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Foreword

The perspective of this work includes discussion of the interactions between sustainable agricultural chemistry and biotechnology, nanotechnology, and other technologies that are on the frontier of knowledge and are associated with increasing production and productivity. It includes trends related to carbon dioxide reduction, water treatment, green chemistry, biorefineries and the bioeconomy from a sustainable point of view, taking into account the United Nations' sustainable development goals. Additionally, opportunities and challenges arising from sustainable agricultural chemistry for the 21st century are pinpointed and evaluated. The agricultural sector is dynamic in its outcomes, production and productivity; since each country has its own peculiarities, specific challenges may arise, and opportunities can change in short or long-term.

The objective of this perspective is to define sustainable agricultural chemistry and to describe the relevance of chemistry for modern agriculture. Furthermore, scenarios and challenges are evaluated to promote a better understanding of ongoing opportunities in this research & development theme.

Guy de Capdeville
Head of Embrapa Agroenergy

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Introduction

In the 20th century, more precisely, after the Second World War, the evolution of agriculture reached one of its most important hallmarks in what became known as the Green Revolution. This period was based on a set of agricultural practices and techniques based on the introduction of genetic improvements in plants and the evolution of agricultural production apparatuses to expand, above all, food production (Pingali, 2012).

Although the Green Revolution is heavily criticized for its environmental impacts and the process of land concentration that accompanied its evolution due to policies that were used to promote the rapid intensification of agricultural systems and increase food supplies (Pingali, 2012), its importance for the development of agriculture in the world is undeniable. Furthermore, improvements resulting from novel technologies in the following decades, such as biotechnology, are still increasing agricultural productivity.

Table 1 describes the main crops cultivated worldwide and their production. These values would not be achieved without the use of agrochemicals, brought to the scene by the Green Revolution.

Table 1. Global production of the five major crops.

Crop	Production, in thousand tons
Sugarcane	1 877 110
Maize (corn)	1 016 740
Rice	745 710
Wheat	713 183
Potatoes	368 096

Source: FAO (2015).

Currently, agriculture must constantly become increasingly more sustainable, with the reduction in its negative impacts on the environment being matched with the demand to increase its positive impacts on society and the economy.

These are challenges and, at same time, opportunities for new production systems.

The United Nations (2019) established 17 sustainable development goals to promote sustainable global growth. Goal 2 (zero hunger) is closely related to agriculture and food security; according to this goal, “a profound change in the global food and agriculture system is needed if we are to nourish the 815 million people who are hungry today and the additional 2 billion people expected to be undernourished by 2050.” Thus, agriculture has a paramount responsibility to find ways to provide food for such increasing demand in the years ahead. At the same time, devising ways to reduce impacts associated with agricultural production that could be considered harmful to the environment is also key.

Chemistry and Agriculture: A Direct Relationship

The contribution of chemistry to agriculture goes back to the 19th century, with the synthesis of inorganic fertilizers and of, by the middle of the last century, a large number of compounds synthesized to control insects, diseases and weeds (Pinto-Zevallos; Zarbin, 2013).

This contribution is clearly and decisively observed in the cycle of nitrogen, an essential element to most molecules that integrate organic matter. Plants, with some exceptions, do not have the capacity to absorb this element from the atmosphere (with 78% nitrogen), the opposite of what occurs with another essential element, carbon, which is absorbed as CO_2 via photosynthesis. The only natural way to close the nitrogen cycle is through the decomposition of organic material from dead animals or plants or through excretion from living things; this form of replenishment is naturally limited (Killops; Killops, 2013). Another natural method, the biological fixation of nitrogen from the atmosphere by some microorganisms and its later release as part of organic matter, although of utmost importance to maintain life on the earth, does not suffice to add nitrogen to meet the high demand presented by modern agriculture.

The capture and use of atmospheric nitrogen in the soil has only been economically possible via the works of the German chemists Fritz Haber and Carl Bosch. They developed the Haber-Bosch reaction or process at the beginning of the 20th century (Ritter, 2008), a reaction that allows the synthesis of ammonia from low-reactivity atmospheric nitrogen and another abundant element, hydrogen, on the industrial scale. Curiously, the incentive that led to this essential innovation was not initially the production of fertilizers but the production of nitrates for military purposes (explosives) to be used in World War I.

Ammonia, a molecule with approximately 82% nitrogen by weight, can be absorbed by plants through the soil after intermediation by microbiological processes that produce ammonium and nitrate. Due to the ease of application, the use of solid substances derived from ammonia, such as urea and ammonium nitrate, as a nitrogenous fertilizer is preferred. The world production of ammonia today reaches approximately 140 million tons per year (United States Geological Survey, 2017), and almost all global production is intended for the synthesis of industrial fertilizers. The percentage of the world population whose food depends on the use of synthetic nitrogen fertilizers is estimated at 53% (Liu et al., 2016).

Taking nitrogen fertilizers as an example, we can conclude that so-called organic farming, which advocates for the exclusion of synthetic fertilizers, can function as a niche market in societies of abundance, but it is certainly not an alternative to feed the entire human population. This example clearly shows the contribution of agricultural chemistry to the well-being of modern society.

Agrochemicals and their Usages

According to Stephenson et al. (2006, p. 2082), an agrochemical is an "*agricultural chemical used in crop and food production, including pesticide, feed additive, chemical fertilizer, veterinary drug, and related compounds*". Currently, we can observe several agrochemical classes according to their uses in agriculture (International Union of Pure and Applied Chemistry, 2019)

- Fertilizers - *any kind of substance applied to soil or plant tissues to provide one or more nutrients essential to plant growth*;
- Plant growth regulators - *(also called plant hormones) - several chemical substances that profoundly influence the growth and differentiation of plant cells, tissues and organs*; and

- Phytosanitary products, pesticides or correctives: *herbicides, insecticides, fungicides, acaricides, bactericides, rodenticides, nematicides, repellents, fumigants, disinfectants, antibiotics, defoliants, and algaecides (or algicide)*.

Agrochemicals move a huge global market that is expected to reach 250.5 billion USD by 2020 (Statista, 2018). However, agrochemicals are one of the main classes of chemical pollutants, with serious negative impacts on public health and the environment (Public..., 1990; Nicopopoulou-Stamati et al., 2016). The search for alternatives to conventional agrochemicals presents itself as an excellent opportunity for the development of sustainable agricultural technologies and for opening new businesses.

Impacts of Agriculture on the Environment and Health

Governments, farmers and consumers show increasing concern related to the negative impacts of the large amount of inputs applied to produce different crops in different regions around the world on the environment and health. Agrochemicals are directly correlated to damage from agriculture, with pesticides with toxicological implications being the main representative class.

In general, the main negative impacts of agriculture on the environment are:

- Water, soil and air pollution due to pesticide applications;
- Depletion of water bodies due to high water demand;
- Erosion and soil degradation due to inadequate management during cultivation;
- Change in biota due to factors already listed;
- Changes in the quality of environmental resources also due to factors already listed;
- Ecological risks for insects, plants and animals associated with the change of the environment; and

- Climate change due to deforestation and biomass combustion.

Regarding the impacts on health, the following can be highlighted:

- Poisoning due to pesticide use and contaminated food consumption;
- Occupational risks to farmers due to the exposure to pesticides; and
- Human infections or emerging infectious diseases that do not respond to treatment due to the use of antimicrobials in agriculture (Grace, 2019).

From these negative impacts, the development of more environmentally conscious and health-friendly agriculture is becoming paramount.

Sustainability and Agricultural Chemistry

Agricultural chemistry is, undoubtedly, one of the fields of research and business whose impact is felt throughout the world, since we all need to eat to survive. Added to this is the fact that, increasingly, technology is intertwining with modern agriculture both regarding new production strategies and the reduction of negative environmental impacts (Herman, 2015).

Sustainability can be seen and understood by means of its three components: environmental impacts, economic impacts, and societal impacts.

Impacts can be positive or negative according to their direct or indirect effects upon the environment, economy and society. Considering that agrochemistry is the application of chemistry and its concepts and technologies to promote better agriculture, economic and societal impacts are expected to be positive, especially the economic impacts. On the other hand, and due to a history of incidents at the global level, environmental impacts are expected to be negative; nevertheless, they could be positive if modern technologies and good agricultural practices are used. A more detailed evaluation of sustainability in agriculture can be seen in Quintero-Angel and González-Acevedo (2018).

Sustainable chemistry, a recent branch of chemistry, was defined as "*(...) a scientific concept that seeks to improve the efficiency with which natural resources are used to meet human needs for chemical products and services. Sustainable chemistry encompasses the design, manufacture and use of* *efficient, effective, safe and more environmentally benign chemical products and processes.*" (Organization for Economic Co-operation and Development, 2019a). From these statements, a relationship with agricultural chemistry can be constructed by means of the *design, manufacture and use of efficient, effective, safe and more environmentally benign agrochemicals. That is, it can be achieved by the establishment of a strong innovation drive in agriculture for the next decades. Furthermore, goals 9 and 12 for the sustainable development depict the necessity of industry, innovation and infrastructure allied to responsible production and consumption* (The United Nations, 2019).

New Technologies and Trends

Some areas of recent technological development closely related to agricultural chemistry have a direct impact on agriculture, and their usages represent trends to be considered in both the short and long term.

Figure 1 depicts the relationship between agricultural chemistry and related scientific and technological fields as an interdisciplinary theme.

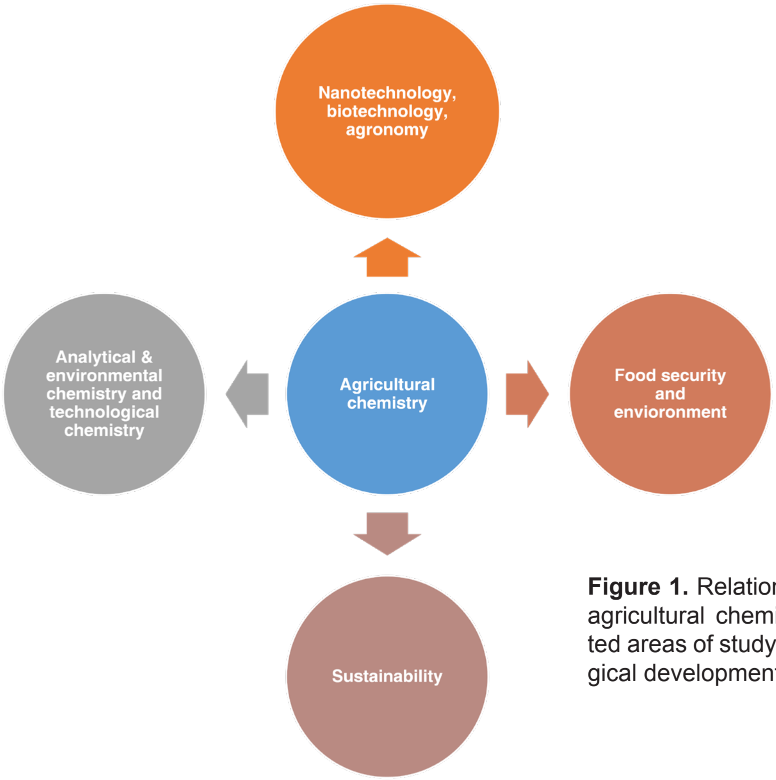

Figure 1. Relationship between agricultural chemistry and related areas of study and technological development.

Analytical & environmental chemistry can provide technological chemistry input techniques, technologies and knowledge that could be essential to analyze, produce and monitor more efficient agrochemicals. Nanotechnology and biotechnology are new technological approaches that can be incorporated to improve agrochemicals aiming for better agronomic performance. Food security and the environment are closely related to agrochemical use and near to the consumer, involving laws, market restrictions and public opinion. Finally, sustainability is a strong demand by society for better quality of life and greater transparency in the productive chain.

Biotechnology

Biotechnological approaches for agriculture take into account the improvement of plant species and plant transformation mainly by means of genetic engineering tools. Moreover, the genetic improvement of microorganisms can be used. Moshelion and Altman (2015) described the main issues to be treated by biotechnological approaches in agriculture:

- Contribution of new plant biotechnological tools to advanced crop breeding;
- Bottlenecks holding back the translation of genomic data to crop plant traits (i.e., the genotype–phenotype gap);
- Plant adaptation and tolerance to abiotic and biotic stress for sustainable agricultural production;
- Role and significance of epigenetics for plant development under changing environmental conditions; and
- Plant biomaterials and biofuels as a novel scope of agricultural biotechnology.

Tools, such as OMICS (genomics, transcriptomics, proteomics, metabolomics) for molecular screening (e.g., secondary metabolites, genetic profile) and CRISPR/Cas9 for genome editing in plants to increase certain compound production, are frequently used (Corujo et al., 2018; Okuzaki et al., 2018). Here, the contribution of analytical chemistry by means of mass spectrometry combined with liquid chromatography (mainly) or gas chromatography to generate experimental data to obtain reliable information for evaluation is clear. Analytical chemistry allied with chemometrics can help in the extraction of the best data for OMICS. Furthermore, it can be associated with spectroscopic techniques, such as ^{1}H and ^{13}C NMR (COSY, HSQC and HMBC) for molecular structural resolution, as in the case of the study of the effects of the allelochemical coumarin in adult plants of *Arabinopsis thaliana* (Araniti et al., 2017).

Currently, synthetic biology is increasingly relevant. For instance, a plant synthetic biology approach can improve sorghum nutritional value by means of the synthetic β-kafirin gene enhancing the protein digestibility by up to 21% in grain (Liu et al., 2019). Furthermore, this approach could be closely related to biorefineries and bioeconomy (as discussed later) to produce renewable chemicals.

Genetically modified organisms (GMOs) can be viewed as the main biotech innovation in agriculture in the last decades. This approach of genetic manipulation promotes the insertion of genes of resistance (e.g., from a bacteria) inside the plant, promoting a defense against certain types of insects. An example is the Bt technology: *Bacillus thuringiensis* (Bt) bacteria are insect pathogens that rely on insecticidal pore forming proteins known as Cry and Cyt toxins to kill their insect larval hosts. The expression of certain Cry toxins in transgenic crops has contributed to the efficient control of insect pests resulting in a significant reduction in chemical insecticide use (Bravo et al., 2011). However, the use of this technology is quite controversial, mainly for foods, and studies are ongoing to confirm the absence of risks to public health due to the potential allergenicity of proteins newly introduced in food components (Batista et al., 2005).

Anderson et al. (2016a) also pointed out themes that demand advanced technology by means of a biotechnological approach, such as nitrogen use efficiency, drought tolerance, combined technologies and salt tolerance.

Nanotechnology

Nanotechnology has emerged as a strong new frontier of knowledge to be applied in many sectors from health to agriculture, with a strong collaboration with chemistry. Moreover, nanotechnology, as in the case of biotechnology, is a theme of technological development related to the bioeconomy concept (see ahead). Particle dimensions in the range of 1-100 nm (International Standard Organization, 2008) can confer some interesting molecular properties to be explored in several applications such as, surface area, porosity, structure, crystallinity, size distribution, surface charge, surface speciation, among others (Hassellöv; Kaegi, 2009).

For agricultural purposes, nanotechnology can be applied in the following situations (Parisi et al., 2015):

- Crop protection: plant protection products and fertilizers;
- Plant breeding: plant genetic modification;
- Diagnostic: nanosensors for plant health and growth, as well as for environment and soil conditions evaluations;
- Soil improvement: water/liquid retention; and
- Water purification and pollutant remediation.

Two classes of nanoproducts deserve a better consideration due their potential for innovation and market value:

- Controlled-release agrochemicals: carriers of organic and/or inorganic materials whose surfaces serve for the adsorption and subsequent release of active compounds (e.g., pesticides and semiochemicals), leading to an improved efficacy of agrochemical formulations, which makes them a focus of great interest in academic and industrial research. Examples of these materials currently under study are clays, silicates, carbonates, metal hydroxides, cyclodextrin, chitosan, bio-coal, lignin and synthetic polymers (Yusoff et al., 2016). The desired characteristics for a given material to be used as a support for agrochemicals are biodegradability, biocompatibility, low toxicity, simplified preparation process, promotion of slow release via nanoencapsulation and low mobility in soil (Yusoff et al., 2016).
- Nanofertilizers: macronutrients (e.g., P, Ca, Mg) and micronutrients (e.g., Fe, Mn, Zn, Cu, Mo) can be prepared as nanoparticles (e.g.,

apatite, calcite, superparamagnetic Fe oxide, metallic Mn, Zn oxide, among others) and can enhance plant-growth in certain concentration ranges. These could be used as nanofertilizers in agriculture to increase agronomic yields of crops and/or minimize environmental pollution (Liu; Lal, 2015). Rios et al. (2019) describe the use of membrane vesicles obtained from *Brassica oleracea* L. as nanobiocarriers of Zn and the evaluation of their potential as a foliar fertilizer, also in *Brassica*. The results show high Zn encapsulation efficiency and high delivery into protoplasts. Additionally, the foliar fertilization experiments demonstrated a very effective system of Zn for plants.

It is expected that agrochemical nanoformulations can provide controlled release to achieve complete biological efficacy without the risks of overdosage (Iavicoli et al., 2017). For instance, Oliveira et al. (2014) observed that the nanoencapsulation of botanical insecticides offers considerable potential for increasing agricultural productivity while at the same time reducing impacts on the environment and human health.

Nanotechnology and biotechnology can be joined to create nanobiotechnology. Examples include nanomaterials-based biosensors and their application in water management, a source of concern in the present and future for agriculture: the observation of harmful algal blooms to understand microbe–environment interactions and allow toxin/pollutant detection with significantly improved sensitivity (Gellert et al., 2018). The authors developed a hydrogel-based array nanoliter habitat system for studies of microalgal growth kinetics. This kind of assemblage can expand the technological and market opportunities of nanotechnology in agriculture.

However, aspects of toxicology related nanoparticle usage and disposal in agricultural/food production need to be take into account. To carry out this evaluation, transcriptomics, proteomics and metabolomics remain the most common techniques and methods, with the discovery of nanospecific toxicity pathways and biomarkers being a prioritized goal (Costa; Fadeel, 2016). Nevertheless, Servin and White (2016) observed that the existing literature is somewhat contradictory, and it is notable that the overall findings seem to suggest low to moderate toxicity to terrestrial plant species. Thus, an ecologically relevant systems approach is needed that includes environmentally realistic studies with sensitive endpoints.

Natural products

Natural products (NPs) comprise those chemicals extracted from plants and microorganisms produced by their secondary metabolism (Seigler, 1998). In a simple understanding, their application in agriculture (e.g., as pesticides) follows a renewable pathway where the natural product obtained from plants can be used to protect other plants against their enemies – the strategy of Nature. Cantrell et al. (2012), analyzing the EPA registrations of new pesticides during the period of 1997–2010, observed that NPs play an important role in the discovery and development of new pesticides.

Considering that pesticides from synthetic routes are responsible for several disasters worldwide which compromise health and the environment, the use of a natural approach is a proposal to reduce the negative impacts, the amount of synthetic agrochemicals applied and to increase the sustainability of agriculture. However, NPs may also present toxicity and risk to the environment and health. As an example of NPs usage, the application of semiochemicals can be highlighted (Eljarrat; Barceló, 2001; Reddy; Guerrero, 2004; Anderson et al., 2016b). These are mainly obtained from plants for the integrated pest management (IPM) of insects, weeds and other pest agents (Stenberg, 2017). Probably the most important physicochemical property for NPs to be used in IPM is vapor pressure, as it defines its volatility, due to the interaction with pheromones present in insect communication (Buss; Park-Brown, 2006).

NPs can be joined to nanotechnology to expand their application possibilities. For instance, the use of the nanoencapsulation of active biomolecules to improve their performance by means of controlled release in agrochemical applications is a promising technology for agriculture (Hack et al., 2012).

Green chemistry for agrochemical production and use

Green chemistry (GChem) emerged in the 1990s as a new philosophy in academia and industry to break old paradigms of chemistry, such as large waste generation and intensive use of petrochemicals, through a holistic view of processes in laboratories and industries (Anastas; Warner, 2000; Anastas; Kirchoff, 2002). This approach, described in 12 principles, proposes consideration of, among other aspects, the reduction of waste generation, the atomic and energy economy, and the use of renewable raw materials.

These principles, which promote clean production and green innovations, are already relatively widespread for industrial applications, such as the production of agrochemicals, particularly in countries with a well-developed chemical industry and with strict control over the emission of pollutants (European Commission, 2013). They are based on the assumption that chemical processes with potential to negatively impact the environment will be replaced by less polluting or nonpolluting processes. Clean technology, reduction of pollutants at the source, environmental chemistry and GChem are denominations that have emerged and were minted over the last two decades to translate concerns for chemical sustainability (Sheldon, 2014). Then, it is expected that the application of GChem principles will reduce deleterious effects from the production of agrochemicals.

O'Riordan (2018) describes the application of GChem in each stages of agrochemical industry comprising chemical research, analytical chemistry, manufacture, formulation and product safety in order to achieve the UN sustainable development goals (The United Nations, 2019). From this statement, we can observe the relevance of GChem to the agriculture chemistry for the production of less toxic agrochemicals.

Currently, we can observe some relevant challenges to agricultural chemistry which could be overcome with a contribution from GChem:

- Development of environmentally friendly agrochemicals with a reduction in the toxicological activity of these molecules and their degradation without the generation of hazardous byproducts;

- Reduction in or elimination of risk to the environment and public health as a consequence of the reduction of toxicological activity;

- Greater effectiveness *versus* reduced application to generate the best dose-response relation to reduce environmental and human risks due to the exposure to pesticides;

- Design and synthesis of green molecules according to the 12 principles of GChem; it is not easy to obey all of them, but always consider the maximum number of principles when possible;
- Release standards in the environment (e.g., coefficient of partition) and procedures based on reliable scientific data, taking into account the specificities of each country, according to requirements of the Food and Agriculture Organization of the United Nations (FAO) and World Health Organization (WHO) (World Health Organization, 2019);
- Presence of emerging pollutants (e.g., antibiotics) that represent a potential risk for environment and health which are not yet well understood;
- Nanotechnology *versus* nanotoxicology; there is not enough data to support the understanding of the agrochemical toxicological properties on the nanoscale.

Moreover, aspects of industrial ecology are desirable to be considered (Manahan, 2005). We can observe disposal pathways as well as recycling and reuse pathways. The disposal takes into account the raw material and the process of fabrication, producing residues to be treated by the most adequate technology. On the other hand, recycling and reuse will take into account the process of fabrication and the use of the final product.

CO_2 emission

The reduction in carbon dioxide (CO_2) emissions from agricultural activities is an issue related to warming and climate change because agricultural systems emit this gas from the usage of land (Anderson et al., 2016a; Ruane et al., 2018). Thus, low-carbon agriculture is a requirement inherent to the 21th century.

According to the FAO (2019), the land-use conversion and soil cultivation have been an important emission source of greenhouse gases (GHGs), such as CO_2, to the atmosphere; it is estimated that they are still responsible for about one-third of GHG emissions. The Intergovernmental Panel on Climate Change (2014) estimates that agriculture, forestry and other land use are responsible for 24% of the global GHGs emissions by the economic sector; here, we can consider the cultivation of crops and livestock and a possible association with deforestation; losing only to the electricity and heat production (25%). However, agricultural ecosystems can capture CO_2 from the atmosphere by sequestering carbon in biomass, dead organic matter, and soils, which offset approximately 20% of emissions from this sector (United States, 2019a).

A strategy for a low-carbon agriculture can comprise (Embrapa, 2019):

- Recovery of degraded pastures;
- Integration of crop-livestock-forest and agroforestry systems;
- Direct planting systems;
- Biological nitrogen fixation;
- Planted forests;
- Treatment of animal waste; and
- Adaptation to climate change.

These strategies depend on the characteristics of each country (i.e., availability of soil and water, climate, value chains, etc.). However, we can note common opportunities for R&D and innovation, mainly those related with environmental chemistry to understand the ultimate fate of chemicals. Moreover, goal 13 of the sustainable development is associated with climate action because climate change is affecting every country on every continent (The United Nations, 2019).

Water management

Clean water and sanitation is the goal 6 of the United Nations' sustainable goals (The United Nations, 2019). Currently, water suffers a high negative impact from agricultural activities due to its extensive use for crops and livestock production. World agriculture consumes approximately 70% of the fresh water withdrawn per year (Unesco, 2019). Moreover, its quality and potability is compromised by the presence of pesticides and emerging pollutants from livestock activities (Vaz Jr., 2018a).

The optimization of water use is paramount for sustainable agriculture, for which we can apply reuse and treatment strategies (United States, 2019b). Recycled water is of special interest for agricultural purposes because it decreases wastewater discharges and reduces and prevents pollution associated with technologies for a reduction of consumption, as per the calculation of net irrigation based on effective crop water requirements (Organization for Economic Co-operation and Development, 2019b).

Finally, there are some general strategies for water management in agriculture:

- Monitoring and control of the presence of metals, organic chemicals and microorganisms in surface water and groundwater;
- Establishment of security plans for the case of pollution events;
- Treatment plants for residual water, mainly those from pesticide applications;
- Control of the use of pesticides, fertilizers, etc., in the field;
- Reuse and recycling; and
- Optimization.

As for CO_2 emission control, environmental chemistry is very relevant to maintain water security because it provides scientific and technological knowledge.

Biorefineries

The concept of the biorefinery is still young and has a somewhat daring objective: to replace products and processes based on sources of nonrenewable raw materials, especially petroleum, for products and processes that use biomass as a raw material. In this context, the development of new technologies that lead to the utilization of the full economic and energy potential of biomass is relevant, and consideration should be given to the sustainability of the production chains, which includes a careful evaluation of environmental, economic and social effects.

The energy and chemical sectors are best able to take advantage of the technical and economic possibilities of biorefineries: first, through the production of biofuels and the generation of electricity and, second, by obtaining high-value chemicals.

Additionally, relatively new concepts emerging in the last 20 years, such as green chemistry, the 12 principles that seek to reduce the negative impacts of chemistry on society (Anastas; Warner, 2000; Anastas; Kirchoff, 2002), and the bioeconomy, the development of an economy based on biological and renewable resources (Organization for Economic Co-operation and Development, 2019b), are closely related to biorefineries.

Biomass for biorefineries

The diversification of raw materials is the main characteristic of plant biomass, which demands different technologies of cultivation and management. At present, agroindustrial vegetable biomass can be divided into four types (Vaz Jr., 2018b): lignocellulosic (e.g., wood, sugarcane bagasse and forest residues), the most representative in terms of the amount of available mass; oleaginous (e.g., soybean, sunflower and palms); saccharide biomass (e.g., sugarcane and sorghum); and amylaceous biomass (e.g., potato, maize and beet). There is a large availability of these biomass sources worldwide, mainly in countries such as Brazil, the USA, China and Russia (Deng et al., 2015). The global biomass supply comprises 11.4 Gtonne/year dry matter (Bos et al., 2017); however, the quantity and quality depends on the agroindustrial production in each country.

The heterogeneity of the chemical composition of the four main types of agroindustrial biomass and the high water content require different conversion or transformation technologies: chemical, thermochemical and biochemical. These three classes of processes are most likely to be used for biomass, depending on the products of interest. It is important to emphasize that the chemical composition of the biomass affects the performance of the biocatalysts or catalysts (Vaz Jr., 2018b).

Economic potential of new products and sustainability

Building block compounds, such as succinic acid, levulinic acid and FDCA, stand out as promising for biorefineries (Bozell; Petersen, 2010). The highest number of promising compounds are derived from first and second generation sugars, mainly from glucose. However, lignin derivatives and oleochemical coproducts are also strong candidates. Polymers are currently one of the main products already obtained by biorefineries. Drop-in products are the main form of greening for chemicals and biofuels. However, green products must create their own market in order to become economically feasible. Moreover, a large variety of O-, N-, S- and P-containing chemicals can be obtained from the chemical and biochemical conversion of biomass (Hülsey et al., 2018), which expands the economic potential of biorefinery products.

As an example of a biorefinery, we can refer the Borregaard's model, a wood-based biorefinery, developed to obtain sustainable products as specialty cellulose, lignin, vanillin and bioethanol (Borregaard, 2019).

Bioeconomy

According to the Organization for Economic Co-operation and Development (2019c), bioeconomy refers to the set of economic activities relating to the invention, development, production and use of biological products and processes. Of course, it possesses a wide scope and it's applicability to agriculture is obvious. Moreover, bioeconomy is aligned with the already mentioned UN sustainable development goals (The United Nations, 2019) due to the promotion of sustainable value chains based on renewable resources.

New opportunities for bioeconomy are largely found in manufacturing, biochemistry and agriculture, but strategies also need to include accelerated innovations for food security and resource protection (Braun, 2018).

In general, a strategy to explore agriculture according to the bioeconomy could take into account these topics:

- Bioproducts and biorefineries: refers to the supply of products resulting from the conversion of biomass into biofuels and bioproducts.

- Biomass chemistry and technology: refers to the supply of biomass on a renewable basis and the development of processes based on the use of biomass.
- Production and use of biomass: refers to the most efficient use of available biomass.
- Renewable energy: refers to the supply of energy-related products from renewable energy sources.
- Climate change: considers more promising alternatives or strategies of the reduction of global warming and adaptation to changes.
- Food and nutritional security: considers regular and permanent access to quality food without compromising access to other needs.
- Use and exploitation of natural resources: consider obtaining benefits from the use of natural resources.
- Valuation of natural resources and ecosystem services: considers environmental benefits resulting from human interventions in the dynamics of ecosystems.
- Transversal to the bioeconomy: presents issues related to investment, the regulatory framework and market and is considered important for the development and application of the concept.

Opportunities

The opportunities arising from sustainable agricultural chemistry can be summarized as:

- Reducing the negative impact on health and the environment by means of more controlled production and application of agrochemicals;
- Improvement in the performance of agrochemicals based on new technologies;
- Development of new markets; and

- Increasing food security.

These related opportunities can change from the short-term to long-term because the agricultural sector is dynamic in products, production and productivity.

Challenges

Some of the challenges arising from sustainable agricultural chemistry are:

- Global reach of the developed technologies or in developing and providing access to them by small and large farmers;
- Public subsidy of new technologies until they become economically feasible;
- Reduction in water use;
- Reduction in CO_2 emission;
- Improvement in hazardous pesticide control; and
- Effective policies for the environment.

Obviously, each country has its own peculiarities that can create specific challenges to be overcome. For instance, the monitoring and control of the market and application (e.g., to combat counterfeiters) to avoid the indiscriminate and uncontrolled use of chemicals is a law enforcement case to be pursued in Brazil and neighboring countries.

Conclusions

Agriculture must constantly become more sustainable, with the reduction of its negative impacts on the environment while increasing its positive impacts on society and economy.

Governments, farmers and consumers shows increasing concern with the negative impacts on the environment and health caused by the large amount of inputs applied to produce different crops in different regions around the world. Agrochemicals have a direct correlation with damage from agriculture, with pesticides as the main representative class with toxicological implications.

The search for alternatives to conventional agrochemicals is an excellent opportunity for the development of sustainable agricultural technologies, as well as new businesses. Such an environment offers opportunities for the creation of new production systems within agriculture and food production, which is supported by the United Nations sustainable goals. New trends and technologies, such as biotechnology, nanotechnology, natural products, green chemistry, reduction in CO_2 emissions, water management, biorefineries and the bioeconomy, can boost the sustainability of 21st century agriculture. To achieve this, R&D&I institutions, companies and society should move together in search of safer and environmentally friendly practices.

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