P, Gottschalk P, Poffet D, McGrath SP, Seneviratne SI, Smith P, Winkel LHE (2017b) Selenium deficiency risk predicted to increase under future climate change. Proc Natl Acad Sci U S A 114:2848–2853. https://doi.org/10.1073/pnas.1611576114

Joy EJM, Kalimbira AA, Sturgess J, et al (2022) Biofortified Maize Improves Selenium Status of Women and Children in a Rural Community in Malawi: Results of the Addressing Hidden Hunger With Agronomy Randomized Controlled Trial. Front Nutr 8:788096. https://doi.org/10.3389/FNUT.2021.788096/BIBTEX

Kato T, Read R, Rozga J, Burk RF (1992) Evidence for intestinal release of absorbed selenium in a form with high hepatic extraction. https://doi.org/101152/ajpgi19922625G854 262:. https://doi.org/10.1152/AJPGI.1992.262.5.G854

Kieliszek M (2019) Selenium–Fascinating Microelement, Properties and Sources in Food. Molecules 2019, Vol 24, Page 1298 24:1298. https://doi.org/10.3390/MOLECULES24071298

Kieliszek M, Bła˙ S, Santi C, Bagnoli L (2016) Current Knowledge on the Importance of Selenium in Food for Living Organisms: A Review. Molecules 2016, Vol 21, Page 609 21:609. https://doi.org/10.3390/MOLECULES21050609

Kieliszek M, Błażejak S, Gientka I, Bzducha-Wróbel A (2015) Accumulation and metabolism of selenium by yeast cells. Appl Microbiol Biotechnol 99:5373–5382. https://doi.org/10.1007/S00253-015-6650-X/FIGURES/5

Kolbert Z, Lehotai N, Molnár Á, Feigl G (2016) “The roots” of selenium toxicity: A new concept. Plant Signal Behav 11:e1241935. https://doi.org/10.1080/15592324.2016.1241935

Kolbert Z, Molnár, Feigl G, Van Hoewyk D (2019) Plant selenium toxicity: Proteome in the crosshairs. J Plant Physiol 232:291–300. https://doi.org/10.1016/J.JPLPH.2018.11.003

König P, Tautenhahn S, Cornelissen JHC, Kattge J, Bönisch G, Römermann C (2018) Advances in flowering phenology across the Northern Hemisphere are explained by functional traits. Global Ecology and Biogeography 27:310–321. https://doi.org/10.1111/GEB.12696

Kovalchuk I (2010) Multiple roles of radicals in plants. In: Reactive oxygen species and antioxidants in higher plants

Kumar P, Kumar S, Tripathi M, … NM-V, 2013 undefined Flavonoids in the development of functional meat products: A review. cyberleninka.orgP Kumar, S Kumar, MK Tripathi, N Mehta, R Ranjan, ZF Bhat, PK SinghVeterinary World, 2013•cyberleninka.org

Kumar S, Singh A, Dikshit HK, Mishra GP, Aski M, Bansal R, Gupta P (2024) Global Scenario of Biofortification. Biofortification for Nutrient-Rich Crops 26–42. https://doi.org/10.1201/9781032690636-3

Kumar V, Sinha AK, Makkar HPS, Becker K (2010) Dietary roles of phytate and phytase in human nutrition: A review. Food Chem 120:945–959. https://doi.org/10.1016/J.FOODCHEM.2009.11.052

Lacour M, Zunder T, Restle A, Schwarzer G (2004) No evidence for an impact of selenium supplementation on environment associated health disorders – a systematic review. Int J Hyg Environ Health 207:1–13. https://doi.org/10.1078/1438-4639-00254

Langyan S, Yadava P, Khan FN, Bhardwaj R, Tripathi K, Bhardwaj V, Bhardwaj R, Gautam RK, Kumar A (2022) Nutritional and Food Composition Survey of Major Pulses Toward Healthy, Sustainable, and Biofortified Diets. Front Sustain Food Syst 6:878269. https://doi.org/10.3389/FSUFS.2022.878269/BIBTEX

Lanza MGDB, Reis AR dos (2021) Roles of selenium in mineral plant nutrition: ROS scavenging responses against abiotic stresses. Plant Physiology and Biochemistry 164:27–43. https://doi.org/10.1016/j.plaphy.2021.04.026

Lanza MGDB, Silva VM, Montanha GS, Lavres J, Pereira de Carvalho HW, Reis AR dos (2020a) Assessment of selenium spatial distribution using μ-XFR in cowpea (Vigna unguiculata (L.) Walp.) plants: Integration of physiological and biochemical responses. Ecotoxicol Environ Saf 207:111216. https://doi.org/10.1016/j.ecoenv.2020.111216

Lanza MGDB, Silva VM, Montanha GS, Lavres J, Pereira de Carvalho HW, Reis AR dos (2020b) Assessment of selenium spatial distribution using μ-XFR in cowpea (Vigna unguiculata (L.) Walp.) plants: Integration of physiological and biochemical responses. Ecotoxicol Environ Saf 207:111216. https://doi.org/10.1016/j.ecoenv.2020.111216

Lanza MGDB, Silva VM, Montanha GS, Lavres J, Pereira de Carvalho HW, Reis AR dos (2021) Assessment of selenium spatial distribution using μ-XFR in cowpea (Vigna unguiculata (L.) Walp.) plants: Integration of physiological and biochemical responses. Ecotoxicol Environ Saf 207:111216. https://doi.org/10.1016/j.ecoenv.2020.111216

Lara TS, Lessa JH de L, de Souza KRD, Corguinha APB, Martins FAD, Lopes G, Guilherme LRG (2019) Selenium biofortification of wheat grain via foliar application and its effect on plant metabolism. Journal of Food Composition and Analysis 81:10–18. https://doi.org/10.1016/j.jfca.2019.05.002

Lavres J, Reis AR, Rossi ML, Cabral CP, Nogueira N de L, Malavolta E (2010) Changes in the ultrastructure of soybean cultivars in response to manganese supply in solution culture. Sci Agric 67:287–294. https://doi.org/10.1590/S0103-90162010000300006

Lazard M, Dauplais M, Blanquet S, Plateau P (2017) Recent advances in the mechanism of selenoamino acids toxicity in eukaryotic cells. Biomol Concepts 8:93–104. https://doi.org/10.1515/BMC-2017-0007/ASSET/GRAPHIC/J_BMC-2017-0007_FIG_002.JPG

Lemire M, Philibert A, Fillion M, Passos CJS, Guimarães JRD, Barbosa F, Mergler D (2012) No evidence of selenosis from a selenium-rich diet in the Brazilian Amazon. Environ Int 40:128–136. https://doi.org/10.1016/J.ENVINT.2011.07.005

Lewis J (2019) Codex nutrient reference values. Rome

Li X, Wu Y, Li B, Yang Y, Yang Y (2018) Selenium accumulation characteristics and biofortification potentiality in turnip (Brassica rapa var. rapa) supplied with selenite or selenate. Front Plant Sci 8:2207. https://doi.org/10.3389/fpls.2017.02207

Liang Y, Li D, Chen Y, Cheng J, Zhao G, Fahima T, Yan J (2020) Selenium mitigates salt-induced oxidative stress in durum wheat (Triticum durum Desf.) seedlings by modulating chlorophyll fluorescence, osmolyte accumulation, and antioxidant system. 3 Biotech 10:1–14. https://doi.org/10.1007/S13205-020-02358-3/FIGURES/5

Lichtenthaler HK, Wellburn AR (1983) Determinations of total carotenoids and chlorophylls a and b of leaf extracts in different solvents. Biochem Soc Trans 11:591–592. https://doi.org/10.1042/bst0110591

Liliana García-Bañuelos M, Pedro Sida-Arreola J, Sánchez E, Mónica García-Bañuelos ML, Juan Pedro Sida-Arreola M (2014) Biofortification - promising approach to increasing the content of iron and zinc in staple food crops. J Elem 19:. https://doi.org/10.5601/JELEM.2014.19.3.708

Lima LW, Pilon-Smits EAH, Schiavon M (2018a) Mechanisms of selenium hyperaccumulation in plants: A survey of molecular, biochemical and ecological cues. Biochimica et Biophysica Acta (BBA) - General Subjects 1862:2343–2353. https://doi.org/10.1016/J.BBAGEN.2018.03.028

Lima LW, Pilon-Smits EAH, Schiavon M (2018b) Mechanisms of selenium hyperaccumulation in plants: A survey of molecular, biochemical and ecological cues. Biochim Biophys Acta Gen Subj 1862:2343–2353

Lindblom SD, Wangeline AL, Valdez Barillas JR, Devilbiss B, Fakra SC, Pilon-Smits EAH (2018) Fungal endophyte alternaria tenuissima can affect growth and selenium accumulation in its hyperaccumulator host astragalus bisulcatus. Front Plant Sci 9:1213. https://doi.org/10.3389/fpls.2018.01213

Liu H, Xiao C, Qiu T, Deng J, Cheng H, Cong X, Cheng S, Rao S, Zhang Y (2022) Selenium Regulates Antioxidant, Photosynthesis, and Cell Permeability in Plants under Various

Abiotic Stresses: A Review. Plants 2023, Vol 12, Page 44 12:44. https://doi.org/10.3390/PLANTS12010044

Liu Q, Zhao X, Ma J, Mu Y, Wang Y, Yang S, Wu Y, Wu F, Zhou Y (2021) Selenium (Se) plays a key role in the biological effects of some viruses: Implications for COVID-19. Environ Res 196:110984. https://doi.org/10.1016/J.ENVRES.2021.110984

Loechl CU, Datta-Mitra A, Fenlason L, Green R, Hackl L, Itzkowitz L, Koso-Thomas M, Moorthy D, Owino VO, Pachón H, Stoffel N, Zimmerman MB, Raiten DJ (2023) Approaches to Address the Anemia Challenge. J Nutr 153:S42–S59. https://doi.org/10.1016/J.TJNUT.2023.07.017

Luciano De Souza Ferraz R, Soares De Melo A, Fernandes Suassuna J, Barbosa De Brito ME, Dantas Fernandes P, Da Silva E, Júnior N (2012) Trocas gasosas e eficiência fotossintética em ecótipos de feijoeiro cultivados no semiárido. Pesqui Agropecu Trop 42:181–188. https://doi.org/10.1590/S1983-40632012000200010

Mafakheri K, Bihamta MR, Abbasi AR (2017) Assessment of genetic diversity in cowpea (Vigna unguiculata L.) germplasm using morphological and molecular characterisation. Cogent Food Agric 3:1327092. https://doi.org/10.1080/23311932.2017.1327092

Malavolta E, Haag HP, Gargantini H, Garcia Blanco H (1967) Absorção de nutrientes pela cultura do feijoeiro. Bragantia 26:381–391. https://doi.org/10.1590/s0006-87051967000100030

Malhotra H, Vandana, Sharma S, Pandey R (2018) Phosphorus nutrition: Plant growth in response to deficiency and excess. In: Plant Nutrients and Abiotic Stress Tolerance. Springer Singapore, pp 171–190

Manaf HH (2016) Beneficial effects of exogenous selenium, glycine betaine and seaweed extract on salt stressed cowpea plant. Annals of Agricultural Sciences 61:41–48. https://doi.org/10.1016/j.aoas.2016.04.003

Mangels AR, Moser-Veillon PB, Patterson KY, Veillon C (1990) Selenium utilization during human lactation by use of stable-isotope tracers. Am J Clin Nutr 52:621–627. https://doi.org/10.1093/AJCN/52.4.621

Manzeke MG, Mtambanengwe F, Nezomba H, Watts MJ, Broadley MR, Mapfumo P (2017) Zinc fertilization increases productivity and grain nutritional quality of cowpea (Vigna unguiculata [L.] Walp.) under integrated soil fertility management. Field Crops Res 213:231–244. https://doi.org/10.1016/j.fcr.2017.08.010

Maria Machado Maia F, Tadeu Abreu Oliveira J, Moreira R, Maia FM, Oliveira JT, Matos MR, Moreira RA, Vasconcelos IM (2000) Proximate composition, amino acid content and haemagglutinating and trypsin-inhibiting activities of some Brazilian Vigna unguiculata (L) Walp cultivars. Wiley Online LibraryFMM Maia, JTA Oliveira, MRT Matos, RA Moreira, IM VasconcelosJournal of the Science of Food and Agriculture, 2000•Wiley Online Library. https://doi.org/10.1002/(SICI)1097-0010(200003)80:4<453::AID-JSFA548>3.0.CO;2-X

Marinho R de CN, Ferreira L de VM, da Silva AF, Martins LMV, Nóbrega RSA, Fernandes-Júnior PI (2017) Symbiotic and agronomic efficiency of new cowpea rhizobia from Brazilian Semi-Arid. Bragantia 76:273–281. https://doi.org/10.1590/1678-4499.003

Marschner P (2011) Marschner's Mineral Nutrition of Higher Plants: Third Edition. Elsevier Inc.

Martineau E, Domec JC, Bosc A, Dannoura M, Gibon Y, Bénard C, Jordan-Meille L (2017) The role of potassium on maize leaf carbon exportation under drought condition. Acta Physiol Plant 39:1–13. https://doi.org/10.1007/S11738-017-2515-5/TABLES/4

Martins MDPSC, Lopes AF de S, Jean A, Damasceno-Silva KJ, E Martins M do C de C, Rocha M de M (2023) Characterization of cowpea cultivars for grain size, color, and biofortification. Revista Caatinga 36:207–214. https://doi.org/10.1590/1983-21252023V36N122RC

Mateus MP de B, Tavanti RFR, Galindo FS, Silva AC da R, Gouveia GCC, Aparecido CFF, Carr NF, Feitosa YB, Santos EF, Lavres J, Reis AR dos (2020a) Coffea arabica seedlings genotypes are tolerant to high induced selenium stress: Evidence from physiological plant responses and antioxidative performance. Ecotoxicol Environ Saf 203:111016. https://doi.org/10.1016/j.ecoenv.2020.111016

Mateus MP de B, Tavanti RFR, Galindo FS, Silva AC da R, Gouveia GCC, Aparecido CFF, Carr NF, Feitosa YB, Santos EF, Lavres J, Reis AR dos (2020b) Coffea arabica seedlings genotypes are tolerant to high induced selenium stress: Evidence from physiological plant responses and antioxidative performance. Ecotoxicol Environ Saf 203:111016. https://doi.org/10.1016/j.ecoenv.2020.111016

Mateus MP de B, Tavanti RFR, Tavanti TR, Santos EF, Jalal A, Reis AR dos (2021a) Selenium biofortification enhances ROS scavenge system increasing yield of coffee plants. Ecotoxicol Environ Saf 209:111772. https://doi.org/10.1016/j.ecoenv.2020.111772

Mateus MP de B, Tavanti RFR, Tavanti TR, Santos EF, Jalal A, Reis AR dos (2021b) Selenium biofortification enhances ROS scavenge system increasing yield of coffee plants. Ecotoxicol Environ Saf 209:111772. https://doi.org/10.1016/j.ecoenv.2020.111772

Mathur S, Sharma MP, Jajoo A (2018) Improved photosynthetic efficacy of maize (Zea mays) plants with arbuscular mycorrhizal fungi (AMF) under high temperature stress. J Photochem Photobiol B 180:149–154. https://doi.org/10.1016/J.JPHOTOBIOL.2018.02.002

Matos RP, Lima VMP, Windmöller CC, Nascentes CC (2017) Correlation between the natural levels of selenium and soil physicochemical characteristics from the Jequitinhonha Valley (MG), Brazil. J Geochem Explor 172:195–202. https://doi.org/10.1016/j.gexplo.2016.11.001

Melo AS de, Costa RR da, Sá FV da S, et al (2024) Modulation of Drought-Induced Stress in Cowpea Genotypes Using Exogenous Salicylic Acid. Plants 2024, Vol 13, Page 634 13:634. https://doi.org/10.3390/PLANTS13050634

Melo F de B, Cardoso MJ (2017) Cultivo de Feijão-Caupi: Dados Sistema de Produção Embrapa Meio-Norte, Embrapa Amazônia Ocidental e Embrapa Agrobiologia

Mendes NAC, Cunha MLO, Bosse MA, Silva VM, Moro AL, Agathokleous E, Vicente EF, Reis AR dos (2023) Physiological and biochemical role of nickel in nodulation and biological nitrogen fixation in Vigna unguiculata L. Walp. Plant Physiology and Biochemistry 201:107869. https://doi.org/10.1016/J.PLAPHY.2023.107869

Miller G, Suzuki N, Ciftci-Yilmaz S, Mittler R (2010) Reactive oxygen species homeostasis and signalling during drought and salinity stresses. Plant Cell Environ 33:453–467. https://doi.org/10.1111/j.1365-3040.2009.02041.x

Mimmo T, Tiziani R, Valentinuzzi F, Lucini L, Nicoletto C, Sambo P, Scampicchio M, Pii Y, Cesco S (2017) Selenium biofortification in fragaria × ananassa: Implications on strawberry fruits quality, content of bioactive health beneficial compounds and metabolomic profile. Front Plant Sci 8:1887. https://doi.org/10.3389/fpls.2017.01887

Mishra GP, Dikshit HK, Priti, Kukreja B, Aski M, Yadava DK, Sarker A, Kumar S (2022) Historical Overview of Biofortification in Crop Plants and Its Implications. Biofortification of Staple Crops 31–61. https://doi.org/10.1007/978-981-16-3280-8_2

Moghaddam A, Heller RA, Sun Q, Seelig J, Cherkezov A, Seibert L, Hackler J, Seemann P, Diegmann J, Pilz M, Bachmann M, Minich WB, Schomburg L (2020) Selenium Deficiency Is Associated with Mortality Risk from COVID-19. Nutrients 12:2098. https://doi.org/10.3390/nu12072098

Montanha GS, Rodrigues ES, Marques JPR, De Almeida E, Dos Reis AR, Pereira De Carvalho HW (2020) X-ray fluorescence spectroscopy (XRF) applied to plant science: Challenges towards: In vivo analysis of plants. Metallomics 12:183–192. https://doi.org/10.1039/c9mt00237e

Moraes MF, Welch RM, Nutti MR, Carvalho JL V, Watanabe E (2009) Evidences of selenium deficiency in Brazil : from soil to human nutrition. First International Conference on Selenium in the Environment and Human Health 73–74

Moreno-Martin G, Sanz-Landaluze J, León-Gonzalez ME, Madrid Y (2019) In-vivo solid phase microextraction for quantitative analysis of volatile organoselenium compounds in plants. Anal Chim Acta 1081:72–80. https://doi.org/10.1016/J.ACA.2019.06.061

Mostofa MG, Ghosh A, Li ZG, Siddiqui MN, Fujita M, Tran LSP (2018) Methylglyoxal – a signaling molecule in plant abiotic stress responses. Free Radic Biol Med 122:96–109. https://doi.org/10.1016/J.FREERADBIOMED.2018.03.009

Mostofa MG, Hossain MA, Siddiqui MN, Fujita M, Tran LSP (2017) Phenotypical, physiological and biochemical analyses provide insight into selenium-induced phytotoxicity in rice plants. Chemosphere 178:212–223. https://doi.org/10.1016/j.chemosphere.2017.03.046

Muñoz-Amatriaín M, Lo S, Herniter IA, Boukar O, Fatokun C, Carvalho M, Castro I, Guo YN, Huynh BL, Roberts PA, Carnide V, Close TJ (2021) The UCR Minicore: a resource for cowpea research and breeding. Legume Science 3:e95. https://doi.org/10.1002/LEG3.95

Muratore C, Espen L, Prinsi B (2021) Nitrogen Uptake in Plants: The Plasma Membrane Root Transport Systems from a Physiological and Proteomic Perspective. Plants 2021, Vol 10, Page 681 10:681. https://doi.org/10.3390/PLANTS10040681

Nascimento SP, Bastos EA, Araújo ECE, Freire Filho FR, da Silva EM (2011) Tolerance to water deficit of cowpea genotypes. Revista Brasileira de Engenharia Agrícola e Ambiental 15:853–860. https://doi.org/10.1590/S1415-43662011000800013

Nassar M, Nassar R, Maki H, Al-Yagoob A, Hachim M, Senok A, Williams D, Hiraishi N (2021) Phytic Acid: Properties and Potential Applications in Dentistry. Front Mater 8:638909. https://doi.org/10.3389/FMATS.2021.638909/BIBTEX

Nassourou MA, Noubissié TJB, Njintang YN, Bell JM (2017) Diallel analyses of soluble sugar content in cowpea (Vigna unguiculata L. Walp.). Crop J 5:553–559. https://doi.org/10.1016/J.CJ.2017.05.005

Natasha, Shahid M, Niazi NK, Khalid S, Murtaza B, Bibi I, Rashid MI (2018) A critical review of selenium biogeochemical behavior in soil-plant system with an inference to human health. Environmental Pollution 234:915–934. https://doi.org/10.1016/j.envpol.2017.12.019

Naz FS, Yusuf M, Khan TA, Fariduddin Q, Ahmad A (2015) Low level of selenium increases the efficacy of 24-epibrassinolide through altered physiological and biochemical traits of Brassica juncea plants. Food Chem 185:441–448. https://doi.org/10.1016/j.foodchem.2015.04.016

Ngigi PB, Lachat C, Masinde PW, Du Laing G (2019) Agronomic biofortification of maize and beans in Kenya through selenium fertilization. Environ Geochem Health 41:2577–2591. https://doi.org/10.1007/s10653-019-00309-3

Nickel A, Kottra G, Schmidt G, Danier J, Hofmann T, Daniel H (2009) Characteristics of transport of selenoamino acids by epithelial amino acid transporters. Chem Biol Interact 177:234–241. https://doi.org/10.1016/J.CBI.2008.09.008

Nissar J, Ahad T, Naik HR, Hussain SZ (2017) A review phytic acid: As antinutrient or nutraceutical. J Pharmacogn Phytochem 6:1554–1560

Nkhoma N, Shimelis H, Laing MD, Shayanowako A, Mathew I (2020) Assessing the genetic diversity of cowpea [Vigna unguiculata (L.) Walp.] germplasm collections using phenotypic traits and SNP markers. BMC Genet 21:1–16. https://doi.org/10.1186/S12863-020-00914-7/TABLES/9

Nutti M, Rocha M, Watanabe E, Carvalho J, Freire Filho F, Silva K (2009) Biofortificação de feijão-caupi no Brasil. In: Embrapa Meio-Norte-Artigo em anais de congresso (ALICE). In: CONGRESSO NACIONAL DE FEIJÃO-CAUPI, 2., 2009, Belém, PA. Da agricultura de subsistência ao agronegócio: anais. Belém, PA: Embrapa Amazônia Oriental, 2009. 26–38

Oliveira A, Fernandes E, Agrícola TR-E, 2005 undefined Condutância estomática como indicador de estresse hídrico em feijão. SciELO BrasilAD Oliveira, EJ Fernandes, TJD RodriguesEngenharia Agrícola, 2005•SciELO Brasil

Paudel D, Dareus R, Rosenwald J, Muñoz-Amatriaín M, Rios EF (2021) Genome-Wide Association Study Reveals Candidate Genes for Flowering Time in Cowpea (Vigna unguiculata [L.] Walp.). Front Genet 12:. https://doi.org/10.3389/FGENE.2021.667038/FULL

Pereira EG, Amaral MB, Bucher CA, Santos LA, Fernandes MS, Vieira Rossetto CA (2021) Proline osmopriming improves the root architecture, nitrogen content and growth of rice seedlings. Biocatal Agric Biotechnol 33:101998. https://doi.org/10.1016/J.BCAB.2021.101998

Peters KM, Galinn SE, Tsuji PA (2016) Selenium: Dietary Sources, Human Nutritional Requirements and Intake Across Populations. Selenium: Its Molecular Biology and Role in Human Health, Fourth Edition 295–305. https://doi.org/10.1007/978-3-319-41283-2_25

Pilon-Smits EA, Quinn CF, Tapken W, Malagoli M, Schiavon M (2009) Physiological functions of beneficial elements. Curr Opin Plant Biol 12:267–274

Pilon-Smits EAH (2015) Selenium in Plants. 93–107. https://doi.org/10.1007/978-3-319-08807-5_4

Pilon-Smits EAH (2019a) On the Ecology of Selenium Accumulation in Plants. Plants 2019, Vol 8, Page 197 8:197. https://doi.org/10.3390/PLANTS8070197

Pilon-Smits EAH (2019b) On the ecology of selenium accumulation in plants. Plants 8:197

PNUD (2022) Towards 2021/2022 Human Development Report. Human Development Reports

Prasad R, Shivay YS (2020) Agronomic biofortification of plant foods with minerals, vitamins and metabolites with chemical fertilizers and liming. J Plant Nutr 43:1534–1554

Raboy V (2020) Low phytic acid Crops: Observations Based on Four Decades of Research. Plants 2020, Vol 9, Page 140 9:140. https://doi.org/10.3390/PLANTS9020140

Raboy V (2003) myo-Inositol-1,2,3,4,5,6-hexakisphosphate. Phytochemistry 64:1033–1043. https://doi.org/10.1016/S0031-9422(03)00446-1

Raggi L, Caproni L, Carboni A, Negri V (2019) Genome-Wide Association Study Reveals Candidate Genes for Flowering Time Variation in Common Bean (Phaseolus vulgaris L.). Front Plant Sci 10:. https://doi.org/10.3389/FPLS.2019.00962/FULL

Rahman M, Rahman K, Sathi KS, Alam MM, Nahar K, Fujita M, Hasanuzzaman M (2021) Supplemental Selenium and Boron Mitigate Salt-Induced Oxidative Damages in Glycine max L. Plants 2021, Vol 10, Page 2224 10:2224. https://doi.org/10.3390/PLANTS10102224

Raij B van, Andrade JC, Cantarella H, Quaggio JA (2001a) Análise química para avaliação da fertilidade de solos tropicais

Raij B van, Andrade JC, Cantarella H, Quaggio JA (2001b) Análise química para avaliação da fertilidade de solos tropicais

Ramos HMM, Bastos EA, Cardoso MJ, Ribeiro VQ, Do Nascimento FN (2014) Produtividade de grãos verdes do feijão-caupi sob diferentes regimes hídricos. Engenharia Agrícola 34:683–694. https://doi.org/10.1590/S0100-69162014000400008

Rayman MP (2012a) Selenium and human health. The Lancet 379:1256–1268

Rayman MP (2012b) Selenium and human health. The Lancet 379:1256–1268

Rayman MP, Duntas LH (2019) Selenium Deficiency and Thyroid Disease. In: The Thyroid and Its Diseases. Springer International Publishing, pp 109–126

Rehman A ur, Masood S, Khan NU, Abbasi ME, Hussain Z, Ali I (2021) Molecular basis of Iron Biofortification in crop plants; A step towards sustainability. Plant Breeding 140:12–22. https://doi.org/10.1111/PBR.12886

Reis AR, El-Ramady H, Santos EF, Gratão PL, Schomburg L (2017a) Overview of Selenium Deficiency and Toxicity Worldwide: Affected Areas, Selenium-Related Health Issues, and Case Studies. In: Springer. pp 209–230

Reis AR, El-Ramady H, Santos EF, Gratão PL, Schomburg L (2017b) Overview of Selenium Deficiency and Toxicity Worldwide: Affected Areas, Selenium-Related Health Issues, and Case Studies. Springer, Cham, pp 209–230

Reis AR dos, Boleta EHM, Alves CZ, Cotrim MF, Barbosa JZ, Silva VM, Porto RL, Lanza MGDB, Lavres J, Gomes MHF, Carvalho HWP de (2020a) Selenium toxicity in upland field-grown rice: Seed physiology responses and nutrient distribution using the μ-XRF technique. Ecotoxicol Environ Saf 190:. https://doi.org/10.1016/j.ecoenv.2019.110147

Reis HPG, Barcelos JP de Q, Junior EF, Santos EF, Silva VM, Moraes MF, Putti FF, Reis AR dos (2018a) Agronomic biofortification of upland rice with selenium and nitrogen and its relation to grain quality. J Cereal Sci 79:508–515. https://doi.org/10.1016/j.jcs.2018.01.004

Reis HPG, Barcelos JP de Q, Junior EF, Santos EF, Silva VM, Moraes MF, Putti FF, Reis AR dos (2018b) Agronomic biofortification of upland rice with selenium and nitrogen and its relation to grain quality. J Cereal Sci 79:508–515. https://doi.org/10.1016/j.jcs.2018.01.004

Reis HPG, Barcelos JP de Q, Junior EF, Santos EF, Silva VM, Moraes MF, Putti FF, Reis AR dos (2018c) Agronomic biofortification of upland rice with selenium and nitrogen and its relation to grain quality. J Cereal Sci 79:508–515. https://doi.org/10.1016/j.jcs.2018.01.004

Reis HPG, de Queiroz Barcelos JP, Silva VM, Santos EF, Tavanti RFR, Putti FF, Young SD, Broadley MR, White PJ, dos Reis AR (2020b) Agronomic biofortification with selenium impacts storage proteins in grains of upland rice. J Sci Food Agric 100:1990–1997. https://doi.org/10.1002/jsfa.10212

Research HB-FC, 1999 undefined Economics of enhanced micronutrient density in food staples. ElsevierHE BouisField Crops Research, 1999•Elsevier

Ribeiro DM, Silva Júnior DD, Cardoso FB, Martins AO, Silva WA, Nascimento VL, Araújo WL (2016) Growth inhibition by selenium is associated with changes in primary metabolism and nutrient levels in Arabidopsis thaliana. Plant Cell Environ 39:2235–2246. https://doi.org/10.1111/pce.12783

Rivas R, Falcão HM, Ribeiro R V., Machado EC, Pimentel C, Santos MG (2016) Drought tolerance in cowpea species is driven by less sensitivity of leaf gas exchange to water deficit and rapid recovery of photosynthesis after rehydration. South African Journal of Botany 103:101–107. https://doi.org/10.1016/J.SAJB.2015.08.008

Ros GH, van Rotterdam AMD, Bussink DW, Bindraban PS (2016) Selenium fertilization strategies for bio-fortification of food: an agro-ecosystem approach. Plant Soil 404:99–112. https://doi.org/10.1007/S11104-016-2830-4/FIGURES/5

Rua RM, Nogales F, Carreras O, Ojeda ML (2023) Selenium, selenoproteins and cancer of the thyroid. Journal of Trace Elements in Medicine and Biology 76:127115. https://doi.org/10.1016/J.JTEMB.2022.127115

Saltzman A, Birol E, Oparinde A, Andersson MS, Asare-Marfo D, Diressie MT, Gonzalez C, Lividini K, Moursi M, Zeller M (2017) Availability, production, and consumption of crops biofortified by plant breeding: current evidence and future potential. Ann N Y Acad Sci 1390:104–114. https://doi.org/10.1111/NYAS.13314

Santos EF, Figueiredo CO, Rocha MAP, Lanza MGDB, Silva VM, Reis AR (2023) Phosphorus and Selenium Interaction Effects on Agronomic Biofortification of Cowpea Plants. J Soil Sci Plant Nutr 23:4385–4395. https://doi.org/10.1007/S42729-023-01357-6/FIGURES/5

Santos EF, Kondo Santini JM, Paixão AP, Júnior EF, Lavres J, Campos M, Reis AR dos (2017) Physiological highlights of manganese toxicity symptoms in soybean plants: Mn toxicity responses. Plant Physiology and Biochemistry 113:6–19. https://doi.org/10.1016/j.plaphy.2017.01.022

Santos JA da. S, Soares CMG, Correa AM, Teodoro PE, Ribeiro LP, de Abreu HKA (2014) Agronomic performance and genetic dissimilarity among cowpea (Vigna unguiculata (L.) Walp.) genotypes. GLOBAL ADVANCED RESEARCH JOURAL OF AGRICULTURAL SCIENCE

Sarkhel S, Roy A (2022) Phytic acid and its reduction in pulse matrix: Structure–function relationship owing to bioavailability enhancement of micronutrients. J Food Process Eng 45:e14030. https://doi.org/10.1111/JFPE.14030

Schiavon M, Lima LW, Jiang Y, Hawkesford MJ (2017) Effects of Selenium on Plant Metabolism and Implications for Crops and Consumers. In: Selenium in plants. Springer, Cham, pp 257–275

Schiavon M, Nardi S, dalla Vecchia F, Ertani A (2020) Selenium biofortification in the 21st century: status and challenges for healthy human nutrition. Plant Soil 453:245–270. https://doi.org/10.1007/s11104-020-04635-9

Schiavon M, Pilon-Smits EAH (2017) The fascinating facets of plant selenium accumulation – biochemistry, physiology, evolution and ecology. New Phytologist 213:1582–1596

Sebetha E, Modi A, Agricultural LO-J of, 2015 undefined (2015) Proteína bruta do feijão-caupi em função do sistema de cultivo, local e adubação nitrogenada. researchgate.netET Sebetha, AT Modi, LG OwoeyeJornal de Ciências Agrícolas, 2015•researchgate.net 7:. https://doi.org/10.5539/jas.v7n1p224

Seliem MK, Hafez Y, El-Ramady H (2020) Using Nano - Selenium in Reducing the Negative Effects of High Temperature Stress on Chrysanthemum morifolium Ramat. Journal of Sustainable Agricultural Sciences 46:47–60. https://doi.org/10.21608/JSAS.2020.23905.1203

Selle PH, Cowieson AJ, Cowieson NP, Ravindran V (2012) Protein–phytate interactions in pig and poultry nutrition: a reappraisal. Nutr Res Rev 25:1–17. https://doi.org/10.1017/S0954422411000151

Shafiq M, Qadir A, Ahmad SR (2019) Biofortification: A sustainable agronomic strategy to increase selenium content and antioxidant activity in Garlic. Appl Ecol Environ Res 17:1685–1704. https://doi.org/10.15666/aeer/1702_16851704

Shankar AH (2020) Mineral Deficiencies. Hunter's Tropical Medicine and Emerging Infectious Diseases 1048–1054. https://doi.org/10.1016/B978-0-323-55512-8.00145-9

Sharma S, Sharma A, Singh D (2018) Effect of sodium selenate on photosynthetic efficiency, antioxidative defence system and micronutrients in maize (Zea mays). Biologia (Poland) 73:137–144. https://doi.org/10.2478/s11756-018-0017-6

Shastun S, Chauhan AK, Singh RB, Singh M, Singh RP, Itharat A, Chibisov S, De Meester F, Wilson DW, Halabi G (2016) Can functional food security decrease the epidemic of obesity and metabolic syndrome? A viewpoint. World Heart J 8:273–280

Shini S, Sultan A, Bryden WL (2015) Selenium Biochemistry and Bioavailability: Implications for Animal Agriculture. Agriculture 2015, Vol 5, Pages 1277-1288 5:1277–1288. https://doi.org/10.3390/AGRICULTURE5041277

Siddique KHM, Li X, Gruber K (2021) Rediscovering Asia's forgotten crops to fight chronic and hidden hunger. Nature Plants 2021 7:2 7:116–122. https://doi.org/10.1038/s41477-021-00850-z

Silva AC da, Santos D da C, Junior DLT, Silva PB da, Siviero RC dos S and A, Silva AC da, Santos D da C, Junior DLT, Silva PB da, Siviero RC dos S and A (2018a) Cowpea: A

Strategic Legume Species for Food Security and Health. Legume Seed Nutraceutical Research. https://doi.org/10.5772/INTECHOPEN.79006

Silva VM, Boleta EH, Martins JT, dos Santos FLM, da Rocha Silva AC, Alcock TD, Wilson L, de Sá ME, Young SD, Broadley MR, White PJ, dos Reis AR (2019a) Agronomic biofortification of cowpea with selenium: effects of selenate and selenite applications on selenium and phytate concentrations in seeds. J Sci Food Agric 99:5969–5983. https://doi.org/10.1002/jsfa.9872

Silva VM, Boleta EH, Martins JT, dos Santos FLM, da Rocha Silva AC, Alcock TD, Wilson L, de Sá ME, Young SD, Broadley MR, White PJ, dos Reis AR (2019b) Agronomic biofortification of cowpea with selenium: effects of selenate and selenite applications on selenium and phytate concentrations in seeds. J Sci Food Agric 99:5969–5983. https://doi.org/10.1002/jsfa.9872

Silva VM, Boleta EH, Martins JT, Santos FL, Rocha Silva AC, Alcock TD, Wilson L, Sá ME, Young SD, Broadley MR, White PJ, Reis AR (2019c) Agronomic biofortification of cowpea with selenium: effects of selenate and selenite applications on selenium and phytate concentrations in seeds. J Sci Food Agric 99:5969–5983. https://doi.org/10.1002/jsfa.9872

Silva VM, Boleta EHM, Lanza MGDB, Lavres J, Martins JT, Santos EF, dos Santos FLM, Putti FF, Junior EF, White PJ, Broadley MR, Carvalho HWP de, Reis AR dos (2018b) Physiological, biochemical, and ultrastructural characterization of selenium toxicity in cowpea plants. Environ Exp Bot 150:172–182. https://doi.org/10.1016/j.envexpbot.2018.03.020

Silva VM, Boleta EHM, Lanza MGDB, Lavres J, Martins JT, Santos EF, dos Santos FLM, Putti FF, Junior EF, White PJ, Broadley MR, Carvalho HWP de, Reis AR dos (2018c) Physiological, biochemical, and ultrastructural characterization of selenium toxicity in cowpea plants. Environ Exp Bot 150:172–182. https://doi.org/10.1016/j.envexpbot.2018.03.020

Silva VM, Boleta EHM, Lanza MGDB, Lavres J, Martins JT, Santos EF, dos Santos FLM, Putti FF, Junior EF, White PJ, Broadley MR, Carvalho HWP de, Reis AR dos (2018d) Physiological, biochemical, and ultrastructural characterization of selenium toxicity in cowpea plants. Environ Exp Bot 150:172–182. https://doi.org/10.1016/j.envexpbot.2018.03.020

Silva VM, Boleta EHM, Martins JT, dos Santos FLM, da Rocha Silva AC, Alcock TD, Wilson L, de Sá ME, Young SD, Broadley MR, White PJ, dos Reis AR (2019d) Agronomic biofortification of cowpea with selenium: effects of selenate and selenite applications on selenium and phytate concentrations in seeds. J Sci Food Agric 99:5969–5983. https://doi.org/10.1002/JSFA.9872

Silva VM, Nardeli AJ, Mendes NAC, Gabriel Filho LRA, Gabriel CPC, Reis AR dos (2023) Does Selenium Application Increase the Yield of Cowpea Plants? Evidence from 29

Genotypes on Ureides and Sugar Index Affecting the Yield. J Soil Sci Plant Nutr 23:5899–5908. https://doi.org/10.1007/S42729-023-01448-4/METRICS

Silva VM, Rimoldi Tavanti RF, Gratão PL, Alcock TD, Reis AR dos (2020a) Selenate and selenite affect photosynthetic pigments and ROS scavenging through distinct mechanisms in cowpea (Vigna unguiculata (L.) walp) plants. Ecotoxicol Environ Saf 201:110777. https://doi.org/10.1016/j.ecoenv.2020.110777

Silva VM, Rimoldi Tavanti RF, Gratão PL, Alcock TD, Reis AR dos (2020b) Selenate and selenite affect photosynthetic pigments and ROS scavenging through distinct mechanisms in cowpea (Vigna unguiculata (L.) walp) plants. Ecotoxicol Environ Saf 201:110777. https://doi.org/10.1016/j.ecoenv.2020.110777

Silva VM, Rimoldi Tavanti RF, Gratão PL, Alcock TD, Reis AR dos (2020c) Selenate and selenite affect photosynthetic pigments and ROS scavenging through distinct mechanisms in cowpea (Vigna unguiculata (L.) walp) plants. Ecotoxicol Environ Saf 201:110777. https://doi.org/10.1016/j.ecoenv.2020.110777

Sim MS, Ogata H, Lubitz W, Adkins JF, Sessions AL, Orphan VJ, McGlynn SE (2019) Role of APS reductase in biogeochemical sulfur isotope fractionation. Nature Communications 2019 10:1 10:1–9. https://doi.org/10.1038/s41467-018-07878-4

Simkin AJ (2019) Genetic Engineering for Global Food Security: Photosynthesis and Biofortification. Plants 2019, Vol 8, Page 586 8:586. https://doi.org/10.3390/PLANTS8120586

Simpson JL, Bailey LB, Pietrzik K, Shane B, Holzgreve W (2010) Micronutrients and women of reproductive potential: required dietary intake and consequences of dietary deficiency or excess. Part I – Folate, Vitamin B12, Vitamin B6. The Journal of Maternal-Fetal & Neonatal Medicine 23:1323–1343. https://doi.org/10.3109/14767051003678234

Sindhu M, Kumar A, Yadav H, Chaudhary D, Jaiwal R, Jaiwal PK (2019) Current advances and future directions in genetic enhancement of a climate resilient food legume crop, cowpea (Vigna unguiculata L. Walp.). Plant Cell Tissue Organ Cult 139:429–453. https://doi.org/10.1007/S11240-019-01695-3/TABLES/1

Singh B (2020a) Feijão-caupi: a leguminosa alimentar do século 21

Singh B (2020b) Cowpea: the food legume of the 21st century. John Wiley & Sons

Singh SK, Raja Reddy K (2011) Regulation of photosynthesis, fluorescence, stomatal conductance and water-use efficiency of cowpea (Vigna unguiculata [L.] Walp.) under drought. J Photochem Photobiol B 105:40–50. https://doi.org/10.1016/J.JPHOTOBIOL.2011.07.001

Sinha R, Kawatra A (2003) Effect of processing on phytic acid and polyphenol contents of cowpeas [Vigna unguiculata (L) Walp]. Plant Foods for Human Nutrition 58:1–8. https://doi.org/10.1023/B:QUAL.0000040322.01063.D4/METRICS

Sitko K, Opała-Owczarek M, Jemioła G, Gieroń Ż, Szopiński M, Owczarek P, Rudnicka M, Małkowski E (2022) Effect of drought and heavy metal contamination on growth and photosynthesis of silver birch trees growing on post-industrial heaps. Cells 11:53. https://doi.org/10.3390/CELLS11010053/S1

Siwela M, Pillay K, Govender L, Lottering S, Mudau FN, Modi AT, Mabhaudhi T (2020) Biofortified Crops for Combating Hidden Hunger in South Africa: Availability, Acceptability, Micronutrient Retention and Bioavailability. Foods 2020, Vol 9, Page 815 9:815. https://doi.org/10.3390/FOODS9060815

Sun W, Zhu J, Li S, Tang C, Zhao Q, Zhang J (2020) Selenium supplementation protects against oxidative stress-induced cardiomyocyte cell cycle arrest through activation of PI3K/AKT. Metallomics 12:1965–1978. https://doi.org/10.1039/D0MT00225A

Tani LSK, Dennouni-Medjati N, Toubhans B, Charlet L (2020) Selenium deficiency-from soil to thyroid cancer. Applied Sciences (Switzerland) 10:. https://doi.org/10.3390/APP10155368

Tavanti TR, Melo AAR de, Moreira LDK, Sanchez DEJ, Silva R dos S, Silva RM da, Reis AR dos (2021a) Micronutrient fertilization enhances ROS scavenging system for alleviation of abiotic stresses in plants. Plant Physiology and Biochemistry 160:386–396

Tavanti TR, Melo AAR de, Moreira LDK, Sanchez DEJ, Silva R dos S, Silva RM da, Reis AR dos (2021b) Micronutrient fertilization enhances ROS scavenging system for alleviation of abiotic stresses in plants. Plant Physiology and Biochemistry 160:386–396. https://doi.org/10.1016/J.PLAPHY.2021.01.040

Teka TA, Retta N, Bultosa G, Admassu H, Astatkie T (2020) Protein fractions, in vitro protein digestibility and amino acid composition of select cowpea varieties grown in Ethiopia. Food Biosci 36:100634. https://doi.org/10.1016/j.fbio.2020.100634

Thomas CL, Alcock TD, Graham NS, et al (2016a) Root morphology and seed and leaf ionomic traits in a Brassica napus L. diversity panel show wide phenotypic variation and are characteristic of crop habit. BMC Plant Biol 16:1–18. https://doi.org/10.1186/s12870-016-0902-5

Thomas CL, Alcock TD, Graham NS, et al (2016b) Root morphology and seed and leaf ionomic traits in a Brassica napus L. diversity panel show wide phenotypic variation and are characteristic of crop habit. BMC Plant Biol 16:1–18. https://doi.org/10.1186/s12870-016-0902-5

Timpanaro G, Bellia C, Foti VT, Scuderi A (2020) Consumer Behaviour of Purchasing Biofortified Food Products. Sustainability 2020, Vol 12, Page 6297 12:6297. https://doi.org/10.3390/SU12166297

Toyota M, Spencer D, Sawai-Toyota S, Jiaqi W, Zhang T, Koo AJ, Howe GA, Gilroy S (2018) Glutamate triggers long-distance, calcium-based plant defense signaling. Science (1979) 361:1112–1115. https://doi.org/10.1126/science.aat7744

Tran TAT, Dinh QT, Zhou F, Zhai H, Xue M, Du Z, Bañuelos GS, Liang D (2021) Mechanisms underlying mercury detoxification in soil–plant systems after selenium application: a review. Environmental Science and Pollution Research 2021 28:34 28:46852–46876. https://doi.org/10.1007/S11356-021-15048-1

Tripathi AD, Mishra R, Maurya KK, Singh RB, Wilson DW (2018) Estimates for world population and global food availability for global health. In: The Role of Functional Food Security in Global Health. Elsevier, pp 3–24

Tripathi K, Gore PG, Ahlawat SP, Tyagi V, Semwal DP, Gautam NK, Rana JC, Kumar A (2019) Cowpea genetic resources and its utilization: Indian perspective – A review. Legume Research 42:437–446

Turck D, Bohn T, Castenmiller J, et al (2023) Scientific opinion on the tolerable upper intake level for selenium. EFSA Journal 21:e07704. https://doi.org/10.2903/J.EFSA.2023.7704

Turrubiates-Hernández FJ, Márquez-Sandoval YF, González-Estevez G, Reyes-Castillo Z, Muñoz-Valle JF (2020) The Relevance of Selenium Status in Rheumatoid Arthritis. Nutrients 2020, Vol 12, Page 3007 12:3007. https://doi.org/10.3390/NU12103007

Ulhassan Z, Gill RA, Huang H, Ali S, Mwamba TM, Ali B, Huang Q, Hamid Y, Khan AR, Wang J, Zhou W (2019) Selenium mitigates the chromium toxicity in Brassicca napus L. by ameliorating nutrients uptake, amino acids metabolism and antioxidant defense system. Plant Physiology and Biochemistry 145:142–152. https://doi.org/10.1016/j.plaphy.2019.10.035

US (2000) Dietary Reference Intakes for Vitamin C, Vitamin E, Selenium, and Carotenoids. National Academies Press, Washington, D.C.

Van Der Straeten D, Bhullar NK, De Steur H, et al (2020) Multiplying the efficiency and impact of biofortification through metabolic engineering. Nat Commun 11:1–10. https://doi.org/10.1038/s41467-020-19020-4

Van Handel E (1968) Direct microdetermination of sucrose. Anal Biochem 22:280–283. https://doi.org/10.1016/0003-2697(68)90317-5

Vandemark GJ, Grusak MA, McGee RJ (2018) Mineral concentrations of chickpea and lentil cultivars and breeding lines grown in the U.S. Pacific Northwest. Crop Journal 6:253–262. https://doi.org/10.1016/J.CJ.2017.12.003

Vasconcelos IM, Maia FMM, Farias DF, Campello CC, Carvalho AFU, de Azevedo Moreira R, de Oliveira JTA (2010) Protein fractions, amino acid composition and antinutritional constituents of high-yielding cowpea cultivars. Journal of Food Composition and Analysis 23:54–60. https://doi.org/10.1016/j.jfca.2009.05.008

Veiga N, Macho I, Gómez K, González G, Kremer C, Torres J (2015) Potentiometric and spectroscopic study of the interaction of 3d transition metal ions with inositol hexakisphosphate. J Mol Struct 1098:55–65. https://doi.org/10.1016/J.MOLSTRUC.2015.05.034

Victor N. E, Justina Y. T, Sunday A. M, Aderonke I. O (2012) DPPH Radical Scavenging Capacity of Phenolic Extracts from African Yam Bean (*Sphenostylis stenocarpa*). Food Nutr Sci 2012:7–13. https://doi.org/10.4236/FNS.2012.31002

Vinceti M, Filippini T, Wise LA (2018) Environmental Selenium and Human Health: an Update. Curr Environ Health Rep 5:464–485. https://doi.org/10.1007/s40572-018-0213-0

Vogels G, biochemistry CV der D-A, 1970 undefined Análises diferenciais de derivados de glioxilato. ElsevierGD Vogels, C Van der DriftBioquímica analítica, 1970•Elsevier

Vogels GD, Van Der Drift C (1970) Differential analyses of glyoxylate derivatives. Anal Biochem 33:143–157. https://doi.org/10.1016/0003-2697(70)90448-3

Wakeel A, Farooq M, Bashir K, Ozturk L (2018) Micronutrient Malnutrition and Biofortification: Recent Advances and Future Perspectives. Plant Micronutrient Use Efficiency: Molecular and Genomic Perspectives in Crop Plants 225–243. https://doi.org/10.1016/B978-0-12-812104-7.00017-4

Wang P, Lombi E, Zhao FJ, Kopittke PM (2016) Nanotechnology: A New Opportunity in Plant Sciences. Trends Plant Sci 21:699–712

Wang R, Guo S (2021) Phytic acid and its interactions: Contributions to protein functionality, food processing, and safety. Compr Rev Food Sci Food Saf 20:2081–2105. https://doi.org/10.1111/1541-4337.12714

Wang Y, Yang XD, Ali A, Lv GH, Long YX, Wang YY, Ma YG, Xu CC (2020) Flowering Phenology Shifts in Response to Functional Traits, Growth Form, and Phylogeny of Woody Species in a Desert Area. Front Plant Sci 11:531690. https://doi.org/10.3389/FPLS.2020.00536/BIBTEX

Wang Y-D, Wang X, Wong Y (2012) Proteomics analysis reveals multiple regulatory mechanisms in response to selenium in rice. J Proteomics 75:1849–1866. https://doi.org/10.1016/j.jprot.2011.12.030

Welch RM (2002) Breeding strategies for biofortified staple plant foods to reduce micronutrient malnutrition globally. Journal of Nutrition 132:. https://doi.org/10.1093/JN/132.3.495S

Wessells KR, Brown KH (2012) Estimating the Global Prevalence of Zinc Deficiency: Results Based on Zinc Availability in National Food Supplies and the Prevalence of Stunting. PLoS One 7:. https://doi.org/10.1371/journal.pone.0050568

White P, phytologist MB-N, 2009 undefined (2009) Biofortificação de culturas com sete elementos minerais frequentemente ausentes na dieta humana - ferro, zinco, cobre, cálcio, magnésio, selênio e iodo. Wiley Online LibraryPJ Branco, MR BroadleyNovo fitologista, 2009•Biblioteca Online Wiley 182:49–84. https://doi.org/10.1111/j.1469-8137.2008.02738.x

White PJ (2016a) Selenium accumulation by plants. Ann Bot 117:217–235

White PJ (2018a) Selenium metabolism in plants. Biochim Biophys Acta Gen Subj 1862:2333–2342

White PJ (2016b) Selenium accumulation by plants. Ann Bot 117:217–235

White PJ (2018b) Selenium metabolism in plants. Biochim Biophys Acta Gen Subj 1862:2333–2342

White PJ, Broadley MR (2009) Biofortification of crops with seven mineral elements often lacking in human diets – iron, zinc, copper, calcium, magnesium, selenium and iodine. New Phytologist 182:49–84. https://doi.org/10.1111/J.1469-8137.2008.02738.X

Wu H, Zhang X, Giraldo JP, Shabala S (2018) It is not all about sodium: revealing tissue specificity and signalling roles of potassium in plant responses to salt stress. Plant Soil 431:1–17

Xu W, Chai Y-R (2017) Differences in Selenium Uptake, Distribution and Expression of Selenium Metabolism Genes in Tomatoes Article in. Int J Agric Biol. https://doi.org/10.17957/IJAB/15.0330

Yadav DN, Bansal S, Tushir S, Kaur J, Sharma K (2020) Advantage of biofortification over fortification technologies. Wheat and Barley Grain Biofortification 257–273. https://doi.org/10.1016/B978-0-12-818444-8.00010-9

Yang J, Yu F, Fu Z, Fu Y, Liu S, Chen M, Li Y, Sun Q, Chang H, Zhou W, Wang X, Zhang L (2019) Pathway and driving forces of selenite absorption in wheat leaf blades. Plant Soil Environ 65:609–614. https://doi.org/10.17221/542/2019-PSE

Yemm EW, Cocking EC, Ricketts RE (1955) The determination of amino-acids with ninhydrin. Analyst 80:209–214. https://doi.org/10.1039/AN9558000209

Yildiztugay E, Ozfidan-Konakci C, Kucukoduk M, Tekis SA (2017) The impact of selenium application on enzymatic and non-enzymatic antioxidant systems in *Zea mays* roots treated with combined osmotic and heat stress. Arch Agron Soil Sci 63:261–275. https://doi.org/10.1080/03650340.2016.1201810

Yu Y, Liu Z, Luo LY, Fu PN, Wang Q, Li HF (2019) Selenium Uptake and Biotransformation in Brassica rapa Supplied with Selenite and Selenate: A Hydroponic Work with HPLC Speciation and RNA-Sequencing. J Agric Food Chem. https://doi.org/10.1021/ACS.JAFC.9B05359/ASSET/IMAGES/LARGE/JF9B05359_0005.JPEG

Zahedi SM, Hosseini MS, Daneshvar Hakimi Meybodi N, Teixeira da Silva JA (2019) Foliar application of selenium and nano-selenium affects pomegranate (Punica granatum cv. Malase Saveh) fruit yield and quality. South African Journal of Botany 124:350–358. https://doi.org/10.1016/j.sajb.2019.05.019

Zhang YY, Stockmann R, Ng K, Ajlouni S (2022) Revisiting phytate-element interactions: implications for iron, zinc and calcium bioavailability, with emphasis on legumes. Crit Rev Food Sci Nutr 62:1696–1712. https://doi.org/10.1080/10408398.2020.1846014

Zhou B, Cao H, Wu Q, Mao K, Yang X, Su J, Zhang H (2023) Agronomic and Genetic Strategies to Enhance Selenium Accumulation in Crops and Their Influence on Quality. Foods 2023, Vol 12, Page 4442 12:4442. https://doi.org/10.3390/FOODS12244442