Review

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Review

Challenges and Opportunities for New Frontiers and Technologies to Guarantee Food Production: A Broad Systematic Perspective

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Abstract: The global food production sector faces unprecedented challenges due to rapid population growth and escalating climate change impacts, necessitating innovative strategies to ensure food security and promote sustainability. This comprehensive review explores cutting-edge solutions across multiple domains of agriculture and food technology. We examine emerging agricultural frontiers, including urban farming technologies that leverage vertical farming, hydroponics, and smart sensors to maximize productivity in limited spaces. The review also delves into agroforestry and regenerative agriculture practices that enhance soil health and biodiversity while sequestering carbon. We investigate advancements in food production in extreme environments, such as desert agriculture and deep space food technologies, which push the boundaries of cultivation in resource-scarce conditions. The transformative potential of biotechnology is highlighted through discussions on plant engineering, synthetic biology, and nanotechnology for enhanced crop yields and nutritional content. Additionally, we explore the role of artificial intelligence in optimizing agricultural management, from precision farming to predictive analytics for crop health. Water management innovations are examined as critical components of food security, especially in water-stressed regions. The review also emphasizes the importance of bioproducts and eco-friendly technological innovations that support sustainable food systems. Furthermore, we discuss the crucial role of public policy, food regulation, and participatory community approaches in ensuring equitable food distribution and adoption of new technologies. By providing a multidisciplinary perspective, this review aims to catalyze further research that integrates emerging technologies with sustainable management practices. Our goal is to inspire the development of a resilient global food system capable of meeting the nutritional needs of current and future generations while preserving environmental integrity.

Keywords: artificial intelligence; synthetic biology; agroforestry and regenerative agriculture; future food; new food production systems; disruptive technologies; public policies

1. Introduction

One of agriculture's biggest challenges for the next fifty years is to find a way to double worldwide food production to reach the expected demands of exponential population growth (Long et al., 2015). Over this timeframe, water deficit, soil nutrient scarcity, as well as raises in both atmospheric carbon dioxide concentration, and temperature will restrict to some extent the food supply chain in many countries (Mittler and Blumwald, 2010). In this context, efforts have been made to find a way to meet the global food demand through innovative technologies, plans and actions, without undermining environmental ecosystems (Mueller et al., 2012). To achieve such goals, a growing body of disruptive technologies has been emerging (Voigt et al., 2020) thereby building a new milestone in this important sector of society.

In this review, we bring breakthroughs on promising technologies that will pave the way for resilient, sustainable, and eco-friendly food production systems able to meet the expected global food demand by the end of this century. We also further discussed multiple aspects regarding food production systems, which spanned urban farming, regenerative agriculture, agriculture in the desert, food in the space, plant engineering, synthetic biology, nanotechnology, enriched foods, bioproducts for agriculture, water management, food security, Artificial Intelligence (AI), public policy and food regulation. Altogether, we raised compelling evidence on how science and technology are contributing to deal with food security for this and the next generations, and that somehow the success of such features depends on public policies and participatory community.

2. New Agricultural Frontiers

The expansion of agricultural frontiers has always been a concern for the preservation of natural biomes worldwide (Phalan et al., 2013; Zeng et al., 2018). However, the genetic manipulation of cultivated species and the technologies for resilient crops, such as regenerative agriculture, aquaponics, aeroponics, and urban and vertical agriculture, allows us to rethink the food production model more sustainable and economically viable. Regenerative agriculture proposes a sustainable food system able to sustain the health of the soil by restoring its carbon content, consequently, improves yield (Massy et al., 2017). Besides that, it can help in climate change issues by estimates that regenerative annual cropping could reduce or uptake 14.5-22 gigatons of CO_2 by 2050 (Project Drawdown, 2021). Aquaponics has been widespread worldwide to introduce the concept of sustainability and efficient use and water integrating fish and plants produced in a quasi-closed recirculating system (Love et al., 2014). Whereas aeroponics is considered a modern plant cultivation technology, in which plants grow without the use of the soil, or substrate (Lakhiar et al., 2018). Besides that, urban agriculture has been shown to make food production more sustainable and resilient, improve food security in low-income countries (Ferreira et al., 2018; Poulsen et al., 2015). Other challenges in agriculture around the world are to extend areas and crops to dry, saline soil environments with changes in elevated temperatures during the day and low temperatures at night, typical conditions of desert regions. However, there is still a strong dependence on plant selection and modification genetics.

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Urban Farming Technologies

The increase of the world's population, as well as the necessity for the high quality of products that are sustainably produced, requires innovative methods for crop cultures to reach such objectives (Alshrouf A., 2017). Innovative methods could require less water and space, increased yield, and also be an opportunity to an annually continuous system of food supply (Van Os, E. A., 1995). One of these innovative methods is aeroponics. The method involves growing crops without soil in an aeroponic chamber, where suspended roots are periodically misted with a nutrient-rich solution in a controlled, dark environment. (Lakhiar et al., 2018). There are several benefits with the use of aeroponics, such as better use of the space related to the cultivation and a decrease of water, fertilizer, and pesticide usage by 98, 60, and 100%, respectively (Shrouf A., 2017). According to Al Shrouf, (2017), plants that grow in aeroponics systems may present a better nutritional value and increased fitting and yield. Another benefit is related to the incidence of pathogens. The nutrient solution in aeroponics systems provides more oxygen on plant roots, which increases root growth and prevents the incidence of diseases (Ferentinos et al., 2018).

Aquaponics is a consortium between aquaculture-hydroponics and is considered a sustainable and alternative food production system (FAO, 1988). Due to the recirculating aquaculture system (RAS) (water reuse), aquaponic is considered an efficient and eco-friendly farming (FAO, 2014). Aquaponics is characterized by the production of both plant and animal biomass simultaneously. The aquatic animals' wastes are converted into nutrients through microorganisms, and subsequently, plants absorb the nutrients and consequently refine water quality for animal's production - in a constant and sustainable cycle (Love et al., 2014; Yanes et al., 2020; Kloas et al., 2015). Both design and methods for aquaponics food systems to produce on different large scales have been developed to control nutrients as fertilizers, plant evapotranspiration, and water consumption. Aquaponics techniques can be applied for different properties such as open systems, domestics, demonstrations, and commercial farms (Palm et al., 2018). Open pond aquaponics systems (OPS) are developed due to the low-cost production of catfish and tilapia and herbivorous fish as grass, silver, bighead carp (Pantanella et al., 2018). OPS has been broadly used in East Asia mainly Thailand, India, and Bangladesh for animal polyculture and okra, spinach, eggplant, tomato, pudina, and other cultures (Roy et al., 2013, Vickers et al., 2017). Differently, the demonstrations and domestic systems are used for small-scale production of aquatic plants, aquatic animals, and are commonly adopted by family farming, urban areas, and as resources to produce food itself (Kotzen et al., 2010). However, the large-scale system has undergone modifications inducing the concept of aquaponics farming 4.0 due to IoT monitoring with sensors and AI (Yanes et al., 2020, Lauguico et al., 2020). The adoption of IoT in aquaponics systems could bring benefits such as a better evaluation of water pH, water temperature and decrease the need for human intervention, and consequently improving the management and efficiency of the system (Manju et al., 2017; Abraham et al., 2017).

Agroforestry and Regenerative Agriculture

Regenerative agriculture (Reg-ag) aims to improve soil health and restore degraded soil (soil organic carbon), which accordingly benefits water quality, local vegetation, and yield (Jiménez-Alfaro et al., 2020). Reg-ag allows soil-mineral cycles that provide nutrients, water cycle and benefit microbiome-soil-plant-animal communities, restoring ecological relationships in food production, introducing a new concept regenerative-ecological agriculture (Reg-eco-ag) (Massay et al., 2017). Reg-eco-ag includes ecosystem restoration through native plants such as herbaceous, woody crops, grazing, horticulture, and pollinators (Jiménez-Alfaro et al., 2020, Harris et al., 2014, FAO, 2018). Reg-eco-ag integrates climate change mitigation and adaptation, carrying out sustainable agricultural strategies to avoid impacts on the environment, which consequently make it climate-smart agriculture (CSA) as an outcome (Gosnell et al., 2019, Lipper et al., 2014).

Reg-eco-ag has the major innovative initiative in Australia with the adoption of a sustainable agroecological farming system using native grasslands, trees to avert floods, crops plants, and animals and is becoming a priority for this century (Cross et al., 2017, Massay et al., 2017, Pearson et

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al., 2007). In the northern plains of the United States, the regenerative corn production systems have shown positive effects in soil conservation and pest management compared with conventional agriculture. Insecticide-treated conventional cornfields have 10-fold more pests than on insecticide-free regenerative farms (LaCanne et al., 2018). In Europe, the consortium of regionally adapted species such as olive groves, grasses, and forbs are suggested as global greening initiatives and a wide inventory of species has been studied for ecosystem restoration (Jiménez-Alfaro et al., 2020). The Reg-eco-ag is applied in different regions of Brazil and has helped the restore biomes impacted. For instance, the consortia of pineapple, banana, palm heart, citrus in Atlantic forest, palm oil in Amazon, horticulture, fruit, coffee in Brazilian savanna ("cerrado"), and tomato, pineapple, papaya, citrus, cacao, mahogany in Brazilian savanna and Atlantic Rain Forest (Andrade et al., 2020).

Africa and the Middle East present the biggest challenge for Reg-eco-ag. A futurist animation envisioned: "What if we terraformed the Sahara Desert?" based on projects that are already being developed (http://twixar.me/snSm, www.afr100.org). The initiative of the Millennium Villages Project (MVP) around Mbola, Tanzania for example, has intensified smallholder agriculture with legume cover crops or trees to promote mineral fertilizers as a source of carbon, nitrogen to rehabilitate soil organic matter (Sanchez et al., 2007, Palm et al., 2010). Nevertheless, ambitious and challenger projects to provide a Great Green Wall in Sahelian-Saharan (www.greatgreenwall.org) to contain the advance of the Sahara desert that extends from the Atlantic coast from Senegal to the Gulf of Aden in Djibouti (Bertolami et al., 2019). It is estimated by 2030, this project can restore 100 million hectares of degraded land, create 10 million jobs, and sequester 250 million tonnes of carbon. Another disruptive initiative has transformed the Mediterrane coast in north Africa. In Tunisia, many attempts with planting thousands of trees have been made to reduce land degradation (Stanturf et al., 2020). In the coastal dunes in north Tunisia, the planting of stone pine (*Pinus pinea* L.) was used for reforestation of the more 21 000 ha to regenerate litter thickness and provide a microclimate moderation growing seedling (Adili et al., 2013). Besides that, Tunisian grapevines have been broadly planted and studies have shown that the soil-microbiome is an important component to promote the growing grape plants (Marasco et al., 2013). While in the Sahara Desert in south Tunisia, it has a genetic diversity of resilience and adapted olive trees to abiotic stresses (Saddoud Debbabi et al., 2021).

Agriculture in the Desert

The heat and salinity are abiotic stress common in semi-arid and desert regions. Plant salinity tolerance mechanisms have been studied such as the maintenance of plant water status, transpiration, and water efficiency (Harris et al., 2010; This et al., 2010; Barbieri et al., 2012) and seed germination and growth (Giménez et al., 2013). Besides that, studies have been observed that crassulacean acid metabolism (CAM) can be induced by high salinity in C_3 plants (Winter & Holtum, 2014). CAM plants are those that hold a photosynthetic CO_2 fixation mechanism, which occurs only during the night. CAM plants close the stomata during the day to reduce the loss of water through transpiration, otherwise opened during the night to capture atmospheric CO_2 (Yang et al., 2015). CAM photosynthesis induced by abiotic stress presents challenges and opportunities in the engineering and genetic breeding of plants (DePaoli et al., 2014).

The genetic breeding of plants tolerant to heat, droughts, and salt stress, has allowed the practice of biosaline agriculture in different soils under salinity conditions in desert areas (Rezzouk et al., 2020). Due to the relevance of biosaline agriculture, research centers have been dedicated to the study and development of tolerant genotypes to irrigation with saline water, and soil salinization on dryland ecosystems. For instance, in the Middle East and North Africa (MENA), the International Center for Biosaline Agriculture (ICBA - "www.biosaline.org/") performs research with quinoa genotypes. In Asia (Uzbekistan), the International Center for Biosaline Agriculture for Central Asia and Caucasus (ICBA-CAC) has a breeding program of quinoa salinity-adapted and climate-resilient (Toderich et al., 2020).

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In South America, specifically in northeastern Brazil in the semiarid characterized by a poor rain distribution, the "Embrapa Semiarido" use saline groundwater irrigation in areas with Caatinga vegetation and crops (Dantas et al., 2014). Other researchers from different institutions are studying strategies that allow the application of bio saline agriculture associated with salt-tolerant plants irrigated with salt-water and soil management systems. The selection of genotypes of crops tolerant to salts, as is the case of cowpea (*Vigna unguiculata* L. Walp.), citrus, corn (*Zea mays*), and sorghum (*Sorghum bicolor*) as well as, the adoption of soil management models, with specific drainage systems, fertilization and aggregation of organic matter, use of forage plants highly tolerant to salinity such as Atriplex (*Atriplex nummularia*), which absorbs large amounts of salts and can later be offered to cattle, sheep, and goats (Leal, 2008). These plant breeding programs have changed the reality, food production, and life prospects for local producers.

In Australia, the Commonwealth Scientific and Industrial Research Organisation (CSIRO) identifies different plant species living in two saline ecosystems, suggesting an important organism model with potential genes for studies and development of transgenic crops for these saline regions. In summary, certainly, the genetics, genetic engineering, and molecular biology of plants are some of the areas of knowledge that will allow the development of capable cultivars adapted to arid, desert, and dry areas. Thus, the development of agriculture in many countries with desert areas could be potential areas agricultural in the future. Satellite images reveal a new agricultural cradle in Egypt's Western Desert (Sahara Desert), between the Nile, northern Sudan, and southeastern Libya (Nahry et al., 2010).

Finally, large expanses of green patches can be seen from the International Space Station in many regions of the Sahara (See Table 1, www.earthobservatory.nasa.gov). Besides that, other countries such as Saudi Arabia, Oma, and the United Arab Emirates, for instance, have technologies for an irrigation system able to reduce water consumption to the cultivation of fodder, palm, quinoa, and potato crops (See Table 1, Al-Omran et al., 2017, Multsch et al., 2017). The reg-ag has been able to not only regenerate the soil but also enable the cultivation of plants in different places on the planet, especially where water scarcity presents the greatest challenge.

Table 1. Geographical position of the desert agricultural.

Country	Latitude	Longitude	Map view
Algeria	27.290702	-0.065070	https://www.google.com/maps/place/27%C2%B017'47.6%22N+0%C2%B003'56.7%22W/
Libya	26.410351	14.348167	https://www.google.com/maps/place/26%C2%B022'36.

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			3%22N+14%C2%B027′57.5 %22E/
Egypt	22.616099	28.543529	https://www.google.com/maps/place/22%C2%B046′21.7%22N+28%C2%B032′56.4%22E
Saudi Arabia	26.281304	43.504683	https://www.google.com/maps/place/26%C2%B016′52.7%22N+43%C2%B030′16.9%22E/
Oma	18.258288	53.828732	https://www.google.com/maps/place/18%C2%B015′29.8%22N+53%C2%B049′43.4%22E/
United Arab Emirates	24.4984106	55.349223	https://www.google.com/maps/place/24%C2%B029′10.2%22N+55%C2%B032′47.6%22E/

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California/Nevada	26°16′52.7″N	43°30′16.9″E	https://www.google.com/maps/place/Sandy+Valley+MX/@36.0372072,-111.9925295

Figure 1. Dimensions of agro-nanotechnology and their derived applications. Source: Adapted from Shafi et al. (2020).

Deep Space Food Technologies

Deep Space colonization is the major challenge of humanity in this century. Humans already inhabit the low orbit earth into the International Space Station (ISS) and, in this decade, NASA's mission to return to the Moon in 2024 and create a sustainable presence in 2028 it's a reality (Brown et al., 2021). New approaches and insights novel products have been suggested for human exploration and settlement on Mars (Rothschild et al., 2016). Fresh food production is essential to space missions of long duration. Studies have been carried out on the food crops grown and alternative proteins in space (Massa et al., 2017, Kok & van Huis, 2021). However, the adaptation of plants in space is a great challenge due to an environmental condition never experienced in its evolutionary cycle (Khodadad et al., 2020). Based on this, projects such as the EDEN ISS project developed a new approach for a growing system for fresh vegetables under the extremely low air pressure, cosmic radiation, microgravity conditions of space missions. The MELiSSA Pilot Plant (MPP) project created a higher plant chamber involving plant growth (Piero et al., 2020). Besides that, the VEGIE hardware was developed for grown plants in the ISS which provides approximately 0.13 m2 area which provides water and nutrients to support the growth of vegetable crops under red, green, and blue LED lighting systems (Massa et al., 2020).

The life support systems for food production to long-term human missions to the Moon and Mars are underlying support of the grown vegetable and other ag-culture in space exploration. Several species of plants have already been grown in space as a food source for astronauts as well as, for studies of understanding the severe environmental response. The microgravity environment provides a series of challenges for plant development. The Lettuce vegetable (*Lactuca sativa*) has been cultivated in the ISS, and many studies have been carried out to understand the response of organism to space flight under the cosmic radiation and microgravity environment (Mou et al., 2011). Studies with rice (*Oryza sativa*) under microgravity at ISS showed attenuation of coleoptile growth, delaying, and reducing germination (Kobayashi et al., 2019, Sugimoto et al., 2016). Different strategies of germination were tested in flax seed (*Linum usitatissimum*) for supporting seed germination, elongation, and root growth in space (Levine et al., 2003). Other plant species such as Chinese cabbage (*Brassica rapa*), wheat (*Triticum aestivum*), and Potatoes (*Solanum tuberosum*) has aroused interest for long-term space Shuttle or as Astro-agriculture (Berkovich et al., 2000, Berkovich et al., 2004, Tripathy et al., 1996, Wheeler et al., 1998).

The cultivation of plants in space is still a challenge that is being overcome with many studies. Arabidopsis is a plant model that has been constantly used in space environments to unravel the molecular mechanisms by which plants respond to microgravity (Paul et al., 2017, Kruse et al., 2020). Microgravity exerts changes in the global gene expression, proteome profile, and consequently in the epigenetic mechanisms (Paul et al., 2017, Ferl et al., 2015, Xu et al., 2018). Whereas elevated radiation levels have been shown to induce mutations in plants and Drosophila (Majeed et al., 2020, Wada et al., 2020). Therefore, the crossing or self-fertilization of plants under exposure to high levels of radiation in space, may not result in the expected phenotypic proportions of Mendelian genetics. The

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plant breeding to microgravity adaptation and elevated radiation levels are environmental conditions that opened an attractive path for scientists in the production of food in deep space.

3. Technology and Innovation for Producing Food

Plant Engineering for Food Production

DNA, the information-rich molecule underpinning all life, governs the characteristics and functions of organisms. This genetic blueprint enables cells to respond to environmental challenges, influencing adaptability and survival. Genes, distinct DNA segments within genomes, encode this vital information. While primarily directing protein synthesis, some genes serve structural or regulatory roles. These diverse genetic functions collectively shape an organism's ability to thrive in varying conditions. (Clamp et al. 2007). Eukaryotic genes are made of coding regions (translated in amino acids) called exons, non-coding portions called introns, and regulatory sites as promoters, enhancers, and silencers (for more information: Stamm et al. 2005; Lynch 2006; Barash et al. 2010). Among protein-coding genes, interesting features can be related to them as seen in plants that resist fungal antagonists or herbicide actions (Meng et al. 2013; Butt et al. 2020). Engineering molecular biology tools can edit genes, in all regions, that change the gene structure for function gain or loss. Among the most used gene-editing tools, the main strategies are zinc-finger nucleases (ZFNs), transcription activator-like effector nucleases (TALENs), and the promising CRISPR–Cas9 RNA-guided technologies (Rancati et al. 2018).

ZFNs are proteins capable of cutting the DNA at specific points. This technology can delete gene pieces (promoters, exons, and so on) to disable mainly functions. The first applications of zinc-finger nucleases were for gene function studies in yeast (Rothstein 1989). Nowadays, we can change transgenes and endogenous genes in corn, for herbicide-resistance-related genes (Shukla et al. 2009); in soybean, for gene functions (Curtin et al. 2011), and even apple and fig trees, for gene deletion assays (Peer et al. 2015). However, this technology can be replaced for others in the future since it has relative major off-target probability and cytotoxicity (Pattanayak et al. 2011). As an alternative, TALEN proteins are also nucleases that were discovered from the *Xanthomonas* sp. bacteria that have the function to contribute to pathogen infestation acting in plant resistance gene promoters (Bogdanove and Voytas 2011). Moreover, edited TALEN was used to generate rice variety resistance to this pathogen, activating a recessive gene, which would be difficult to express by interbreeding (Han et al. 2020). However, we still do not know how the off-target effects are important in the TALEN technology. Finally, CRISPR system came in 2012 and rapidly switched how molecular biologists edit genes and genomes. This tool was discovered as part of Archaea and Eubacteria adaptive immune systems against viruses, targeting their alien DNA (Jinek et al. 2012; Lander 2016). The system CRISPR-Cas9 has a synthetic ~20 nucleotide long length RNA, as a guide, for targeting the interesting genome region, adding deletions or insertions (Ran et al. 2013). Nowadays, in plants, the CRISPR-Cas9 technology has a huge potential to establish new crops to deal with the constantly growing population. As seen in sorghum where a gene was silenced in a manner to turn the proteins more digestible for livestock feed (Li et al. 2018) or protein content gain in wheat grains (Zhang et al. 2018). Also, CRISPR has been used in plants to confer tolerance for environmental stresses such as salinity in rice (Zhang et al. 2019), and for disease tolerance as seen in Banana (*Musa* sp) against the *banana streak virus* (Tripathi et al. 2019) and tomato plants resistance to bacteria speck (Ortigosa et al. 2019). As shown, CRISPR technology is a science breakthrough and will be the future of gene editions, since it is relatively accessible.

Unpredictably, gene edition has opened a window of possibilities for us to study how organisms and, especially, plants deal with biotic and abiotic challenges for survival. The ability to understand how these awesome organisms get along with such difficulties is making it possible to feed the growing human populations and decrease the agriculture impacts over the planet.

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Synthetic Biology in Food Production

Advances in high-throughput DNA sequencing technologies allowed the availability of the human genome and of other species, mainly plants, that introduced a post-genomics era in many areas of knowledge (Gerstein et al., 2007). Whereas the accumulated knowledge in system biology and plant molecular biology allows plant scientists a new era with synthetic biology (SynBio) (Cheng et al., 2012). SynBio can play an important role in the food production system as a disruptive and revolutionary technology in agriculture and bioengineering (Wurtzel et al., 2019). SynBio is revolutionizing food production by enabling the design and construction of novel biological systems or the redesign of existing ones to create innovative functions (Brophy et al., 2014). In agriculture, SynBio's potential is particularly transformative, allowing for the engineering of crops with enhanced traits such as improved drought tolerance, elevated nutritional content, and increased resistance to pests and diseases (Roell et al., 2020,). By precisely introducing specific genes or gene pathways, this cutting-edge field offers a disruptive approach to bioengineering that promises to significantly contribute to the development of more resilient and sustainable food systems. Conventional plant breeding has achieved maximum yield and SynBio has mainly focused on improving water-use, nutrient-use, and photosynthetic efficiency to improve fitting and yield in crops (Borland & Yang, 2013, Batista-Silva et al., 2020). The improvement of photosynthesis has been concentrated in carbon-concentrating mechanisms (CCM), crassulacean acid metabolism (CAM) into C4 and C3 plants to enhance carbon gain and resource-use efficiency of photosynthesis respectively (Maurino & Weber, 2013, Borland and Yang, 2013). Both strategies provide opportunities in the agricultural SynBio, however, there are long ways to realize the new studies.

SynBio food production has achieved progress and around 2020-2030 the first food produced using this technology will be found commercially. Based on products from engineered cells such as iron-containing heme, leghemoglobin, for instance, can result in a new eating experience with plant-based burgers (Voigt et al., 2020). Studies have shown that producing iron-containing heme is an important component for improving the taste of meat (Varadan et al., 2019). While that, yeast leghemoglobin produced in plant-based burgers has flavors and aromas desirable to the human palate (Voigt et al., 2020). Other applications of SynBio in food production include pest control in agriculture through mating disruption using insect sex pheromones ((*Z*)-hexadec-11-en-1-ol and (*Z*)-tetradec-9-en-1-ol) at the expense of insecticides (Holkenbrink et al., 2020). The sex pheromones are produced in yeast (*Yarrowia lipolytica*) engineered by oxidation of fermented fatty alcohols. This approach has been effective in the control of cotton bollworm. Cotton bollworm is one of the most devastating pests in agriculture which requires sophisticated control and handling. Besides that, the SynBio applications in plant microbiome engineering for biofertilizers, biostimulants, and biocontrol agents in agriculture have been extensively revised (Ke et al., 2020).

Many countries have introduced a new way of producing enriched food based on microalgae and cyanobacteria (e.g *Spirulina*) in human diets. SynBio has allowed a sustainable production of food and nutrients such as proteins, lipids, and synthesized carbohydrates through engineering cyanobacteria (Liu et al., 2021). Many progresses in different aspects and prospective trends to use SynBio for food production have been achieved. However, the adoption of synthetic biology in different areas of knowledge will depend on professionals and other emerging areas such as bioinformatics, biotechnology, and bio-AI respectively (Milshteyn et al., 2018, Kautsar et al., 2017, Nesbeth et al., 2016).

Nanotechnology for Food Production

Nanoscience represents a multidisciplinary field of study in which particles in a nanometric scale (i.e., 1 to 100 nm) are synthesized and applied for several interests in many fields, such as agriculture, also known as agro-nanotechnology or agro-nanotech (Shafi et al., 2020; Bayda et al., 2020). The raise of agro-nanotech is motivated due to the need for increasing the food production and also its nutritional quality, playing a key role on the feasibility of food security for the next decades (He et al., 2019). In addition, other reasons related to this raise of agro-nanotechnology are related to the

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development of agriculture 4.0, because of the possibility to integrate green and eco-friendly solutions (e.g., pesticides and fertilizers) to agricultural practices, and also improve economic gains, since it is a cost-effective solution able to reduce pollutants in environment and increment sustainable practices (Zulfiqar et al., 2019).

Nanotechnology in agriculture has been largely exploited in the field of precision agriculture, either by using the particle or sensor technology, especially concerning to the application of fertilizers and pesticides (He et al., 2019; Shafi et al., 2020). Agro-nanotechnology enables an efficient and balanced strategy to crop nutrition as well as for smart applications of chemicals in agriculture (Shang et al., 2019; Zulfiqar et al., 2019). Under this dimension, (Zulfiqar et al. (2019) highlighted the ability of nano-fertilizers in plants increase the tolerance against abiotic stress and for the efficient use of nutrients by them, due to the slow nutrient release. Chhipa (2017) proposed an investigation about nano-fertilizers carbon nanotubes-based on the most common macro and micronutrients for plants. The author identified that the application of these nanotubes represented a more efficient system for plant nutrition. Chhipa also investigated the composition of nanoparticles (especially Ag, Cu, SiO2, and ZnO) for the formulation of nano-pesticides and the solutions based on nanotechnology also presented a higher protection efficiency when compared to conventional pesticides.

The exploitation of nanoparticles as an enhancer nutrient for plant nutrition is also an emergent interest in precision agriculture. Savassa et al. (2018) evaluated the effect of ZnO nanoparticles in the germination of common beans. Besides the possibility of correcting the intrinsic deficiency of Zn in about 50% of worldwide soils, the authors highlighted that the nano-solution designed did not affect the germination rate. Another important conclusion of this study is the biotransformation that ZnO nanoparticles suffer into Zn organically bound, what contributes to the enhancement of food nutritional quality delivered to consumers. Leonardi et al. (2021) proposed the development of a new fertilizer for eco-friendly agriculture based on nanomaterials produced after the complexation of polyelectrolytes, composed of sodium alginate complex, chitosan, and CuO nanoparticles. After the characterization of the material synthesizeds, the authors highlighted the benefits of the composites in the development of the plants. This process happens due to a synergic and beneficial role in seeding and germination.

Although the many advantages that this technology can bring to agriculture, there are blank spaces to be solved such as quality assurance and adequate controls (Kah et al., 2018). Other points that need to be further investigated according to the same authors are the impact of these materials in field conditions, as well as their toxicity to the environment and human health. Another important remark highlighted by several researchers is the central role of the regulatory agencies in counteracting these limitations and preventively mitigate consequences for the environment and human health (Kah et al., 2018; Kookana et al., 2014; Walker et al., 2018).

Enriched Foods

The addition of nutrients to foods is already a well-established practice and it has been carring out since 1920's, what is helping many countries to overcome several public health problems, e.g., malnutrition, annemia, rickets, pellagra, and other chronic diseases (Mannar; Hurrell, 2018). Enrichment of food can also be done voluntary by food industries, what can lead to a achieve specific target consumers, especially those ones oriented to the healthiness claim (WHO, 2006; Olson et al., 2021). Some good examples of these practices were the addition of iodine in salt in 1923 in Switzerland and 1924 in the USA, resulting in the drastic reduction of cretinism and goiter in those regions. In the following decades, several strategies were proposed and applied worldwide and the diseases provoked by malnutrition were virtually eliminated in the major part of the world. At the end of the 1980's the *Codex alimentarius* framed guidelines to the addition of these compounds in foods, as well as for the terminology nominations for the area (Mannar; Hurrel, 2018).

Since then, several studies have been carried out worldwide to ensure the addition of the nutrients that are being required to mitigate the consequences of malnutrition. Cormick et al. (2020) discussed about the enrichment of foods with calcium since it remains an improper daily intake in

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low- and medium-income countries, which can provoke the well-known diseases in bones, but also disorders in pregnancy, blood pressure, and cholesterol rates (Cormick et al., 2020). Nölle et al. (2017) investigated how to enrich mushrooms with vitamin D. These researchers developed an interesting and cheap strategy based on UV-B light and concluded that some simple processes of food technology (such as solar drying and slicing the referred foodstuff) associated with its exposure to ultraviolet radiation could boost the concentration of the desired vitamin in mushrooms.

Although a lot has been already proposed regarding food enrichment, Mannar & Hurrel (2018) pointed out that some micronutrients (i.e., vitamin A, iodine, iron, folic acid, and vitamin D) still represent a challenge in the mitigation of malnutrition all around the world. Song et al. (2019) also highlighted that this enrichment can also be segmented considering the new demands of the consumers, especially from the older generations, and their perception about healthy food and the adequate intake of proteins.

4. Innovation in Agricultural Management

Bioinputs to Benefit Food Production

A microbiome is a community of microorganisms living in a specific environment. It's important for plant survival, due to the symbiotic-ecological relationships it develops with plant structures (roots, flowers, leaves, fruits, and stem) for the availability of essential nutrients and defense (Vandenkoornhuyse, et al. 2015). Besides, the relationship between pollinators and plant microbiomes is responsible for insect attraction, allowing pollen dispersion (Vanette, 2020). The insertion of beneficial microorganisms in production areas tends to be an increasingly adopted practice by ag-techs in the near future, as observed in the use of mycorrhizal fungi (Ferrol, Tamayo, Vargas; 2016). These fungi are capable associate to plant root and make it easier both the nutrient and water uptakes; relieving the plants of heavy metal toxicity; and they also contribute to the phytoremediation of soils affected by heavy metals (Ferrol, Tamayo, Vargas; 2016).

Another example is the adoption of antagonistic microorganisms for the biological control of plant pests and pathogens, like the adoption of Trichoderma to control Fusarium wilt (*Fusarium oxysporum*) in pepper plants (*Capsicum annum*). This approach can lead to an efficiency in controlling the pathogen from 35.71% to 85.75% in an infested cultivation area (Hewedy, Abdel-Lateif, Bakr; 2020).

Some microorganisms produce metabolites which degrade and cause dysfunctions in other pathogenic organisms. Some bacteria release chitinase, an enzyme that metabolize/ chitin, the main insect's exoskeleton, and fungi cell wall component (Veliz, D; Martínez- Hidalgo; Hirsh, 2017). Bacteria of the genus *Bacillus* have great potential for application in agriculture. According to Amaresan *et all*. (2019), tomato plants associated with different species of *Bacillus*, showed better yields, as some isolates produce indole acetic acid (AIA), which contributes to tomato growth and flowering. Besides, its antagonistic effect for a wide range of pathogens allows a lower incidence of bacterial wilt, "damping off", root rot, and leaf spots in these plants. Also, *Bacillus velezensis* acts in the biocontrol of bitter apple rot, as an antagonist of *Colletotrichum gloeosporioides* (Kim, *et all.*; .2021). Another microorganism to be mentioned is the Trichoderma fungi, which are already available on the market as controllers of pests, diseases, and growth promoters, are widely used by farmers and have a wide range of activities (Alfiky & Weisskopf, 2021).

Bacteria and fungi are emerging candidates for biocontrol and growth promoters in plants. Studies and scientific advances in microbiology clarify how such small organisms are important for plant health, increasing yield, and decreasing agriculture inputs such as pesticides and synthetic nutrients. Since plant ally bacteria/fungi can control disease and facilitate water/nutrient uptake. Until now, new works and findings open the horizons in this potentially impacting field. Therefore, we hope that in the future all farmers will be able to develop, grow, and apply their bioproducts based on these species easily and feasibly.

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Artificial Intelligence in the Food Production

AI is an emerging field from computer science, is being applied across various areas of knowledge. In the food sector, AI has positively impacted the sustainability and innovation of food systems (Camaréna et al., 2020). Its applications range from precision agriculture and livestock management to detecting consumer patterns, food waste, and behavior change (Onishi et al., 2019; Dorea et al., 2020; Camaréna et al., 2020).

AI has introduced innovative solutions in agriculture, particularly in fruit detection and crop disease management. Convolutional neural networks (CNN) and deep learning techniques have been employed for real-time fruit counting in crop trees (Bresilla et al., 2019). In viticulture, hyperspectral imaging and machine learning algorithms have been used to classify grapevine varieties (Gutiérrez et al., 2018). For cassava, a crucial food security crop in Africa that is a major source of calories and income, especially for women (Legg et al., 2014), CNN models have been developed to diagnose diseases like Cassava Mosaic Disease (CMD) and Cassava Brown Streak Disease (CBSD) (Ramcharan et al., 2019). Machine learning has also been applied to classify viral pathogens affecting cassava and other plant species (Silva et al., 2017a, Silva et al., 2017b, Pei et al., 2020).

AI is transforming agriculture, with notable applications in harvesting, where it enhances the efficiency of mechanical fruit harvesting methods, reducing plant damage and increasing recovery rates by 36% compared to traditional methods in China (Ansah et al., 2018; Yang, 2020). Beyond harvesting, AI is used in pesticide application, image analysis for breeding, yield prediction, and plant disease recognition (Jha et al., 2019). Ferentinos (2018) demonstrated AI's capability in plant disease recognition with models achieving up to 99% accuracy. AI also improves farm management through sensors, data, and imagery, aiding decision-making and reducing labor demands (Smith, 2018). These advancements provide non-destructive techniques under field conditions, offering global benefits in food production.

AI is transforming the food processing industry by enhancing quality control and efficiency. In food production, AI-powered systems can inspect products in real-time, detecting defects or contaminants that might otherwise go unnoticed. For instance, computer vision technologies using deep learning algorithms can analyse images of food products on the production line, identifying any irregularities or quality issues, improving the overall quality of the final product and reducing the risk of food safety incidents. Companies like TOMRA and Key Technology are already implementing such systems in various food processing facilities, including those for fruits, vegetables, and meats (Bhat et al., 2024). By analyzing data from various sources, including sensors, RFID tags, and historical records, AI models can predict potential food safety risks and identify the origin of contaminated products quickly. For example, IBM's Food Trust platform uses blockchain and AI to track food products from farm to table, enabling rapid recall of contaminated items and reducing the risk of foodborne illnesses (Ahmad et al., 2024).

AI is also being used to innovate and optimize food formulations. Machine learning algorithms can analyse vast amounts of data on consumer preferences, nutritional requirements, and ingredient properties to suggest new and improved food recipes. For instance, companies like McCormick & Company are using AI to develop new flavours profiles and ingredients that meet changing consumer tastes and dietary needs (Queiroz et al., 2024). This approach accelerates the product development process and ensures that new products are more likely to succeed in the market. AI can significantly contribute to reducing food waste as well, a critical issue in the food production sector. By analysing data on production, storage, and consumption patterns, AI can predict where and when food waste is likely to occur. For example, AI-powered platforms like Afresh and Spoiler Alert use machine learning to optimize inventory management and predict demand, helping retailers and producers to reduce the amount of food that goes to waste (www.spoileralert.com/). Additionally, AI can help in the development of smart packaging that monitors the freshness and quality of food products, further reducing waste.

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Future integration of AI with other emerging technologies such as the IoT, blockchain, and SynBio is expected to revolutionize food production. The use of IoT sensors in food processing facilities can provide real-time data on temperature, humidity, and other environmental factors, which AI can then analyse to optimize production conditions. Blockchain allows for real-time tracking of products as they move through the supply chain. Each step, from planting and harvesting to processing, packaging, and distribution, can be recorded on the blockchain and automatically evaluated by open-source AI-powered software. This transparency will enable stakeholders to trace the origin and movement of products, ensuring accountability and trust in the supply chain. The combination of AI with SynBio is also leading to the development of novel food products with enhanced nutritional profiles and sustainability. As these technologies continue to evolve, they will play a key role in ensuring a sustainable, efficient, and safe global food system.

Water Management and Food Security

Fresh water is a resource that is becoming precious, due to its availability in both quality and quantity, highlighting scarcity and overexploitation (Hoekstra and Hung, 2003; van Oel and Hoekstra, 2012; Zhang et al., 2013; Lovarelli et al., 2016). It is also considered a resource that affects economic development and ensures the protection of healthy environments (Xiang et al., 2021). Besides that, proper water resource management stimulates economic growth, expanding the ability to provide water for various uses, increasing job creation, and positively impacting the quality of life of the population (Moreno-Pizani, 2021). Therefore, it is necessary to manage water resources to strengthen and supply according to the food cycle (Xiang et al., 2021). The tools and strategies used to achieve food security should be aligned with food security and public health, as well as sustainability (Vågsholm et al., 2020). Food losses need to be eliminated, promoting the reduction of food waste to achieve sustainability, in line with the objectives of reducing irrational use of resources and thus reducing the impact of environmental footprints (Vågsholm et al., 2020)

In recent years the role of quantification of environmental impacts and the study of processes and strategies to mitigate the impact of anthropogenic actions on the environment has been increased. The water footprint is one of the indicators that allows determining the virtual amount of water in products and/or services (Lovarelli et al., 2016). This recently developed concept raises awareness of water content in products and services and the changes that can be implemented in production processes for positively impact areas such as diets and market trades. There are different approaches to water safety (WS): one of them involves the protection of water-related ecosystems; achieving political stability and sustainable development; the other one ensures that everyone has access to safe drinking water and that vulnerable people are protected from water risks. FAO (2008) focuses more on water and water pollution in agriculture, while UN-Water (2013) refers to WS considering sustainable water use for current and future generations. WS is associated in addition to food security and energy security, with a very close link and with the adaptability of human society, and humans irreversibly alter the characteristics of water in the environment (Lall et al., 2017; Su et al., 2020).

Recently, sustainable water management tools have been proposed in urban areas based on AI using adaptive dynamic resource planning (AIDWRP), considering different future climate scenarios. With cascading modeling (CMA) approach, to optimize processes by reducing water supply costs, incorporating Bayesian belief network (BBN) methods and Markov decision-making processes for water resource management, and planning on a given finite horizon is presented in regions subject to water restriction (Xiang et al., 2021). Unfortunately, many water-scarce countries suffer from a lack of proper agricultural planning and resource management. Some water-scarce countries overexploited their non-renewable water sources for short-term economic benefits through agricultural exports. (Dalin et al., 2017; Abdelkader and Elshorbagy, 2021).

There are implications of this trade on water and national food security, and the complex interrelationships between food security and other national water-dependent development plans (Abdelkader and Elshorbagy, 2021). Any reduction in agricultural production leads to a decrease in national gross margin in the agricultural sector, a decrease in food self-sufficiency, and an increase in

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the economic cost of food imports. Efficient agricultural water management, therefore, has a multitude of socio-economic implications and for such is considered a high priority. However, this management must consider physical and socio-economic considerations of both water and food safety (Abdelkader and Elshorbagy, 2021). A good water management project requires consideration of forms of the water drop, including drinking water, wastewater, surface water, groundwater, and water for the environment (Su et al., 2020). AI applications in intelligent packaging and sensor implementation (gas, time, temperature indicators (TTI) and identification labels, radio frequency identification) have great potential to reduce food waste and thus improve food safety (Newsome et al., 2014; Poyatos-Racionero et al., 2018; Vågsholm et al., 2020). Another important aspect is water recycling that has been studied as part of one of the key components of sustainable off-border water management on the International Space Station (ISS). For NASA, as well as other business missions it is necessary to remain in a partial gravity environment, there are already technologies that allow water recovery in these special feature environments.

Recently, a biological approach to water processing has been investigated for future space applications to recover water and other wastewater resources, through a steam compression distillation segmented and urine processor (UPA) submitted by Americans; however, the Russian system also uses a multifil ration bed and rotary separator; where the Chinese use a bioreactor in conjunction with activated charcoal (Xie et al., 2017), filtration and distillation. Other studies have reduced moving parts with frontal osmosis membrane contact and a reverse osmosis module (Meyer and Schneider, 2018). Some of the challenges presented are to carry out systems that increase the rate of evaporation of water; carry out tests with the processing of greywater and sewage, to recover useful gases and reduce the volume of waste; test the final wastewater product (brine) to stabilize urine from subsequent batches; and carry out tests to determine the quality of the water recovered throughout these processes (Arai and Fricker,2021).

5. Public Policy, Food Regulation and Participatory Community

Regardless of the government political system, public policies start a fundamental rule for food security because food must be a human right (Barichello et al., 2021). Public policies and the cooperation between community and government leaders can be key elements to achieve more just, equitable and sustainable food systems. Also, the public-private relationship is a crucial component for strengthening investment decisions, performing new studies, to foster innovative food production systems (Buckley et al., 2021, Sani et al., 2021). Besides that, the effective participation of companies, scientists, and citizens can be an important action for performing new studies, popular suggestions in implementation, and government decisions. The effective action of the relationship between scientists-smallholder farmers has been questioned by the absence of engagement with smallholders and their families such as ending hunger which has been neglected (Editorial Nature, 2020; Nat. Plants, 2020). Nevertheless, the action of citizen science has been effective to reduce food loss and food waste, to monitor and implement sustainable development goals in new ways of food production and new agricultural approaches (Pateman et al., 2020, Fritz et al., 2019, Ryan et al., 2018).

At the beginning of this century, already foresaw many challenges to feed 10 billion people in 2050, and whose child malnutrition still will persist in many countries. Also, public policies would be necessary for resilient food production and global food security (Rosegrant et al., 2003). Due to climate change, growing population (food demand) new technologies, new genetic approaches, and the emerging disruptive technologies in food production systems many countries are rethinking the public policies and regulations such as, new approaches genetics to supply the demand for nutrition and new foods (Voigt et al., 2020, Ahmad et al., 2021, Sutkovic et al., 2020). A comprehensive review of the workable policies has been revised and suggested that clinicians can help implement a healthy food system even in the absence of government action (Peeters et al., 2018). These policies implemented by clinicians are effective, such as the Brazilian pediatrician Dr. Zilda Arns Neumann, was recognized internationally and nominated three times for the Nobel Peace Prize by the Brazilian government by fighting malnutrition and maternal-infant mortality in Brazil and Haiti respectively

(McGuire et al., 2001, Lee 2012). Other actions implemented around the world in food environment policies for improving diets of children and adolescents (Micha et al., 2018).

Another important aspect related to food production is the regulation of GMOs. The recent technologies as well as GMOs, SynBio, and CRISPR/Cas-mediated genome editing tools in plants have been broadly used for new crop improvement (Devos et al., 2014). The regulation of GMOs has also been discussed in the EU and can be determined as a new future for EU crop biotechnology (Davison et al., 2017). However, countries such as Czech Republic, Romania, and Slovakia, Portugal, and mainly Spain have cultivated maize MON810 on small scale. GMOs are emergent technology for food enrichment. For instance, diabetes mellitus is a metabolic syndrome characterized by elevated blood glucose and the control of the disease is the invasive method which consists of insulin application, and other alternatives have been studied. Such transgenic rice plants reduced blood glucose levels in this animal model, opening a promising path towards the treatment of diabetes mellitus disease based on food enrichment (Park et al., 2019, Xie et al., 2008b). The GMO regulations in Australia and New Zealand have the participation of citizens and farmers to auxiliary public participation, discussion, and democratic decision-making of the government (Hindmarsh et al., 2008). Popular participation in decision-making can be a key element for GMO regulations and insertions of recent technologies in food production.

6. Conclusions and Perspectives

Technology is changing food systems of production and it is being a key point to their transformation into a more resilient, inclusive, and affordable way. It is also enabling this transformation due to its transversal and multidisciplinary approach, so different scientific areas can interact and be able to deliver important advances and benefits for agriculture, food security, and to the environment, such as nanotechnology, new agricultural frontiers, enriched foods, and the disruptive technologies such as applied AI . Besides, the digital transformation of food systems can improve the efficiency of agricultural practices towards sustainability and food security. However, the success of such technologies and sets of management to feed 10 billion people worldwide rely on public policy and regimentations, as well as a participatory community, which is represented by its common citizens and eminent agents. Otherwise, income concentration and technology monopoly will put all of us at their mercy, thereby frustrating all the endeavoured objectives.

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