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Increasing the impact of science and technology to provide more people with healthier and safer food

Perla N. Chávez-Dulanto¹  | Arnaud A. A. Thiry²  | Patricia Glorio-Paulet³  |
Oliver Vögler⁴  | Fernando P. Carvalho⁵ 

¹Department of Plant Sciences, Faculty of Agronomy, Universidad Nacional Agraria La Molina, Lima, Peru

²The Lancaster Environment Centre, Lancaster University, Bailrigg, Lancaster, United Kingdom

³Department of Food Engineering, Faculty of Food Industry, Universidad Nacional Agraria La Molina, Lima, Peru

⁴Group of Clinical and Translational Research, Research Institute of Health Sciences (IUNICS-IdISBa) Department of Biology, University of the Balearic Islands, Palma de Mallorca, Spain

⁵Laboratório de Protecção e Segurança Radiológica, Instituto Superior Técnico—Universidade de Lisboa, Lisboa, Portugal

Correspondence

Perla N. Chávez-Dulanto, Department of Plant Sciences, Faculty of Agronomy, Universidad Nacional Agraria La Molina, Av. La Molina s/n, La Molina, Lima 12, Peru.

Email: perlachavez@lamolina.edu.pe

Abstract

Ensuring adequate food availability to an increasing world population constitutes one of the biggest challenges faced by humankind. Scientific and technological advances in food production during the last century enabled agriculture to cope with the concomitant increase in food demand. For example, cereal yields have more than doubled from a global average of 1.5 metric tons per hectare in the 1960s up to 3.2 metric tons per hectare in 2018. This was made possible by the work in different research fields such as agronomy, engineering, and plant sciences, showing that an inter and multidisciplinary approach is indispensable for significant progress. This manuscript is aimed at generating reflexion and analysis about the challenges that agriculture faces at present to satisfy projected food demands, which implies a further doubling of food production by 2050, according to the latest estimates. Relevant issues related to food production (climate change, pollution of water and soils by pesticides and fertilizers, loss of germplasm and biodiversity) are discussed and potential solutions to achieve food security in quantity and quality are reviewed, mainly from the plant breeding and crop-production perspectives, always associated with environmental health preservation and improvement. A broad transdisciplinary effort is needed to increase the impact of science and technology to provide more people with healthier and safer food, produced in a sustainable way. Nonetheless, science and technology alone will not succeed to meet those challenges. Education and knowledge transfer strategies are needed to guarantee responsible production and consumption everywhere, therefore allowing the benefits of scientific and technological progress reach the world population. Simultaneously, adequate action by regulatory authorities and governments concerted at international level, with thorough application of the Precautionary Principle, and aiming at environmental and social justice are imperatively required to meet the challenge and achieve the goal.

KEYWORDS

climate change, food security, genetic erosion, integrated pest management, mycotoxins, water-saving agriculture

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1 | INTRODUCTION

Long-term global food security depends on the balance between the supply and demand of the major food crops (Parry & Carmo-Silva, 2016). Food production increased tremendously during the past century thanks to outcomes from research and technology-transfer initiatives that took place between the 1930s and the late 1960s. This food production increase, globally known as “green revolution,” was based on selecting high-yielding cereal varieties, especially semi-dwarf wheats and rice, increased mechanization, expansion of irrigation infrastructure, greater application of chemical fertilizers, and introduction of synthetic organic crop-protection chemicals (Peshin et al., 2009; Weisenburger, 1993). Altogether, these initiatives doubled crop productivity per hectare (Carvalho, 2006), particularly in the developing world (Hazell, 2009), thus saving over a billion people from starvation (Farmer, 1986).

Despite the great improvement that this technology-package brought up for humankind, collateral negative effects to people and the planet by some of those technologies, unpredicted at their introduction, have emerged with time. For instance, pesticide resistance developed by pests triggered the increase of demand and further usage of pesticides, while evidence of harmful effects on human health and the environment were perceived during the last few decades only (Nicolopoulou-Stamati et al., 2016). Furthermore, modern agriculture has been accused to be the greatest source of water pollution with contamination of aquifers with nitrates, mainly from the increased usage of synthetic fertilizers and animal manure in farming (FAO and IWMI, 2018). Modern agriculture has been directly associated also with the increasing shortage of water especially potable water for human consumption, decrease in biodiversity, and disruption of functional ecosystems, which in turn have led to more frequent climatic catastrophic events (Ward et al., 2018). Thus, it is evident that the need to produce more and healthier food renders food production even more complex and challenging than thought years ago.

Food security constitutes one of the main today's challenges that include the need to further increase the production of adequately nutritional and safe food using sustainable methods to preserve healthy and functional ecosystems, while restoring those that have been disrupted. However, there are still some paradoxes to be solved before achieving this goal, as the huge amount of food wasted throughout the food production chain, and the long list of social, cultural, and economic constraints that developing countries would need to address to reach a more equitable situation, hence enabling a strong global effort at the unison. These paradoxes have led some authors to state no relationship among hunger, food production and human population growth, indicating that the real causes of hunger are poverty, inequality and lack of access

to food and land, as for every densely populated and hungry nation (like Bangladesh or Haiti) there is a sparsely populated and hungry nation (like Brazil and Indonesia) (Altieri & Rosset, 2002). Aligned, other researchers have indicated that human population growth varies in function of food availability, and therefore, the effect of increasing food production will be an increase in the human population (Paoletti et al., 2011), then turning food security into a permanent unbeatable challenge, leading humankind to extinction as all Earth resources are plausibly disappearing. Although this forecast would be in accordance with the population's dynamic ecology theory, we do believe humankind is able to thrive. To do so, it is imperative to rethink and improve our entire food production system through multi, trans and interdisciplinary work, as all disciplines are interconnected despite their apparent nonrelativeness, as suggested in Figure 1.

Some publications have addressed the main concerns and challenges related to food and nutrition security, tackling the most innovative advances of science and technology to achieve this goal, as the one by Tian et al. (2016). However, some of the innovations described therein, such as DNA barcoding, nanosensors and “Lab on a chip”, are still at experimental level and, although promising, do not necessarily mean a tangible contribution applicable right away. Similarly, Myers et al. (2017) described the potential impacts of climate change on agriculture, fisheries and animal husbandry that would lead to negative effects on food security and health, thus highlighting the importance of research, although remediation alternatives remain to be suggested.

Thus, the purpose of this manuscript is generating reflection and analysis about the challenges that agriculture faces at present, by exposing the issues, discussing the underlying causes, providing examples being applied successfully in case they exist, and proposing potential solutions to achieve food security (Figure 2) in accordance to the FAO (1996) concept [i.e., “(...) physical and economic access to sufficient safe and nutritious food in order to meet people's dietary needs and food preferences for a healthy and active life” (Pinstrup-Andersen, 2009)] and the Sustainable Development Goals of the 2030 (SDG 2030) Agenda of the United Nations (UNO, 2015), mainly from the plant breeding and crop-production perspectives.

2 | WATER SCARCITY AND CLIMATE CHANGE AS A CHALLENGE

2.1 | Climatological phenomena

Atmospheric CO₂ concentration ([CO₂]) is directly linked to global temperature. [CO₂] is predicted to increase from near 400 μmol/mol in 2015 to 550 μmol/mol in 2050, along



FIGURE 1 Scheme of the multi, intra and interdisciplinary nature of Food Security, showing the most relevant issues and topics addressed throughout the manuscript, focusing in achieving the Sustainable Development Goals of the 2030 Agenda of the United Nations

with other greenhouse gases produced by industrial activities. Consequently, the global mean temperature will increase around 2°C (RCP8.5 scenario; IPCC, 2013), as well as the frequency and severity of heat waves (and droughts) in many cropping areas (IPCC, 2014). Temperature could even rise up to 6°C, if the global economy and human population continue to grow at their current rates (Pachauri et al., 2015).

Changes in air temperature alter rainfall patterns and the occurrence of climatic phenomena. High-temperature heats up Earth surfaces and the nearby air masses, giving way to the convection process (air masses movements), simultaneously to the increase in vapor pressure (ability to contain relative humidity) of air. Such changes can result in

the extension of water shortage periods, followed by heavy rains, thus limiting food production due to water stress, either by drought (Christensen et al., 2007; Dai & Zhao, 2016; Lobell & Field, 2007; Tebaldi & Lobell, 2008)—especially on rainfed crops—, and/or flooding. For instance, the cascade of climatological events occurred in southern Peru due to El Niño Southern Oscillation (ENSO) phenomenon during 2016–2017—heat and drought (from October to January) followed by strong rainfalls, floods, landslides, thunderstorms, snowfalls and hailstorms brought by an unusual drop in temperatures due to the subsequent La Niña phenomenon (known also as “friaie”)—caused the loss of 25,671 ha of crops, 61,403 ha of crops affected, and 6,593 irrigation

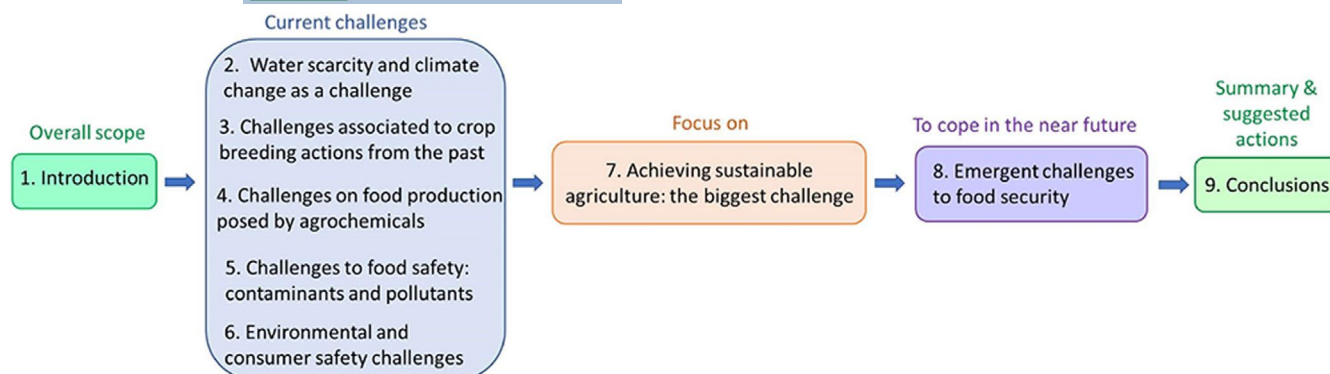


FIGURE 2 Scheme of the read-flow of the manuscript

channels destroyed (INDECI, 2017), thus threatening seriously the food and nutritional security of the Peruvian population. These phenomena have turned recurrent, since the south of Peru was newly affected in February 2020, while a new ENSO episode is predicted for 2020–2021 (DG, 2020). Thus, climate change can be the main cause of famine, while contributes to malnutrition and poor health, among other associated social disasters (Funk et al., 2019).

2.2 | Water-use efficiency in crops

Concomitantly to the explained above, global warming also increases evapotranspiration, that is, water loss by plants, whose effects largely depend on the properties of soil and of the own plants (Minasny & McBratney, 2018). Soil water availability to plants relies on water supply and the water-holding capacity of soil, either under irrigation or rainfed conditions. In this regard, it has been stated that, as long as the water content of soils is sufficiently available for plants, elevated $[\text{CO}_2]$ would trigger the mitigation of water stress by promoting a decrease of stomatal aperture (via genetic responses driven by the joint effect of specific proteins and phytohormones, mainly abscisic acid, that would control guard-cell movements), thus avoiding water loss while increasing net photosynthesis (Leakey et al., 2009; Tausz-Posch et al., 2012). In contrast, water scarcity and drought would result into a small—or null—net (positive) effect of the theoretical “benefits” of increased $[\text{CO}_2]$ on yields (Lobell & Field, 2007; Zhang et al., 2018), as stomatal closure (to avoid water loss) would impede CO_2 intake by the plant, and therefore, photosynthesis. Therefore, enhancing the water-use efficiency of plants would be key to cope with climate change effects on crops (Zhang et al., 2018).

Climate change exerts a strong influence on water at all scales, from individuals to the environment. Scarcity of this limited resource affects every continent (FAO, 2016). At present, nearly two thirds of world population suffer water scarcity at least during part of the year, and it is estimated

that 700 million people worldwide could be displaced due to severe water scarcity by 2030 (Global Water Institute, 2013). Agriculture is the largest user of freshwater (Li et al., 2019). Therefore, implementing water-use efficiency strategies in food production is crucial to ensure sufficient water for both food production and human consumption (FAO, 2016). For instance, development of crop varieties with significant yielding capacity under extreme temperatures and water stress conditions (drought and flooding), while developing methods to increase soil water-holding capacity—as incorporation of organic material to soils—as vegetal charcoal (biochar) and compost while promoting the development of beneficial flora and fauna—for example, the earthworm *Eisenia foetida* and related species, and microorganisms (fungus, bacteria, among others)—simultaneously, would be an asset. Also, implementation of water-saving agriculture technologies to buffer crop yields against future adverse weather conditions would increase the success to face water scarcity in the near future.

Among the water-saving agriculture technologies, the Regulated Deficit Irrigation (RDI) is being successfully applied for intensifying agriculture and improving yields and quality, while reducing the use of water according to the phenology and physiology of the crop. This technology, applied as partial root-zone irrigation or drying (PRI or PRD, respectively), intentionally seeks to supply a reduced volume of water locally in 50% of the root system, so that the other half is subject to a moderate degree of drought (McCarthy et al., 2002). Doing so, the emission of chemical signals from the dry part of the root system to the stem, generates a response in the plant aimed at saving water (stomatic closure) (Davies et al., 2002), while the contribution of water from the wet part allows the plant to continue its growth, thereby increasing its water-use efficiency (Dodd, 2009). A more precise use of the PRD technique would alternate the irrigated and dry halves of the root system from time to time, in order to maintain the potential chemical signal in both halves of the plant (along with the water flow) (Dodd et al., 2008). The application of PRD would allow

for the extension of irrigated areas without additional water consumption, thus keeping the expenses of water as usual and contributing significantly to achieving food security, particularly in arid areas (Garcia-Tejero et al., 2018). At present, high-irrigation technology investments have been done in agriculture aiming in improving water management. However, implementing knowledge-transfer and capacity-building strategies on water-saving, as PRD, are urgently needed for a proper application of the technique and profitability of the implemented technology (Chávez-Dulanto et al., 2018).

3 | CHALLENGES ASSOCIATED TO PAST CROP-BREEDING ACTIONS

3.1 | Loss of biodiversity

Crop breeding in the last century directed crop selection toward increasing the economic yield of cultivated species, focusing on selecting particular traits, such as high-yield and easy harvest, leaving aside traits that are the hereditary basis for crop survival during both biotic (pests, pathogens, herbivores) and abiotic (drought, flooding, nutrient deficiencies, salinity) stresses. These traits were rarely selected and are thus rare or absent in modern cultivars (Palmgren et al., 2015; Reif et al., 2005; Sramkova et al., 2009; Zamir, 2001), as less productive wild types were underestimated by crop breeders, thus causing a decrease of the genetic variation of commercial crops, that is, genetic erosion. Consequently, current (modern) cultivars tend to require high-external agronomic inputs, as fertilizers for enhanced production and pesticides for crop protection (van Bueren et al., 2011).

Landraces, defined as local and native varieties of crops, are a source of genetic diversity, as they contain precisely the genes for resistance to drought, extreme temperatures, pests and diseases, as well as for high content of nutrients and other health-promoting substances (e.g., flavonoids, carotenoids, oligo elements, vitamins), among other features. However, in the developed world, current agriculture replaced many traditional varieties of major field crops and discarded landraces (van de Wouw et al., 2009). Fortunately, in developing countries, local varieties are still cultivated in extended areas, especially for crops with high importance for food security, as wheat, rice, potato and maize. Likewise, the importance of landraces still prevails in the major centers of genetic diversity, such as for potato in the Andes (Brush et al., 1995) and wheat in the Middle East (Bardsley & Thomas, 2005; Kebebew et al., 2001). Although farmers are not acknowledged as the true guardians of crop biodiversity, mostly (Girard & Frison, 2018), their role as preservers of local and native varieties of crops (landraces) in which natural

selection has favored mechanisms of adaptation and survival, is nowadays recognized and seems crucial for food security (Cattivelli et al., 2008).

To cope with the permanent threat of disappearance for local and native varieties due to their limited commercial demand, global efforts for collection and long-term conservation of germplasm—the hereditary material (genes) transmitted to the offspring through germ cells—have been developed during the last decades. Germplasm banks have been created and established to store, conserve, and subsequently make available the plant genetic resources of major crop plants and their wild relatives. The International Board of Plant Genetic Resources (IBPGR), one among several international initiatives, have been established for germplasm conservation, whose main objective is to provide the necessary support for collection, conservation and utilization of plant genetic resources throughout the world. Germplasm conservation efforts are focused on crops of major importance to food security (i.e., apple, bambara groundnut, banana, barley, bean, carrot, chick-pea, cowpea, eggplant, fava bean, finger millet, grass pea, lentil, oat, pea, pearl millet, pigeon pea, potato, rice, rye, sorghum, sunflower, sweet potato, vetch and wheat) (Dempewolf et al., 2014; FAO, 2009). Further research on germplasm preservation of these and another high-nutritional quality crops must be encouraged to assure survival in case of (unexpected) constraints and/or disasters. Per example, the current global covid-19 quarantine has been unfavorable to many farmers in developing countries, who therefore would need urgent aid from their Governments and international organizations to get access to germplasm (and other resources) to assure survival.

3.2 | Loss of nutritional quality of food crops

Several recent research papers have suggested that, when commercial quality parameters (i.e., colour, size, shape, easy harvest, among others) are privileged, then the nutritional quality of the product along with other desirable traits (e.g., resistance to pests and diseases, resilience to drought, among others) decreases. Loss of nutritional quality was highlighted in the work by Fan et al. (2008) who assessed the mineral concentration of archived wheat grain and soil samples collected from the Broadbalk Wheat Experiment in the United Kingdom since 1843. They found that concentrations of Zn, Fe, Cu and Mg in the grains had decreased significantly (approximately 20%–30%) since 1968, right at the time at which semidwarf high-yielding cultivars were introduced. This decrease of oligo element concentrations in grains occurred despite the fact that their concentrations in soil either increased or remained stable (Fan et al., 2008). This fact would show that the harvest index (HI) has increased while the nutrient

uptake by the plant has been kept the same as from the original wheat, thus creating an imbalanced nutrient intake by modern wheat cultivars, a fact to be assessed from a genetic perspective, in order to find high-resilient genotypes to biotic and abiotic stresses brought up by climate change, as seen in the precedent section.

Plant domestication also has led to a severe reduction in genetic diversity within most crops (Dempewolf et al., 2014; Olsen & Gross, 2008) and changed crop quality. A good example is wheat, in which the introduction of semidwarfing genes to increase HI has decreased grain protein (Sramkova et al., 2009; van Bueren et al., 2011) and micronutrient (zinc (Zn), iron (Fe), copper (Cu) and magnesium (Mg)) concentrations compared to their wild relatives (Fan et al., 2008; Garvin et al., 2006; Verma et al., 2005), as seen above. Commercial tomato varieties (*Solanum lycopersicum*) provide another example in which breeding efforts have narrowed its genetic base, leading to a loss of genetic diversity, nutritional value and flavor due to a decreased concentration of sugars, acids, volatile compounds (Tiemann et al., 2017; Wang et al., 2016; van Bueren et al., 2011) and carotenoids (Zsögön et al., 2018). From the latter, lycopene and β -carotene largely determine the nutritional value of tomato (Zsögön et al., 2018). The first one, lycopene, has shown anti-inflammatory properties, and its dietary intake is correlated with reduction of cardiovascular and cancer risks (Clinton, 2009; Zsögön et al., 2018). However, lycopene content is low in the commercial cherry tomato, 60–120 mg/kg lycopene, compared to its pea-sized wild parent *Solanum pimpinellifolium*, where this antioxidant accumulates to levels of up to 270 mg/kg (Zsögön et al., 2018). Another example of how breeding efforts may unintentionally cause some specific traits to disappear, is the maize gene acyl-CoA: diacylglycerol acyltransferase (abbreviated DGAT), a key enzyme in the production of triglycerides that leads the production of oil with the healthy mono-unsaturated fatty acid oleic acid. During maize domestication, a small deletion of three bases in the DGAT gene occurred, and consequently, a significant loss in the activity of the encoded mutant protein (Palmgren et al., 2015). Consequently, from a nutritional point of view, corn oil contains relatively more omega-6 and less omega-3 polyunsaturated fatty acids and, therefore, it is not considered a particularly healthy vegetable oil. Likewise, potato breeding prioritizing on high-productivity and commercial characteristics, such as short crop cycle and aspects of tubers (clear skin, shape—oval or rounded, superficial eyes, large and uniform size) has diminished characteristics related to nutritional quality, such as, high content of dry matter and low content of reducing sugars and glycoalkaloid among others, as well as traits for resistance to biotic (pests, diseases, etc.) and abiotic environmental stresses (frost, drought, hail, salinity, etc.) (Cahuana et al., 2012).

In the last decades, fighting against malnutrition has been selected as one of the targets of crop breeding in developing countries. Malnutrition includes overt nutrient deficiencies and diet-related chronic diseases (e.g., heart disease, cancer, stroke, and diabetes). Micronutrient deficiencies are responsible for the slow socioeconomic development of many nations due to its contribution to increased morbidity, disability, stunted mental and physical growth of population (Wang et al., 2019; WHO & FAO, 2003). Micronutrient deficiencies are associated to food insecurity (King, 2018), being more severe at lower income countries and more prevalent in those with poor dietary diversity (Ritchie & Roser, 2017). An estimated 17.3% of the world's population suffers micronutrient deficiency mainly due to inadequate Zn (Wessells & Brown, 2012) and Fe intake (Murray & Lopez, 2013; WHO, 2008, 2009). Zn deficiency causes the annual death of nearly a half million of children under the age of five, while Fe deficiency causes anemia in approximately 25% of the world's population (WHO, 2008, 2009). Since staple-grain cultivated varieties can contain suboptimal quantities of micronutrients as Fe and Zn (Borrill et al., 2014), crop-breeding international programs are producing bio fortified crops with vitamin A, Zn and Fe to avoid blindness, promote growth in children and diminishing anemia, respectively.

“Harvest Plus” is an example of these international initiatives to fight micronutrients deficiencies. Special efforts are concentrated on crops with the highest consumption per capita around the world, that is, rice [*Oryza sativa* L.] (Borlaug, 2000; Trijatmiko et al., 2016), wheat [*Triticum aestivum* L.] (Borlaug, 2000; Borrill et al., 2014; Bouis & Welch, 2010; Guzman et al., 2016), maize [*Zea mays* L.] (Borlaug, 2000; Bouis & Welch, 2010; Queiroz et al., 2011), cassava [*Manihot esculenta* Crantz] (Bouis & Welch, 2010), pearl millet [*Pennisetum americanum* Leake] (Bouis & Welch, 2010), beans [*Phaseolus vulgaris* L.] (Bouis & Welch, 2010), potato [*Solanum tuberosum* L.] (Borlaug, 2000; Kromann et al., 2017) and sweet potato [*Ipomoea batatas* L.] (Bouis & Welch, 2010; Laurie et al., 2015), among other crops. These efforts to compensate or correct nutrient imbalance in many food crops further underline losses in food quality due to reduced biodiversity and genetic erosion caused by past cultivar selection procedures.

These facts have demonstrated that to protect and ensure nutritional quality of food, current global efforts for collection and long-term conservation of germplasm should enhance focus on crops of major importance to food security (quantity and quality), and biodiversity preservation. Consequently, high productivity and stress-resilience should be bred jointly, not separately. Therefore, crop-breeding should focus on developing new tools to assess both criteria of germplasm, as, per example, the mathematical-statistical method developed by Thiry et al. (2016), described further in section 8.1.

4 | CHALLENGES ON FOOD PRODUCTION AND AGROCHEMICALS

4.1 | Pesticides

Synthetic chemicals used as pesticides became part of agriculture systems during the past century. Although they contribute to increased yields of crops, a number of collateral effects were reported on human health and wildlife (Carvalho, 2017). Pesticide exposure of humans is particularly worrisome.

Pesticide exposure can be classified as intentional and unintentional exposure. Intentional exposure is associated with suicides, mostly in developing countries, according to Sabarwal et al. (2018). In turn, unintentional exposure can be classified into occupational and nonoccupational exposure, with the former related to laborers engaged in manufacturing, transportation and trading of pesticides, farmers, applicators and sellers of fruits and vegetables in the markets, and the latter linked to exposure mainly at the consumer level, comprising humans and animals, via ingestion of fruits, vegetables, and grains (Sabarwal et al., 2018).

During the last decades, occupational exposure to agrochemicals has been demonstrated to affect the health of farmers (Alavanja et al., 2013) and their families (Alavanja et al., 2014; Carvalho, 2017; EEA, 2013; Yanggen et al., 2003) including children (Bassil et al., 2007) and spouses (Parks et al., 2016). These two groups (children and spouses) would be affected indirectly, that is, via unintentional nonoccupational exposure. In children, cancer development is associated with parental exposure to pesticides at work (Bassil et al., 2007). Pesticide effects can be transmitted to offspring via a metabolic (genotoxic) response on the DNA or another molecule, such as a protein that may induce a mutation (Bonvallot et al., 2018; Farmer, 1997). For instance, in Vietnam, female floriculture workers exposed to pesticides had increased abortion rates, infant prematurity and congenital malformations in their offspring (Frazier, 2007; Weisenburger, 1993). Similarly, in Peru, malformations of mouth and palate, cardiovascular system, extremities, genital-urinary system, central nervous system and others, have been reported for children whose mothers were in contact and lived near pesticide fumigated fields during pregnancy (Gonzales-Tipiana et al., 2017).

Table 1 summarizes the observed effects of active ingredients of pesticides as described by several authors. It was demonstrated that most of these compounds are deleterious to human health and the International Agency for Research on Cancer (IARC) has recognized a few as human carcinogens (Group 1) or probable human carcinogens (Group 2A) (Bonner & Alavanja, 2017). Table 2 presents a summary of these, based on information provided in IARC's website (2018).

Global population could reach 9 billion on 2050 (United Nations, 2015), that is, almost 1.3 billion more than today's population calculated at 7.7 billion (Worldmeters, 2019). As most agricultural land is already in use, new agricultural land to produce additional food for the expanding population is very limited (Bonner & Alavanja, 2017; Carvalho, 2017). Thus, to addressing global food security for the growing population, the challenge is to achieve a sustainable food production with the existing agricultural land. Current agriculture systems see pesticides as an unavoidable tool to protect crops and ensure good yields. However, due to collateral effects, many of classic synthetic pesticides, such as the organochlorine compounds, were banned in most countries and the current wish is to abandon or replace the harmful synthetic pesticides. A selection of agro-pesticides with environment friendly and proven low (preferably none) nontarget toxicity, and improved pesticide application methods (e.g., nanoparticles containing pesticides) as part of a tightly controlled integrated production system, may help farmers to maintain or increase crop yields without the awkwardness of synthetic pesticides. The implementation of integrated pest management strategies would be the most straightforward way to achieve it, as explained in section 7.1.

4.2 | Chemical fertilizers

Chemical fertilizers became a routine component of agriculture systems. However, these products might contribute also to environmental contamination and ecosystem damage. It was highlighted that contamination caused by chemical fertilizers occurs mainly through two ways: contamination with the desired components of fertilizers (nitrogen, phosphorus, and potassium) and contamination with the undesired elements present in fertilizers such as heavy metals (arsenic, cadmium, and uranium) (Schnug & Lottermoser, 2013). Both have a negative impact on the health of farmers, their families, food consumers, and environment. Further information on contamination of food via heavy metals is provided in section 5.2.

Nitrogen (N) is fixed in soil by biological and physical processes as nitrate (NO_3) and nitrite (NO_2) forms mainly, which can readily be used by living organisms including food crops. Due to anthropogenic activities linked to food production such as agriculture (e.g., soil fertilization, animal waste) and also combustion of fossil fuels, nitrogen is released in large amounts to the atmosphere and soils. Those N reactive forms are leached by rains and flooding episodes, and transferred to water bodies, thus contaminating groundwater and surface waters. Nitrogen contamination of water bodies in intensive agricultural areas become the most extensive problem in developed countries with negative impacts on biological diversity, human health, and climate (Steevens, 2019), as discussed below.

TABLE 1 Associated effects of exposure of active ingredients of pesticides on human health

Research facts	Active ingredient	Observed effects	References
Children with parents involved in pesticides' management	Lindane Parathion Chlorophenol Atrazine	Acute myelocytic leukemia (AML) via damage of genes responsible to encode enzymes to metabolize carcinogenic substances Risk during mothers' pregnancy	Infante-Rivard et al. (1999) Flower et al. (2004)
Male	2,4-dichlorophenoxyacetic acid (2,4-D) Lindane DDT Malathion Endosulfan Dichlone Carbaryl 2,4-DB (2,4-D metabolite) Glyphosate	Prostate, testis and male reproductive system cancers: <ul style="list-style-type: none"> • Stimulation of cells proliferation • Increasing localization of androgen receptor in the nucleus from the cytosol acting as tumor promoter 	Kim et al. (2005)
Woman	2,4-D	Breast cancer via suppression of luteinizing hormone*	Niehoff et al. (2016)
Meta-analysis	diazinon	Non-Hodgkin lymphoma via disruption of neuro-immune system	Hu et al. (2017)
Male and woman	Organ-phosphates (OPs) Benomyl and its metabolite thiocarbamate sulfoxide	Parkinson disease: associated to patients with variant genotype NOS1	Fitzmaurice et al. (2013)
Woman	Maneb Mancozeb	Rheumatoid arthritis Thyroid diseases: inhibition of thyroid hormone production	Parks et al. (2016); Goldner et al. (2010) Pastorelli et al. (1995)
Exposed agricultural workers in Colombia	Glyphosate	Genotoxic effect via chromosomal damage Non-Hodgkin lymphoma	Bolognesi et al. (2009) Schinasi and Leon (2014)
Long-term study with farmers and pesticide applicators in USA	Pendimethalin (herbicide) Dieldrin (insecticide) Parathion (insecticide, miticide) Chlorimuron-ethyl (insecticide)	Lung cancer incidence	Bonner et al. (2016)
Adolescent applicators of pesticides in Egypt	Chlorpyrifos	Deficits in neurobehavioral performance	Rohlman et al. (2016)
In vitro study with human cells and rats	Mancozeb (fungicide) Ethylene-bis-dithiocarbamate (EBDC)	Inhibits thyroid hormone production	Pastorelli et al. (1995)
Long-term exposure at low doses	Paraquat Dieldrin Organochlorine Organophosphates	Generation of Reactive Oxygen Species (ROS) causing neurotoxicity positively related to Alzheimer disease	Yan et al. (2016)
Meta-analysis	Dichlorodiphenyldichloroethylene (breakdown product of DDT) Hexachlorocyclohexane (lindane) Chlordane Hexachlorobenzene	Non-Hodgkin lymphoma	Luo et al. (2016)

(Continues)

TABLE 1 (Continued)

Research facts	Active ingredient	Observed effects	References
Couples (men and women) from Shanghai, China	Organophosphate and Pyrethroid pesticides metabolites assessed in urine samples [dimethylphosphate (DMP), dimethylthiophosphate (DMTP), diethylphosphate (DEP), diethylthiophosphate (DETP), dimethyldithiophosphate (DMDTP) and diethyldithiophosphate (DEDTP)] and three metabolites of PYRs [3-phenoxybenzoic Acid (3PBA), trans/cis-3-(2,2-dichlorovinyl)-1-methylcyclopropane-1,2-dicarboxylic acid (TDCCA and CDCCA, respectively	Couple fertility adversely affected, assessed as time to pregnancy (TTP)	Hu et al. (2018)
Two generations tests with rats, dogs and mice	Spinosad	Endocrine disruptor: toxic for the reproduction, adverse effects on multiple organs including endocrine organs (thyroid, thymus, pancreas, adrenals, epididymides, ovaries, uterus)	Arena et al. (2018)
Japanese male workers exposed to ortho-toluidine	Ortho-toluidine (precursor to the herbicides metolachlor and acetochlor)	Bladder cancer. Patients did show high rates of gross hematuria (70%) and cystitis (70%) in their past medical histories.	Nakano et al. (2019)

Contamination of water by nitrogen has been associated to health problems such as methemoglobinemia (NO_2 interference with the oxygen carrying capacity of the blood) in infants under 6 months of age (Ward et al., 2018), leukemia and other cancers at childhood (Mueller et al., 2004), but also at adulthood (Espejo-Herrera et al., 2015; Jones et al., 2016; Zeegers et al., 2006). Indeed, since 2010, the IARC classifies both NO_3 and NO_2 as Group 2A—probable human carcinogenic (IARC, 2018). Despite the excess of N introduced in the ecosystems, it does not mean it is available to plants, and therefore, it does not automatically induce a significant increase in crop yields (Steevens, 2019). Paradoxically, there is still a vast extension of lands where N scarcity in soils represents a serious limitation for agriculture production and thus for food security. Indeed, nitrogen distribution in soils could be used as indicator of the huge disturbance of Earth's nitrogen cycle at global scale (Steevens, 2019).

The issue turns critical as runoff waters from agricultural fields bring many dissolved molecules of nitrogen and phosphorus (P) into freshwaters and oceans. Both fertilizers stimulate the growth of phytoplankton, which is decomposed by bacteria that need oxygen to act (aerobic), thus leading to eutrophication, that is, the creation of low oxygen concentration (hypoxia) areas (“dead zones”) that are unable to support life and, therefore, cause an obvious decrease of marine fisheries. Such “dead zones” are increasing in number and extension around the world (Breitburg et al., 2018). The Gulf of Mexico dead zone would be the largest one due to the discharges of the Mississippi river into the Gulf. From 1950s up to date,

the Mississippi has triplicated the annual amount of nitrogen discharged, while phosphorus has doubled due to intensive agriculture in the river catchment (Christensen, 2019).

In face of these effects, it becomes crucial to manage, reduce and control the release of agrochemicals into the environment to ensure environmental preservation and the potential for food production.

5 | CHALLENGES TO FOOD SAFETY: CONTAMINANTS AND POLLUTANTS

Agrochemicals, as seen above, have been instrumental to increase food production although with collateral effects on farmer's health and consumer's health through the impact of chemical residues on human and environment health. Other chemicals may also contaminate food and have an impact on human health and must be referred herein: mycotoxins and heavy metals.

5.1 | Mycotoxins

Food quality, in terms of safety and nutritional aspects, is a key concern. Food is a source of macro and micronutrients and bioactive substances for human consumers but can also be an optimal substrate for living organisms, such as microscopic fungi, which are ubiquitous in the environment. Some

Active ingredient	IARC classification	Observed effects	References
Ortho-toluidine	Group 1—Human carcinogenic	Bladder cancer	IARC (2012)
Lindane	Group 1—Human carcinogenic	Immuno suppressive effects	IARC (2016)
DDT	Group 2A—Probable human carcinogenic	Immuno suppressive effects in human cells Increase of oxidative stress in human peripheral blood mononuclear cells. Stimulation of human colon cancer and liver cancer cell proliferation in vitro Estrogenic effects and androgenic-receptor antagonism in human cells in vitro	IARC (2016)
Malathion	Group 2A—Probable human carcinogenic	DNA and chromosomal damage in humans through its bioactive metabolite malaoxon	IARC (2017)
Diazinon	Group 2A—Probable human carcinogenic	Chromosomal damage	IARC (2017)
Glyphosate	Group 2A—Probable human carcinogenic	Chromosomal damage	IARC (2017)

TABLE 2 Active ingredients of pesticides recognized as affecting negatively human health, according to the International Agency for Research on Cancer (IARC)

microscopic fungi produce toxic substances called mycotoxins, which are considered secondary metabolites excreted in certain stages of their growth. During food production and storage, extrinsic factors such as temperature, humidity and the presence of oxygen and others can favor fungi proliferation and thus contamination of food with mycotoxins (Bhat & Reddy, 2017). Several mycotoxins embody a serious health hazard to human consumers. For example, wheat grains can be contaminated by mycotoxins, mainly deoxynivalenol or DON, produced by the fungus *Fusarium graminearum* and other fungi species (Guzman et al., 2016), and such wheat derived products are toxic to humans. Thus, selecting varieties with resistance to mycotoxins-producing fungi has become a priority of breeding programs and research agencies worldwide.

Mycotoxins are released in ppm or ppb concentrations but are still able to generate health problems to consumers due to their high toxicity (De Vicente, 2020; Quiles et al., 2016). Therefore, the monitoring of mycotoxins in the food chain is essential to ensure public health, quality of life and honest international trade (Chauhan et al., 2016; Lu et al., 2016; Ortiz, 2020). Indeed, several accreditation and certification programmes have been developed to control and certify food safety (Table 3). Good Agricultural Practices (GAP), Hazard Analysis and Critical Control Points (HACCP),

ISO (International Standardization Organization) and the FSMS (Food Safety Management Systems) certifications, among others, followed by the application of Good Hygienic Practices (GHP) and Good Manufacturing Practices (GMP), are examples of those.

To ensure food safety it is needed to avoid biological, chemical, and physical hazards at all stages of the food chain, from food production to preparation, packaging, and even distribution processes. A collection of all standards, guidelines and codes of practice adopted in food production, process and management is compiled in the Codex Alimentarius (FAO/WHO, 2018). With the increase of international trade and food market globalization, application of these procedures is absolutely needed and aim at having a large impact on food safety at international level (Van Boxtael et al., 2013).

5.2 | Heavy metals

Likewise, food contamination by heavy metals in crops has become an important concern. A heavy metal (HM) refers to any metallic element with relatively high-atomic density that is biologically toxic or poisonous even at low concentration (Lenntech, 2004). This term includes Cadmium (Cd), Copper (Cu), Zinc (Zn), Nickel (Ni), Cobalt (Co), Chromium (Cr),

TABLE 3 Summary of certifications on food safety and innocuity available at present

Certification				
Acronym	Denomination	Scope	Purpose	Addressed to
HACCP	Hazard Analysis of Critical Control Points	Internationally	Recognition of having developed, documented and implemented systems and procedures to help identify and control food safety hazards that may occur within the food business.	Food business and food manufacturers, from primary production to transport and distribution
				Reference HACCP organization https://haccpmentor.com/haccp/haccp-certification/
GAP	Good Agricultural Practices	Internationally	Independent certification system on product safety, environmental impact and the health, safety and welfare of workers and animals—safe and sustainable food production.	Business: Business-to-business standard that connects farmers and brand owners around the world to provide reassurance for consumers.
				Global G.A.P. https://www.globalgap.org/uk_en/index.html
GMP	Good Manufacturing Practices	Internationally	Ensuring that products are safe, pure, and effective, via a quality approach to manufacturing, enabling companies to minimize or eliminate instances of contamination, mix-ups, and errors.	Manufacturers, processors, and packagers of drugs, medical devices, some food, and blood
				International Society for Pharmaceutical Engineering https://ispe.org/initiatives/regulatory-resources/gmp
Rainforest Alliance Certified	Sustainable Agriculture Certification	Internationally	Ensuring decrease of environmental footprint, safeguarding forestland and waterways, protecting wildlife, generating income for farming families, providing employment to locals and playing in regional conservation initiatives.	Farmers and farmers' groups
				Rainforest Alliance https://www.rainforest-alliance.org/business/solutions/certification/agriculture/
LEAF	Linking Environment And Farming	Internationally	Recognizing more sustainably farmed products, standing for more environmental sustainability under the principles of Integrated Farm Management (IFM)	Farmers, food brands and retailers
				Linking Environment And Farming https://leafuk.org/farming/leaf-marque
BIO	Organic farming	European Union	Certify that at least 95% of ingredients of agricultural origin come from organic farming.	Farmers, food brands—food products that are fully or partially processed in the European Community
				European Community https://ec.europa.eu/info/food-farming-fisheries/farming/organic-farming/organics-glance_en BIO https://www.oekolandbau.de/en/bio-siegel/
No GMO	Non Genetically Modified Organisms	Internationally	Proof and verify that non-genetically modified (non-GMO) products are present on food	The whole supply chain: Seed supply, Farming, Trading, Processing. Also Storage, Transport, Sampling and analysis
				SGS https://www.sgs.com/en/agriculture-food/commodities/audit-certification-and-verification/certification/non-gmo-certification

(Continues)

TABLE 3 (Continued)

Certification				
Acronym	Denomination	Scope	Purpose	Addressed to
SQF	Safe Quality Food	Internationally	Food safety and quality codes to meet industry, customer, and regulatory requirements for all sectors of the food supply chain—from the farm all the way to the retail stores to	All sectors of the food industry, from primary production to transport and distribution
BRC	British Retail Consortium	Internationally	Provide assurance to customers that products and process are safe, legal and of high quality, in compliance to industry best practices	Finished Food Manufacturers (branded & unbranded products), raw material and ingredient suppliers, packers of primary products (e.g., fruit & vegetables)
IFS	International Featured Standards	Internationally	Auditing food safety and quality of processes and products of food manufacturers (process or handle food or food ingredients), logistics, storage and distribution industry.	Industry, retailers and retailers' own brands
FSSC 22000	Food Safety System Certification 22000	Internationally	Certify food safety systems of companies in the food chain that process or manufacture animal products, perishable vegetable products, products with a long shelf life and other food ingredients like additives, vitamins and bio-cultures.	Food manufacturers, based on the ISO 22000, ISO/TS 22002-1 and ISO/TS 22002-4 standards
BAP	Best Aquaculture Practices	Internationally	Define the most important elements of responsible aquaculture. Provide quantitative guidelines to address environmental and social responsibility, animal welfare, food safety and traceability for aquaculture facilities.	Aquaculture business and companies
ISO	International Standard Organization	Internationally	Provide requirements, specifications, guidelines and/or characteristics that can be used consistently to ensure that materials, products, processes and services are fit for their purpose.	Producer and manufacturer companies to work with world-class specifications for products, services and systems, to ensure quality, safety and efficiency, thus facilitating international trade
				International Organization for Standardization (ISO) https://www.iso.org/about-us.html
				NSF International http://www.nsf.org/services/by-industry/food-safety-quality/global-food-safety-certification
				NSF International http://www.nsf.org/services/by-industry/food-safety-quality/global-food-safety-certification
				Global Food Safety Initiative (GFSI) http://www.ifs-certification.com/index.php/en/
				Global Food Safety Initiative (GFSI) http://www.nsf.org/services/by-industry/food-safety-quality/global-food-safety-certification
				British Retail Consortium https://www.brcgs.com/
				Global Food Safety Initiative (GFSI) https://www.ifs-certification.com/index.php/en/

Lead (Pb), Mercury (Hg), Arsenic (As) (Khan et al., 2008; Yadav, 2010) and also Tin (Sn) and Vanadium (V) (Su, 2014). HMs can be highly hazardous to organisms, and HM concentrations and toxicity can be enhanced through the food chain. Cr, As, Cd, Hg and Pb are the most potentially harmful HM for mammals due to their strong affinity for sulfur (S), enabling HM binding to enzymes that control metabolic reactions via thiol groups (–SH). The resulting sulfur-metal bonds impede the adequate performance of the bonded enzymes, causing deterioration of health and also death of individuals (Baird & Cann, 2012; Rusyniak et al., 2010). Hexavalent forms of Cr and As have been proved to be carcinogens, while Cd causes a degenerative bone disease, and Hg and Pb damage the central nervous system (Baird & Cann, 2012; Rusyniak et al., 2010).

Agricultural soils in many parts of the world are contaminated by HMs (Su, 2014) resulting from atmospheric deposition, irrigation with sewage, deposition of dust from smelters, disposal of industrial waste, long-term use of pesticides and fertilizers (Duxbury et al., 2003; Khan et al., 2008; Passariello et al., 2002; Schwartz et al., 2001; Zhang et al., 2011), proximity to roads with fumes from leaded gasoline (Khan et al., 2008; Love, 1998) and dust produced by automobile tire wear (Khan et al., 2008). In plants, the uptake of heavy metals depends on the root and foliar efficiency of plant species in absorbing (or excluding) metals, and accumulation of heavy metals in plant structures may have toxic effects and lead to reduced crop yields (Rattan et al., 2005). For instance, arsenic toxicity in rice is known to cause reduced growth and sterility of florets in panicles (Duxbury et al., 2003). Furthermore, accumulation of HMs in plants may transfer them to humans. For example, soil contamination by Cd, Pb, Zn, and Cu and the use of HM polluted water for irrigation (Khan et al., 2008; Nan & Zhao, 2000) leads to accumulation of these metals in wheat (*Triticum aestivum* L.), rice (*Oryza sativa*), radish (*Raphanus sativus* L.), maize (*Zea mays*), green cabbage (*Brassica juncea* L.), spinach (*Spinacia oleracea* L.), cauliflower (*Brassica oleracea* L.), turnip (*Brassica napus*), and lettuce (*Lactuca sativa* L.) which poses health risks to consumers.

In some regions, such as Bangladesh, occurrence of high concentrations of arsenic (As) of natural origin in the groundwater has led to a widespread human exposure to As through drinking water and rice consumption (Duxbury et al., 2003; Karim, 2000; Paul et al., 2000). In different parts of the world, especially in Asian countries (Hassan et al., 2017) and in the USA (Potera, 2007; Schilling, 2016), arsenic has been found also in rice grains but originated from other sources (Williams et al., 2005, 2007; Zavala & Duxbury, 2008). In these cases, high As contents in rice were due to the high As content in soils resulting from past use of As a pesticide (Schilling, 2016). USA has been the world's leading user of arsenic, with about 1.6

million tons used in agriculture and industry since 1910 (Schilling, 2016). Although As was banned in 1980s, residues still linger on in agricultural soil today. High-arsenic values have been found also in rice grown in soils where cotton used to be grown with the help of frequent treatments with arsenical pesticides to combat the cotton boll-weevil beetle (Schilling, 2016).

As a consequence of the widespread arsenic contamination of agriculture soils in USA, inorganic arsenic has been found also in baby food and rice-based food products for 4–6 month infants and young children (Signes-Pastor et al., 2017). Ingestion of these contaminated foods may have an impact on their neurological, cardiovascular, respiratory and metabolic development throughout lifespan (Meharg et al., 2008; Rintala et al., 2014; Signes-Pastor et al., 2017).

The development of treatments for HM accumulation and toxicity in humans is currently under research and natural substances such as the milk thistle seed extract, dandelion leaf extract, garlic bulb (*Allium sativum*), cilantro leaf extract, and L-glutathione, N-Acetyl-L-Cysteine are being tested as chelating agents to eliminate arsenic from the body (Schilling, 2016).

Remediation of soils contaminated by HMs is difficult and it may take one or two hundred years to reach a significant decrease in soil contamination (Su, 2014; Wood, 1974). Hence, the lesson to learn here is the need to apply the Precautionary Principle, which is defined as discretionary decisions and/or actions on issues considered uncertain due to the lack of extensive scientific knowledge on the matter, thus emphasizing caution and sound scientific evidence before leaping into actions that may result harmful. Thus, in case of introducing new chemicals in agriculture systems, the existing tiered protocols and robust methodologies to assess their genetic and toxic effects should be applied as a basis for their licensing (EFSA, 2016).

6 | ENVIRONMENTAL AND CONSUMER SAFETY CHALLENGES

Agrochemicals for crop protection include a variety of organic compounds, mostly synthetic, used against pests and diseases. Soon after their introduction in the 1940s, the generalized application of pesticides was shown to have collateral effects in nontarget species, such as pollinating insects, birds, and aquatic species, for example, causing massive shrimp and fish kills. The book «Silent Spring» by Rachel Carson published in 1962 was an early warning of the environmental impact of pesticides (Hester & Harrison, 2017), such as the organochlorine pesticides, due to their massive use and high persistency in the environment, causing resistance of pests and accumulation and harmful effects on nontarget biota and humans (Alavanja et al., 2013, 2014;

Carvalho, et al., 2009). Furthermore, after pesticide application, often it was observed the formation of degradation products and metabolites sometimes more toxic than their parent compounds, such as, for example, DDE formed from DDT, and endosulfan-sulfate formed from endosulfan, thus evidencing the need for tighter eco-toxicity testing and licensing processes of chemicals before their commercial release (Carvalho, et al., 2009). These facts led to an international environmental treaty, the Stockholm Convention on Persistent Organic Pollutants (POPs), signed in 2001 and effective from May 2004, aimed at the elimination or restriction of production and use of POPs.

Since then, POPs have been gradually replaced by other chemicals from the groups of organophosphorus and carbamates, believed to be less persistent in the environment, less bio accumulative and less toxic (Bonner & Alavanja, 2017; Carvalho et al., 1997). However, further studies revealed that these substances (organophosphorus and carbamates) were neither rapidly degraded nor “environment friendly” as expected. Instead, they were shown to persist in soils, and reach aquatic environments to impact on aquatic fauna (Carvalho et al., 1997, 2003). For example, chlorpyrifos used to protect banana plantations from pests was revealed to be toxic to aquatic invertebrates at concentrations as low as 30 ng/L. Later on, new agrochemicals, such as glyphosate, chloramphenicol, and pharmaceutical residues including antibiotics, have also been reported in many aquatic ecosystems with toxic impact in biota, including fishery resources. Residues of most agrochemicals and antibiotics are these days found in surface waters and crops especially in North-America and Europe where such residues currently are closely monitored (Carvalho, 2017; González et al., 2019; IARC, 2017; WHO, 2010).

A significant challenge to agricultural production (and including also meat and fish production), is how to produce more food without contamination by harmful chemicals. Desirably, less chemical residues should be present in food when it arrives at the consumer's dish, and (ideally) any residue should neither contaminate the environment nor harm other species or degrade ecosystems' health and services (e.g., Carvalho, Villeneuve, Cattini, Rendón, et al., 2009; Carvalho, Villeneuve, Cattini, Tolosa, et al., 2009). Thus, applying pesticides becomes a key activity that needs improved control. In many countries, the access to agrochemicals and application methods is still poorly controlled and many farmers misuse the chemicals. Hence, reinforcement of education about the harmful effects of exposure to such chemicals in the population in general, and especially in farmers, becomes essential to enhance food safety (IARC, 2016).

Indeed, it is critical that food producers and manufacturers are responsible for the quality and safety of their products placed on the market (Baron & Brule, 2016), as specified in

the 93/43/EEC Directive of the European Union (EU). To this end, the European Food Safety Authority (EFSA) oversees the food safety for consumers based on the toxicity of pesticides, assessing and ensuring that their residues are under the maximum residue limits (MRL) allowed in food. According to the Regulation of the European Community (EC) 396/2005 and amendments, EU's legislation covers the inspection of MRL of around 1,100 pesticides currently or formerly used in agriculture in or outside the EU, covering the safety of all consumer groups (e.g., babies, children, vegetarians, etc.). Furthermore, in case a pesticide is not specifically mentioned in the legislation, for consumer's protection EFSA assumes as a default MRL value the concentration of 0.01 mg/kg (European Commission, 2018). Additionally, the EU has adopted new policies to control industrial chemicals (REACH initiative) aimed at to achieve improvements in human life quality (EEA, 2013; EFSA, 2016).

Thus, producing and applying pesticides at last becomes an activity in the spotlight of regulatory, public health, and environmental authorities which seems the appropriate pathway for a reduced and controlled use of chemicals in order to protect humans and environment (Figure 1).

7 | ACHIEVING SUSTAINABLE AGRICULTURE: THE BIGGEST CHALLENGE

7.1 | Integrated pest management

Agrochemicals (pesticides, growth regulators and fertilizers) have been widely used since their introduction in conventional food production (Peshin et al., 2009; Stoetzer, 2016). It has resulted in the development of pesticide resistance of target pests, harm to nontarget species such as predators, parasitoids and pollinators, water contamination and overall ecological degradation, food contamination and occupational and public health problems (Palacios-Lazo et al., 2003; Peshin et al., 2009; Stoetzer, 2016). Consequently, due to the lack of pest-resistant cultivars, nonadoption of control measures, and nonavailability of effective bio-control agents, new resistant pests have developed on several crops, while the effectiveness of a number of insecticides has decreased (Palacios-Lazo et al., 2003; Peshin et al., 2009; Stoetzer, 2016).

The biggest failure of pesticides to control pests was reported for 1956 in cotton crop in Peru, Cañete Valley (Stoetzer, 2016), and other documented cases in Sudan and other places (Peshin et al., 2009). In Peru, cotton yields dropped from about 500 to 365 kg/ha, due to disappearance of natural enemies of pests due to insecticide applications, thus allowing pesticide resistant pest populations to continue

to grow. To cope with this, the Farmers' Association of the Cañete Valley organized an integrated pest control (IPC) program with the support of the Government, which included a ban on the use of synthetic organic pesticides, reintroduction of beneficial insects, crop diversification schemes, planting early maturing varieties and the destruction of cotton crop residues right after the season (Peshin et al., 2009). Consequently, farmers were able to reduce the use of synthetic pesticides drastically, and the natural biological control of pests was restored and strengthened by the release of *Trichogramma* sp. wasps, lady beetles and a carabid beetle (Stoetzer, 2016). With these actions, pest problems declined dramatically, and pest control costs were substantially reduced (Hansen & Geyti, 1987). Due to its success, cotton-IPC was expanded to all coastal valleys of Peru, and abroad, under the term of "Integrated Pest Management" (IPM) that means the integration of various control measures, where the least hazardous pesticides are used and only as a last resort, ensuring that crop loss caused by pests remain below the economic threshold (Stoetzer, 2016).

Nowadays, several decades after its first enunciation, IPM is recognized as one of the most robust concepts arisen in the agricultural sciences since the beginning of the second half of the twentieth century (Kogan, 1998) and the base to achieve a sustainable and healthier food production (Pretty & Bharucha, 2015). Based on the analysis of 85 IPM projects implemented in Asia and Africa over the past 20 years, some authors have stated that integrated agriculture allows a reliable transition to zero pesticide use (Pretty & Bharucha, 2015). Furthermore, integrated agriculture has been proposed as the most appropriate system to manage weeds in a sustainable way as an alternative to herbicides (Korres, 2019) and more specifically to glyphosate (PAN, 2018), as this latter would eventually disappear from the market, due to its carcinogenic and genotoxic risks (IARC, 2018). Despite that, to succeed, IPM needs to make use of cultivars with high resilience to stress, and implement pest "managing" instead of "controlling" procedures (Peterson et al., 2018).

The main advantages of IPM agriculture have been stated as: (a) IPM yields are as high as in conventional agriculture. In comparison, yield reductions in organic agriculture production (OAP) average 10%–15% relative to conventional agriculture; (b) IPM reduces drastically the use of agrochemicals (Stoetzer, 2016), therefore, IPM products are available on the market sometimes certified as containing no-detectable residues (NDR) of pesticides; (c) IPM prices are similar to that of conventional agriculture, and therefore, reachable to all publics. In contrast, OAP's high-yield losses are compensated by lower input costs and higher gross margins (Lotter, 2003), which also

means that OAPs are not available to all due to its high price (Gerehou, 2015).

7.2 | Challenges related to consumers' food preferences

Negative impacts of agrochemicals on human health, the environment, and animal welfare have driven an increasing demand for certified OAP worldwide (Baranski et al., 2014; Kyrylov et al., 2018; Oughton & Ritson, 2007; Reganold & Watcher, 2016; Yiridoe et al., 2005), despite their higher prices, compared to conventional and IPM products. Consumers believe that, additionally to their "nonresidues" advantage, OAPs are more nutritious (Baranski et al., 2014; Yiridoe et al., 2005) and tasty (Lotter, 2003; Yiridoe et al., 2005) than those from conventional agriculture, and this believe has sustained the increase of OAP sales and the expansion of organically farmed land in recent years (Willer & Lernoud, 2016). For example, only in the USA, since 1990 the OAPs sales increase 20%–25% per year (Baranski et al., 2014; Lotter, 2003; Oughton & Ritson, 2007; Yiridoe et al., 2005). However, there is no scientific evidence on the nutritional advantage of organic food compared to nonorganic and conventional food, as the concentration of potentially health-promoting (e.g., antioxidants, (poly)phenolics, vitamins and certain minerals) and potentially harmful (e.g., Cd and Pb) compounds (Brandt et al., 2011; Cooper et al., 2011; Dangour et al., 2009; Smith-Spangler et al., 2012) do not differ significantly in comparative studies (OAPs vs. conventional). However, some authors pointed out that statistics and procedures used in these studies remain unclear and a re-assessment should be made (Baranski et al., 2014; Bourn & Prescott, 2002).

Compared to foods grown conventionally, OAPs have proved to contain only one-third of the concentrations of pesticide residues (Baker et al., 2002; Baranski et al., 2014), while in IPM foods such concentrations range between those in organic and in conventional grown foods (Baker et al., 2002; Pussemier et al., 2006). Notwithstanding, OAPs are not completely free of residues of synthetic pesticides. Most residues of pesticides in OAPs come from environmental contamination by former pesticide use, or by "drift" from adjacent conventional nonorganic farms (Baker et al., 2002; Baranski et al., 2014; Pussemier et al., 2006). Additionally, OAPs allow to use biopesticides, which are biocides based on the pesticidal metabolic products of living organisms, which tend to be target-specific, without developing resistance to their effects in the target pest (EPA, 2006; Goettel et al., 2001). Biopesticides have been stated to be innocuous to air and water quality, less destructive to beneficial fauna and less acutely toxic to mammals than conventional pesticides (Quarles, 2011). However, their high-potential risk to

humans has been adverted during the last decade. For example, the active ingredient spinosad (allowed for OAP production in the EU), has been recently shown to act as endocrine disruptor in mammals, as announced by the EFSA (Arena et al., 2018).

Therefore, careful toxicity testing and control need to be applied to all foodstuffs, regardless of how they are produced (González et al., 2019), while the potential risks of biopesticides to the environment, human health, and animal welfare should be also simultaneously and extensively investigated.

8 | EMERGENT CHALLENGES AND POSSIBLE SOLUTIONS TO ACHIEVE FOOD SECURITY

This section describes some possible options to address relevant food security issues, considering them simultaneously as solutions and challenges, because of two main reasons: (a) their associated potential risk, mostly unknown at present, and, (b) the degree of complexity to be applied, which would depend on the specific characteristics of the area, country or region of application in order to assure access, availability and sustainability of food production. For example, in developing countries, there may be additional social and/or technical constraints, which are summarized in Table 4, while proposing possible solutions to achieve this goal.

8.1 | Climate change and social phenomena relationship

Despite several reports showing that globally much more food is produced and supplied than in the past, there is still a big gap between current food needs and food production. This gap must be filled in order to feed the global population and support an active and healthy life worldwide. It has been pointed out that in some regions, climate change events (droughts, flooding, heat and cold waves, etc.) through constraining food production and supply bring about concomitant social phenomena, such as wars and human migrations, among others (Carvalho, 2006).

Borlaug (2000) estimated that food crop production, especially cereals, must increase substantially, by 50% to 2030 and 70% by 2050. Furthermore, if society continues on its current dietary trajectory Berners-Lee et al. (2018) recently estimated that the increase in edible crops required by 2050 will be of 119%. Therefore, beyond satisfaction of food needs that must be envisaged within the food security concept (FAO, 1996), also current agriculture practices need to adapt to climate change. To achieve this goal, a turnaround in research is needed: agronomists should make use of the novel

crop management techniques, and plant breeders should make full use of genetic diversity contained in landraces and heirloom varieties that are still cultivated by small-scale farmers (Dempewolf et al., 2014) and wild plant species closely related to food crops (Guarino & Lobell, 2011).

This effort to increase agriculture production could include more widespread irrigation of land already committed to agricultural production but currently under rainfed conditions. This requires high investments on irrigation infrastructure that in some cases may foster the destruction of natural habitats, deforestation and carbon storage, which, in addition to the rising greenhouse gas concentrations and climate change, might still further impact food and water systems. This interconnection of things renders extremely necessary to consider the implementation of water-saving agriculture technologies (detailed in section 1) focusing on food-energy-water as an interconnected system (Winchester et al., 2018) and its social implications.

8.2 | Food waste

In the pathway to improve food security, losses of produced food must also be taken into account. However, reducing food losses is not a simple task, and to further increase production either by 70% or even 119% (to meet food demands on 2050) is not easy either (Berners-Lee et al., 2018). Most people ignore the magnitude and consequences of food waste resulting from current commercial pathways, resource pressure, on top of crop losses (WRAP, 2009). Gustavsson et al. (2011) calculated that the proportion of cumulative losses of food (lost or wasted) in the chain from production to consumption is approximately one-third of the total food produced. Similarly, Alexander et al. (2017) calculated that the global agricultural dry biomass consumed as food is just 6%, and that up to 44% of crop dry matter is lost prior to human consumption.

High percentages of food produced are lost due to damage during transportation and to poor conditions during food storage. Some of the produced food is jeopardized due to lack of adequate, proper handling and conservation measures (refrigeration, bacterial or even other contamination) before it reaches the final consumer. Therefore, application of accreditation and certification programs to assure a proper management of food products, with a circularity focus—to achieve recycling of resources and eliminate waste at all levels of the food chain—must be envisaged at all steps of the food chain.

8.3 | Integrating agriculture, landscape and human well-being

Environment preservation efforts need to integrate agriculture within the wider landscape, to reduce the negative

TABLE 4 Summary of the main issues to be solved by developing countries in the pathway to achieve food security

Related area	Issue	Consequences	Possible solution
Resources availability	Unequal and/or patchy distribution of (financial) resources	Official organizations unable to perform appropriate research and extension activities. Hence, agriculture research is mostly performed by private industries that restrict the access to proprietary technologies and limit the expansion of the research (Tiwari, 2017). Lack of official extension and advisory services promotes the assumption of this task by agrochemical companies focused in selling their products (pesticides, fertilizers, etc.) instead than providing relevant assistance to farmers (Beyer Arteaga, Rodríguez Quispe, Collantes González, & Joyo Coronado 2017).	Proper allocation of financial resources by governments to allow R + D + I. Whole system needs to change otherwise the agricultural sector (and others) will soon face a critical stage of survival.
	Lack of proper infrastructure and equipment	Deficit of technological–scientific equipment and facilities due to their high cost. It constitutes the main barrier for skilled researchers trained in renowned institutions to apply the new knowledge acquired, often causing a "flight of talents" to developed countries.	Similar to above, promoting Public–Private–Partnership (PPP) to strengthen overall capacity through an equitable effective collaboration to share technology, skills and knowledge. Partnership between public and private sectors/ developed and developing countries can boost the technology potential to achieve food security.
	Low purchasing power of (small-scale) farmers	Scarce or null access to information, technology and training to facilitate decision-making and agronomic management, turning farmers vulnerable to market preferences, climate, information management, among others factors.	Development of social programs and policies aimed in allowing farmers access to recirculating financial aids. Increase farmer's physical and human capital by improving their access to resources, technology, and information.
Education	Illiteracy and/or low educational level of farmers	Restricted or nonaccess to information, causing in turn null or limited capacity-building and knowledge-transfer, and consequently, null technology adoption.	Proper allocation of financial resources by governments to allow development of a proper, high-quality education program at all levels, emphasizing in low-accessible rural areas. Literacy training for rural communities and increased education (with emphasis in women) will increase today's and future's productivity.
	Old-fashioned and poor training of scientists and technicians	Vulnerability to climate change driving food insecurity due to scarce development of crops adapted to environmental stresses. Production does not meet the quality level required by the market and industry.	Promote valuable partnership with renowned organizations with availability of analysis tools and data management, via sustainable capacity-building and knowledge transfer programs. International collaboration can be useful only with a proper legislation system in order to regulate collaborative R + D + I activities, for example, exchange of genetic material.
Land tenure	Small property (representing over 80% of the total agricultural units in developing countries)	Small-scale farming, joined to lack of extension and advisory services among other issues, limits participation of small-scale farmers in the market-share, thus reducing income generation and rentability	Promote social processes that emphasize association and community participation to enhance and stabilize yields, as well as ecological services such conservation of biodiversity, soil and water restoration and conservation, integrated pest management mechanisms, among others (Altieri & Rosset, 2002).

(Continues)

TABLE 4 (Continued)

Related area	Issue	Consequences	Possible solution
Legal framework	Lack of legal framework to enhance and protect food security	Food security unattended due to corruption and (economic) conflicts of interests. Transboundary movement of products whose innocuity needs to be proved—agrochemicals, transgenic products and seeds, among others.	Develop a proper legislation system in bio-safety and germplasm protection in agreement with evolving international policies. Regulate the trade, management and use of agrochemicals and biotechnological products (GMO, mutagenic seeds and produce, etc.) to ensure food security and maintain a healthy competitiveness of the own production in the international market.
Policy making & implementation	Constraints in developing and implementing proper policies due to high level of corruption, short term gains or inappropriate channelling to address key aspects.	Key food security aspects unattended due to corruption and (economic) conflicts of interests, for example, bio-safety and (native) germplasm protection. Lack of regulation on agrochemicals undermines population health due to uncontrolled sale, indiscriminate use and management by farmers, and consumers' exposure to residues in food.	Help official breeding entities to stabilize and protect their germplasm (via Plant Variety Protection) from transnational seed companies. Regulate and monitor residues of agrochemicals and pollutants in food for local consumption in accordance with international standards, via certification bodies. Implementation of a farming supportive program including integrated pest management strategies.

impacts of lack of food (and poverty) and associated social conflicts (Carvalho, 2006; Lundqvist, 2010). This can be seen as part of the strategies needed for a better management of the planet at global scale, but there are other dimensions in this issue, in particular in industrialized countries and urban environments.

Recent population trends show that more and more people live in large cities, mostly in coastal areas, and far from rural and agriculture areas. As a consequence, human behavior is changing and mental diseases and sufferance resulting from social changes have taken a growing share of human diseases.

Studies have demonstrated that being more in contact with nature promotes mental, psychological and physical well-being, thus improving quality of life in a way that cannot be reached by other means (Abraham et al., 2010; Maller et al., 2006; Russell et al., 2013). For instance, it has shown to promote less-aggressive behavior and reduce crime (Kuo & Sullivan, 2001); promote social integration (Kweon et al., 1998) and increase self-confidence and personal or community identity (Horwitz et al., 2001; Maller et al., 2006). Also, access to a naturally integrated landscape promoted physical well-being, such as enhancing recovery after surgery (Ulrich, 1984) and lowering blood pressure (Lohr & Pearson-Mims, 2006); relieving stress (Leather et al., 1998); increasing positive mood (Maller et al., 2006) and reducing mental fatigue (Staats et al., 2003). Similarly, a study based on grey literature by Reed et al. (2017) suggested that landscape approaches constitute a powerful attempt to reconcile conservation and development and improve social capital, enhance community income and employment opportunities while simultaneously reducing land degradation and conserving natural resources. However,

the authors highlighted that comprehensive data on the social and environmental effects of these benefits still remain incomplete.

This integration of agriculture, landscape and human settlements could be a ground of improved social justice, enhanced well-being, and a more balanced way of living compared to the current abandon of rural areas, such as observed in Asia and America, and human migrations from Africa.

8.4 | Understanding and implementing supportive technologies to crop breeding

8.4.1 | Plant breeding leverage

Crop breeding started soon after the rediscovery of Mendel's laws at the beginning of the twentieth century (Mattoo & Handa, 2017). Originally, the application of classical genetics principles through visual selection is defined as *conventional plant breeding*, usually based on yield. However, yield, quality and nutrient and water use, are all multigene traits whose complexity hinders breeding efforts (Parry & Carmo-Silva, 2016). Therefore, conventional breeding needs the use of indicative plant traits which in turn need to be fast, easy, cheap to measure, and consistent (Monneveux et al., 2012). Application of imagery and spatial data analysis gathered via remote-sensing technologies, have demonstrated their potential to reveal those traits in a noninvasive and nondestructive manner (Chávez et al., 2012). During the last decade, progress in plant breeding by combining bioinformatics, modelling

and analytical (mathematical/physics/statistical) work in phenotyping—whose basic concept can be summarized as the description of individuals based on their observable traits—, biotechnological tools in genotyping—determination of genetic differences by examining the individuals' DNA sequence to reveal the alleles inherited from their parents—and other (novel) approaches, has proven—at experimental level—its feasibility to accelerate the selection of desirable traits in crops, thus shortening the time to obtain improved cultivars within a (conventional) crop-breeding program (Thiry et al., 2016).

Merging technologies for high-precision crop phenotyping in crop breeding

Novel technological approaches offering the feasibility of performing nondestructive analysis, have contributed tremendously to accelerate crop breeding. Remote-sensing technology (visible, near-infrared, thermal radiation/image-based analysis) in phenotyping allows for monitoring and detecting biotic (pests, diseases, etc.) and abiotic stresses (drought, nutrition deficiencies, etc.) in crops before symptoms are visible, and therefore, selecting those genotypes with outstanding performance, at small (individual) and large scale (high throughput). Successful results at the experimental phase in potato and wheat have been achieved with the combination of the remote-sensing-based early-stress detection (Chávez et al., 2010, 2012; Chávez et al., 2009) and high productivity and resilience score indices (Thiry et al., 2016) for high-throughput selection of high-yielding genotypes with resistance/resilience to biotic and abiotic stresses (data not shown). An additional advantage of these merged technologies would be the possibility to react before the stress extends over the whole field (Chavez et al., 2012) and the application of IPM, thus contributing with sustainability of agriculture.

8.4.2 | Genomics and development of new breeding techniques

The development of DNA technologies and molecular tools, genome sequencing and applied genomics, allowed the genetic basis for traits of agronomic importance to be determined, which dramatically enhanced the efficiency of plant breeding—thus raising the commonly called new breeding techniques (NBT)—, either via *cisgenesis* (artificially introducing a recessive resistance gene from wild relatives to crops) or *transgenesis* (introducing an exogenous gene—called a transgene—into a living organism so that the organism will exhibit a new property and transmit it to its offspring), thus allowing the development of genetically engineered plants (Peleman & Van der Voort, 2003).

Despite the acknowledged significant contribution of DNA technology since the early 1980s to shortening the time for developing new superior varieties from around twenty to within 5–10 years (Peleman & Van der Voort, 2003), it becomes crucial to get a compromise with the society. Hence, social demands for transparency and proper information from the food industry must be taken into account when alternative technologies are developed and proposed to cope with increasing food demand, as detailed in section 8.7.

Genetically modified organisms

Genetically modified organisms (GMOs) and genetically modified foods are imprecise terms that refer to the use of transgenic crops (Borlaug, 2000) whose genome has been modified to enhance selected characteristics (e.g., resistance to pests, resistance to drought, more productive grains) that can potentially contribute to increased food production (Qaim & Kouser, 2013). Indeed, several authors have stated that transgenic plants can enhance household income and living standards of small-scale farmers in developing countries (Ali & Abdulai, 2010; Kathage & Qaim, 2012), such as adoption of the BT (*Bacillus thuringiensis*) cotton in India, which has significantly improved calorie consumption and dietary quality, reducing food insecurity by 15%–20% among cotton-producing households (Qaim & Kouser, 2013). However, the role of transgenic plants is still under a huge controversy, which in turn is translated into a public reticence and opposition that eventually prevents their more widespread cultivation (Qaim & Kouser, 2013).

Consumption of GMOs is subject to passionate discussions. Experimental studies have shown contradictory results, either demonstrating that consumption of GMOs causes a number of diseases in laboratory test organisms, while others do not show any impact on their health (Novotny, 2018). In many countries, the Precautionary Principle was neglected in the case of GMOs and these have been introduced in farming without convincing evidence about their harmlessness to humans and wildlife. This created a conflict where from the public there is, on one side, rejection to control crops at the cost of unrestricted environmental impact, and, on the other side, a resistance of consumers to foods produced with GMOs because of their potential harmful health effects. Both arguments are based on past negative experiences implying technological developments implemented without precaution.

The long-term research of the European Commission (EC) stated in 2010 that the established technology on transgenics (ETGM) is not per se riskier than conventional plant breeding technologies (CBT). During the last years, the EC has published clarifying information about ETGM, CBT and a growing number of NBT currently being used for food production (European Commission, 2019a, 2019b). Indeed, some of them has been ruled, as the GMOs and crops

developed through the editing-gene technology (section Genome-editing technologies).

Mutation breeding technologies

Mutation breeding, also called mutagenesis, consists in exposing seeds to mutagen factors, either chemical (ethyl methane sulfonate EMS) or environmental (ultraviolet light, ionizing radiation as X-rays, gamma-rays) in order to generate plant mutants with desirable traits (Tanaka et al., 2010). Mutations are generated by spontaneous mutation. The resultant selected mutants—usually called mutagenic plants—are used as parents to be bred with other cultivars in breeding programs.

According to Vives-Valles and Collonnier (2020), organisms obtained by (nontargeted) mutagenesis are not considered as genetically modified organisms GMOs by the European Directive 18/2001/EC (Broll et al., 2019; Ledford, 2019). Independently of that, at present, it is unclear how many varieties coming from mutagenic plants are used in agriculture around the world, as these seeds are commonly not labelled as having a mutagenic provenance (GLP, 2016).

An example of the use of mutagenesis to address food security is the development of a modified variety of rice developed in Vietnam with a shorter life cycle, which allows three crops per year instead of only two, thus contributing to an increased annual rice production (Do, 2009; FAO-IAEA, 2017).

Genome-editing technologies

Genome-editing—also known as gene-editing or genome engineering—is a new type of genetic engineering that allows to insert, delete, modify or replace a given allele in a particular locus of an individual in a precise manner (González-Recio et al., 2017). At present, genome-editing is being rapidly disseminated due to its capability to induce modifications at specific points of the genome, thus conferring a very low incidence of unwanted side effects—compared to earlier genomic technologies that enabled DNA insertions “randomly” only—and its accessibility, as it does not require a significant investment of infrastructure to be applied (González-Recio et al., 2017). This technology does not incorporate transgenic modifications and is far superior to mutagenesis (Georges & Ray, 2017), leading to the development of plants that could also exist by natural means or by conventional breeding techniques (Duensing et al., 2018). Hence, several authors believe that there would be strong arguments to classify and regulate genome-edited crops similarly to conventionally bred crops (Duensing et al., 2018; Georges & Ray, 2017; Ma et al., 2018), and therefore, a potential societal acceptance to this technology (Georges & Ray, 2017; Ma et al., 2018).

Indeed, the US Department of Agriculture of the United States (USDA), as well as Brazil, Argentina and Australia, announced in June 2018 that, as these mutations could have

also occurred in nature, there would be no necessity to regulate gene-edited crops (Ledford, 2019). But, contrastingly, in July 2018, the European Court of Justice (ECJ) ruled gene-edited crops under the same European Directive 18/2001/EC established for GMOs (Broll et al., 2019; Ledford, 2019), therefore restricting the sale of unauthorized gene-edited food crops. At the current state-of-the-art, there is not (yet) a straightforward way to detect the few DNA bases altered in gene-edited crops—in contrast with conventional GMOs in which long stretches of DNA are transplanted from one species to another—, thus turning these gene-editing alterations indistinguishable from naturally occurring mutations (Ledford, 2019). Certainly, this EC decision pushes plant scientists to find a time and cost-effective method to evidence the “imperceptible” gene-editions in food crops, as their presence in the international market poses the risk that a gene-edited food could eventually reach the supermarket shelves in those countries where they are not explicitly regulated and/or approved.

8.5 | Enhancing the use of underutilized crops and resources

Underutilized crops as legumes, roots, Andean cereals and other neglected crops, are a proven food source of high-nutritional value (Cullis & Kunert, 2017) that could help to meet the challenge of achieving food security in the near future. For instance, quinoa, an Andean cereal cultivated since before the Inca's Empire in Peru and Bolivia, has been globally recognized as a key crop to eradicate hunger, malnutrition and poverty, due to its high-protein content, thus being cultivated nowadays also in the USA, Europe, Africa (Kenya) and the Himalaya region, among other areas around the world (FAO, 2013). We need more success stories, such as this of quinoa, to achieve a sustainable food production, especially in terms of protein sources, in order to cope with its increasing demand from the continuous growing population.

Several attempts to provide with protein sources for animal and human consumption have been proposed. However, the per se nature of the approaches has not always matched with consumers' preferences. A good example is the in vitro cultivation of cells of beef-meat, for example, to create an edible burger, proposed by a research study developed by Maastricht University in 2014 (Tian et al., 2016). Although with higher acceptance, the combination of plant sources—currently soy, wheat, rice, corn, peas, canola and potato—in order to achieve adequate essential amino acid profiles, has also raised concerns, due to the fact that plant protein utilization at large scale means an increase of cropping-land for these crops, thus cancelling the benefits of the reduction of the environmental impact by using vegetal instead of animal food sources (Marinero, 2018).

In the last decade, there has been a worldwide rediscovery of insects as a source of proteins, which eventually may contribute to turn some agricultural pests into usable food. Consumption of insects as staple food has been present throughout history in Asia, Africa and Americas, but was forgotten in contemporary western civilization. A recent “rediscovery”, more or less at the same time in Canada and The Netherlands in early 2010s, called attention on edible insects as an important protein source (Tian et al., 2016; Van Huis, Dicke, & van Loon 2015; Van Huis, Van Gurp, & Dicke 2014), that achieved global recognition source by FAO in 2015. In Peru, insects were long time used as a common food source by native communities from the Amazon region. Currently, the Demolitor project of the National Agrarian University La Molina is promoting insect-based food in form of energetic cacao-cereals bars. These are made with flour of *Tenebrio molitor* (Insecta, Coleoptera) as main ingredient, which provides twice the Fe content compared with meat, combined with native cereals, such as quinoa (*Chenopodium quinoa*) and kiwicha (*Amaranthus caudatus*), and has shown great acceptance by consumers in the whole country (Toribio-Chahua, 2019).

8.6 | Sustainable agriculture coping with above-mentioned challenges

Achieving a sustainable agriculture that embraces all the above-mentioned challenges is not an easy task. Several authors concur that IPM—also named integrated agriculture—is the most suitable option to achieve the goal of producing healthier, safe food to satisfy global demands (Farrar et al., 2016; Peshin et al., 2009; Reganold & Watcher, 2016; Stotzer, 2016) as it represents economic and ecological sustainability (Peterson et al., 2018).

The permanent threat of pests in the agricultural, medical, and commercial sector has three main effects, commonly underestimated. These are (a) introduction of new pests into regions where their natural controllers are not present; (b) pesticides' resistance developed by pests, thus pushing to the use of higher doses and/or a different (usually more toxic) pesticide; (c) detrimental effects of pesticides on health, either by occupational or nonoccupational exposure. *Xylella fastidiosa*, a vector-borne plant pathogenic bacterium native from the Americas that causes dramatic losses in several crops such as grapes, citrus, olives, and stone-fruits, and recently (2013) reported in Europe (Italy, France, Spain and Portugal), is an example of these above-mentioned points. As *X. fastidiosa* is transmitted by Hemiptera insects (spittlebugs, cicadas and sharpshooters) that feed (almost) exclusively on xylem vessels (Morente et al., 2018), Hemiptera insects with this characteristic in the new infected areas of Europe represent a risk of bacterial

transmission, as in the Balearic Islands, Spain. There, farmers have increased the frequency of pesticide application to control the potential vectors, exposing themselves to the effects of these products on health, and imposing a selection pressure on insects, while (new) phytosanitary products are being tested and developed at global level by the industry to cope with this plant pathogen. Hence, these three points seem to trigger the development of new toxic molecules, thus creating a sort of never-ending pesticide cycle—a toxic (pesticide) molecule followed by a more toxic molecule, which in turn is followed by an even more toxic molecule, and so on. This cycle of pesticide—resistance—new-pesticide, has been long-known and shown not to be a pest control solution.

Reducing the use of agrochemicals in food production, while reducing dietary exposure to synthetic chemicals, for example, pesticide residues, is an important goal of public health and environmental authorities. Indeed, a market for alternatives to chemical pesticides has been created (Quarles, 2011a, 2011b, 1993a; Rey, 2016; Weston et al., 2004). For example, in the last decades, beneficial nematodes, bacteria as *Bacillus thuringiensis* (BT), and a number of products derived from fungi and viruses have been developed for use as allies in crop protection within greenhouse, turf, field, orchard and garden crops (Butt et al., 2001; EPA, 2006; Grewal et al., 2005; Hom, 1996). All these are important assets to developing a sustainable agriculture.

8.7 | Increasing access to education, information and technology

Scientists make their best to develop novel science and technologies in order to provide a solution to global food security issues and achieve the objectives of SDG-2030. However, the new techniques often do not get consumer's acceptance easily. A study conducted by Frewer et al. (2011) revealed that the reason for lack of confidence on new food technologies is mainly due to consumers' lack of knowledge on the technologies per se, and due to fear on consequences of their applications. Especially those technologies that interfere with the genomes, such as the genetically modified crops and derived foods, are the ones that raise most of consumers' concerns (Frewer et al., 2011). According to Tian et al. (2016), in consumer's attitude a consumer decision is largely influenced by personal experience and by messages spread by social media, and both are imbedded of a great deal of subjective and emotional judgement. To achieve a rational consumer's understanding and acceptance, there is a lot to do in terms of education and information regarding advances in science and technology, which would imply the translation of scientific language into a colloquial, more in-use language, in order to achieve an effective knowledge-transfer at all levels of society.

Quality education, together with access to technology and information, represent key tools for society to thrive at every location, raising human capital and reinforcing economic growth. It refers to education in all its forms, that is, formal and informal, comprising extension, capacity-building, knowledge transfer and management. Information and Communication Technologies (ICTs) constitute a supportive tool to life sciences to bring out benefits in the near future (Frech, 2017), allowing reinforcing education of farmers about the entire agro-ecosystem, in order to get a better management of water, soils and crops.

As seen in previous paragraphs, present approaches of novel science and technology offer the means to succeed, although demand the implementation of an educational program focused on knowledge transfer and research at all levels of the food chain. EU activities against *X. fastidiosa* are an example of this, as they include, in addition to the surveillance and eradication/containment programmes (Regulation EU-652/2014), the implementation of knowledge transfer activities and the use of advisory services (Regulation EU-1305/2013) for farmers, and research activities to cope with them, as the POnTE, X-factor and other (pilot) projects conducted in the framework of the HORIZON-2020-EU program (European Commission, 2019a, 2019b). This complementarity underlines the high importance of the multi, inter and transdisciplinary teams in research, development, and innovation activities stated above.

Similarly, current research on potato constitutes an example of how novel science and access to technology approaches can boost food security. Scientists consider potato as a difficult crop to breed since its tetraploid genetic characteristic confers a low chance of inheriting desirable alleles in all four copies of chromosomes, compared to diploid species that have only two copies of chromosomes. Thus, potato breeders are nowadays developing diploid potato varieties via parental inbreeding, similar to that used in hybrid maize production (Stokstad, 2019). The diploid condition increases the likelihood of obtaining a highly stress-resilient and nutritional potato by introducing genes from wild relatives to the cultivated potato in about a half of the time required by conventional breeding means, which also allows the use of true potato seeds for sowing (Stokstad, 2019). The latter would enable the cultivation of the crop in poorly accessible areas of the Peruvian Andes highlands and elsewhere (Stokstad, 2019). The project is conducted with the engagement of native Andean communities in Peru, including a knowledge-transfer and capacity-building program using ICTs, which indeed increases the likelihood of success.

9 | CONCLUSIONS

During the last century, novel scientific and technological advances in food production have profoundly affected human

nutrition and health, the environment and wildlife globally. On the positive side, wheat production has almost doubled over the last 50 years supporting the population growth. Behind this achievement lays the work in different disciplines, and this work continues daily.

In spite of this, we realize today that agriculture and food production suffer with several issues and do not seem to be able to meet the challenge of producing more and healthier food for the current and future generations.

From the data reviewed across this manuscript, it is concluded there are four main themes that need to be addressed in priority, taking lessons from the past to rethink and formulate new directions.

The first theme is the use of synthetic pesticides. The poisoning of soil and water and biodiversity losses, together with human health deterioration, are more than enough to demonstrate this is not a good path. IPM must be implemented everywhere to reduce applying synthetic pesticides without losing food production, thus enabling a simultaneous development of new environment-compatible food production strategies.

The second is the misuse of fertilizers that have too high-environmental costs and compromise drinking water quality and life in vast areas of the oceans. To pursue the same avenue will not bring a better future. We need to reassess, regulate, and make a better use of fertilizers and because this issue has already significant transboundary environmental impacts, the solutions must be agreed and implemented at global level.

The third is the need for strengthening genetic resources, that is, maintaining germplasm banks and adopting more suitable varieties and landraces in a wise and wide consensus.

The fourth theme is the need to achieve efficient plant/crop-breeding programs, strengthening the inclusion of genetic resources through a wise and prudent use of the new breeding technologies to develop highly resilient and productive crop varieties able to cope with both environmental stresses and consumer/market preferences.

Nonetheless, science and technology alone will not succeed to meet these challenges. Across these complex issues, education must prevail as the key to provide people with healthier, safer food in a sustainable fashion. In developing countries, knowledge transfer is needed to improve agriculture and feed people, provide better health and fix populations in their regions, preventing at the same time wars and mass migration that do not help achieving social justice. Likewise, in developing and developed countries, dissemination of knowledge can help to reach wider consensus on topics that remain as causes of societal unrest, as for example, GMOs.

Finally, thorough application of the Precautionary Principle must be present and transversal to all these areas to avoid unwise and careless initiatives like those in the past that

have caused destruction of the environment. Having a future depends on healthy and functional ecosystems.

To succeed, the scientific and technological progress clearly requires also adequate action by regulatory authorities and governments, concerted at local, national, regional and international level, aiming at environmental and social justice.

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CONFLICT OF INTERESTS

The authors declare no conflict of interests.


ORCID

Perla N. Chávez-Dulanto  <https://orcid.org/0000-0003-2057-4565>

Arnauld A. A. Thiry  <https://orcid.org/0000-0001-8908-7082>

Patricia Glorio-Paulet  <https://orcid.org/0000-0001-9236-8141>

Oliver Vögler  <https://orcid.org/0000-0002-9234-1456>

Fernando P. Carvalho  <https://orcid.org/0000-0002-6639-6138>

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