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Plant organic farming research – current status and opportunities for future development

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ABSTRACT

This paper reviews the recent development of the scientific, legislative, economic and environmental aspects of plant organic farming. The impact of organic farming on biodiversity and soil fertility is discussed in comparison with conventional systems. A significant barrier for wide application and future development of organic farming is the existing diversity of national and international policy instruments in this sector. Special attention is paid to up-to-date research techniques that could help solve a number of the problems typically faced in plant organic farming. It is argued that organic farming is still not productive enough to be considered fully sustainable. This underlines the necessity of strong support for more effective implementation of scientific research innovations and improvement of the networking between all stakeholders – organic producers, scientists and corresponding policy makers at the national and international level.

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Introduction

The need of continuously raising the yield, relevant to the continuously increasing market demand, has led to inordinate utilization of the natural and non-renewable resources and energy. Conventional farming in the face of the Green-revolution system allows the agricultural production capacity to be significantly increased, leading to the highest possible yield per hectare. The improvement of soil fertility through additional application of fertilizers and plant protection chemicals, as well as the utilization of modern agricultural machineries for tilling, irrigation, sowing and crops harvesting, could reach the most remarkable economic benefits on the farm level and thus to provide food production necessary for the fast growing human population [1–4]. The high yield per hectare and good quality products for the market have given farmers the guarantee of a secure income and consumers the availability of a large spectrum and choice of agricultural products at a reasonable price, independent of the season. The overproduction of different foodstuffs, e.g. sugar, wheat, milk, meat etc., is the luxury problem of the consumerist society. Most of the agricultural foodstuffs on the market in developed

countries are mainly produced by such intensive agriculture systems. The excessive use of synthetic chemicals, which vastly contaminate the environment, as well as the mechanical soil disturbance and irrigation, have led to a generation of resistant insects, fungi, weeds, etc., accumulation of chemicals in crops and soil, pollution of water and air and consequently contribute to some extent to the greenhouse effect and global warming [5].

To set boundaries to this method of production, the European Commission initiated a quota regulation system with a guaranteed price for a limited production of milk and sugar beet per farm [6]. In the former Common Agricultural Policy (CAP) this quota system was coupled with the set-aside of arable land [7]. The European Commission enacted several regulations and directives to oblige governmental authorities of the member countries and also to motivate farmers in changing their attitude and to pay more attention in respect to the quality of life and preservation of environment. Council Directive 75/440/EEC determined the maximum allowed nitrate concentration in drinking water, while Directive 91/676/EEC refers to the water protection against the pollution with nitrates from agriculture). The regulation

that is most relevant in this regard is Regulation 2078/92 [8], about demonstration projects dealing with less input of fertilizers and chemicals in agriculture [9].

Attempting to minimize the negative impacts from the intensive agricultural practices on the environment, the World Commission on Environment and Development, aka the Brundtland Commission Report [1987] (United Nations document A/42/427), defined 'sustainable development' as 'development that meets the needs of the present without compromising the ability of future generations to meet their own needs.' Some authors see this system as the next evolutionary stage in the progress of agricultural production [10], containing three aspects of sustainability: social, economic and environmental. The social aspect refers to the creation of a good quality of life for the rural population. The economic one refers to the effective use of resources and achievement of competitiveness and vitality of the rural economy. The environmental aspect should cover the sustainable preservation of overall production resources. Sustainable agriculture should be based on technologies that improve the productivity and minimize the negative effects on both the environment and the human factor. The specific agricultural practices that have less negative impacts on the environment are those of organic farming. This 'new/old' agricultural practice combines well-known farming approaches used in the past, such as crop rotation, manure, green manure, organic pest control etc., and some technical and methodological innovations. Organic farming leads to preservation of natural resources, causes minimal negative impact on nature and could be defined as a self-sufficient system. It fully meets the definition of sustainable agriculture, because food is produced while conserving the soil (minimum mechanical soil disturbance [no-tillage]), water, energy and biodiversity [11]. Others consider these as separate concepts that should not be equated, because nowadays, as the food demand steadily increases, the productivity should be high enough to provide a global food supply but on condition that special care is taken of the natural resources [12–15]. Banjara and Poudel [16] report that there was a significant contribution made by organic agriculture to improve the socio-economic status of farmers in Nepal as well as to carry the relationship between the human being and their environment on the fundamental base of the family farming system. The authors also showed that the roles of government, non-government, private sectors, individual farmers and consumers are equally important for the sustainability of organic agriculture and focused on the collective effort of all responsible stakeholders. Considering the regional, human and environmental specificities worldwide, it is necessary to test the effectiveness of this model

modified in a manner consistent with that. Organic farming needs appropriate management of resources and understanding of ecological and biological processes in order to provide protection from pests and pathogens [15]. Furthermore, it is also important to note that organic farming must be managed in a way that the market ensures maximum profit for the farm, too [17]. The prohibited utilization of agricultural synthetic chemicals and their replacement with organic fertilizers such as compost or manure, is expected to lead to reduced soil carbon losses, less soil erosion, less nitrogen and phosphorus leached as pollution to the groundwater and, finally, to conservation of the ecosystems [18–21]. The problem of water pollution due to nitrogen leaching was approached by Carlier et al. [22] from a different perspective, by asking why nitrate leaching should differ because of its origin, organic or mineral. The nitrogen released by clover may leach to the water table under grassland as well. The authors suggest that a high stocking rate on pastures causes more problems due to nitrate leaching than cut grass fertilized with mineral nitrogen. Nevertheless, the organic farming systems rely mostly on prevention due to the best use of environmental goods and services [23].

Challenges and opportunities for development of plant organic farming research

Organic farming and biodiversity

The intensive agricultural systems disturb natural habitats and their heterogeneity, which results in less biodiversity [24]. Both organic and low-input farming could minimize this negative impact so as to maintain biodiversity and control weeds, insects and other pests through natural approaches. Letourneau and Bothwell [25] presented evidence for enhanced insect pest control as a consequence of greater biodiversity in organic farms. Furthermore, organic farming may help to reverse the declines of the habitual species in regions, where conventional agriculture is traditionally applied [26,27]. The positive impact on biodiversity is one of the advantages of organic farming that is most frequently pointed out in comparison to the conventional production system [28–30]. Meta-analysis of data spanning a period of 30 years from regions that practice organic farming showed increased species richness by about 30%, the effect size varying with the organism group and the crop studied [31]. In earlier studies, it was also reported that the response of different organisms is not equal to the condition of organically managed fields. Döring and Kromp [32] found that the population densities of some predators were usually higher in organic farms than in

conventional ones. Nevertheless, the common view is that pest damage on many crops is usually not greater in the case of a well-managed organic field [33]. Other authors have suggested that the positive effect of organic farming on species richness could be expected in intensively managed agricultural regions, but not in small-scale landscapes, which include different, non-crop biotopes [28]. In spite of the expressed opinion for the need of prolonged investigation of the effect of organic farming on biodiversity, some studies have shown that, at the farm scale, this effect is highly heterogeneous [34,35]. A growing amount of published research evidence indicates that the effect of organic farming in increasing biodiversity is obviously promising. Generally, the biodiversity in organic farming is between 10.5% and 30% higher than in conventional farming [29,31,36]. However, the assessment of diversity vs. crop yield of important farmland taxa in organic and conventional farms shows that, in the case of intensive productive systems, the biodiversity preservation unfortunately correlates with respective reduction in the crop yield. To partly bridge the yield gap between both production systems, Gabriel et al. [37], proposed to find the balance between conservation of agro-ecosystems and sustained productivity. In their opinion, this could be achieved in low-productivity agricultural systems, where organic farms are concentrated in hotspots.

Organic farming and soil fertility

Badgley et al. [12] express an opinion that organic systems for food production can contribute substantially for feeding the fast growing human population on the current agricultural land base, while maintaining soil structure and fertility. The so-called conservation agriculture is being widely promoted in many areas mostly for the recovery of degraded soils. This practice aims to improve farm productivity, profits and food security based on three principles: minimum mechanical soil disturbance, permanent soil cover and crop rotation [38]. Positive effects of conservation agriculture on the agroecosystems have been widely reported: e.g. prevention or minimization of soil erosion and soil organic carbon loss, improvement of water use efficiency, nutrient cycling and mitigation of greenhouse gas emissions [39,40]. There is usually high level of organic matter in the soil of an 'organic field', due not to the higher inputs of organic fertilizers, but rather to a cascade effect owing to the activity of microorganisms decomposing the organic residues [41]. In order to better understand these processes, researchers need to strengthen the investigations on the humus content, the spectrum of microorganisms and the soil structure. Whereas some analyses with respect

to tillage processing, where tillage is mechanical soil disturbance, show that many soil physical and biochemical properties could be enhanced at reduced or no tillage conditions [42–44], soil metagenomics show a different and more complex pattern. Many works have employed soil metagenomics to explore the complexity of soil microbiology in many different soil types and in diverse agricultural conditions. There are significant differences in the microbiota structures and taxonomic composition between cultivated soils under conventional and no-tillage systems [45]. It seems therefore that agronomical use and the type of tillage system could induce shifts in the microbiota of the same soil types. The trend is that the microbiota of conventionally cultivated soils, under higher nutrient amendment, present tends towards copiotrophy, whereas the microbiota of non-cultivated soils appear to be more oligotrophic. It seems that conventional tillage might trigger copiotrophy more than no tillage with the consequence of decreasing the soil organic matter stability and increasing the nutrient availability [45]. This simple observation could explain the empirical development of tillage at the beginning of agriculture. Similar soil metagenomics works have explored the influence of crop management (rotation or succession of same cultures) in conventional tillage or no tillage agronomical systems. Surprisingly, the differences in microbiota were more important between tillage and no tillage, and were less associated with crop management [46]. Such works add evidence that the microbiota of conventionally cultivated soils with tillage have greater abundance of bacteria involved in residue decomposition, carbon and nitrogen cycling and xenobiosis. The microbiota of no-tillage soils hosted more nitrogen-fixing Rhizobiales and Archaeobacteria, usually inhabiting soils rich in organic matter. The few differences in tillage and no-tillage systems, between crop rotation or crop succession leads suggests that the agronomical management has very little influence on the microbiota diversity, which is congruent with the fact that the main interest of crop rotation is to break the plant–pathogen cycle [46]. Metagenomics could be a tool of choice to explore and understand the biological basis of disease suppressive soils and understand the antagonistic potential of such soils. Some selected phytopathogen-suppressive soils have been analysed for their antagonistic potential, in the frame of the collaborative European project Metacontrol (2002–2007) and a number of different suppressive soils have been screened. The hypothesis of this project was that the microbiota of suppressive soils could provide reservoirs of genes involved in *in situ* antibiosis or antagonism (antibiotics, chitinase, etc.) [47]. In future, soil metagenomics would be part of the needed innovations in

organic agriculture and would help to better understand the biology underlying pathogen suppressive soils, maybe leading to a possible engineering of such suppressive soils. The biological properties of soil are recovered not only by minimum tillage, but also by utilization of natural, non-synthetic products; biological weed, disease and pest control; composting, mulching, intercropping etc. [45–49]. Crop rotation is also very important for the balance of soil microflora in organically managed fields, because various plants have a specific impact on it [50].

The soil fertility is improved by increasing the populations of beneficial species grazing microbial films and thus stimulating soil nutrient mineralization [51]. Therefore, many authors pay particular attention to mycorrhizal fungi as a source of innovation in organic farming practices for improvement of nutrient uptake, biocontrol and microbial ecology [52–54]. Arbuscular mycorrhizal fungi (AMF) are a large group of soil-borne microorganisms that plays an important role in agricultural ecosystems [55,56]. Arbuscular mycorrhiza (AM) is a symbiotic association between plants and fungi where the fungus hyphae penetrate into the cells of the roots of vascular plants. This association is also known as vesicular-arbuscular mycorrhiza due to the formation of vesicles (bladder-like structures) and arbuscules (branched hyphae) after colonization of the root cells. Arbuscular mycorrhiza is the most common type of symbiotic association. It is assumed that up to 90% of the world's plant species have the ability to form a mycorrhizal relationship [57]. This type of symbiosis increases the absorption surface area of the root and brings benefits to the plant in terms of water and nutrients [58], meanwhile, providing protection from biotic and abiotic stress factors [59]. Fungal hyphae are much thinner than plant roots and easily reach even limited spaces in soil. The plants provide the fungi with sugars (carbon source) obtained by photosynthesis [60]. AM also brings significant agroecosystem sustainability as it leads to the maintenance and improvement of the soil structure and microbial ecology [61]. Verbruggen et al. [62] reported that organic management enhances the diversity of AMF assemblages, when compared with conventionally managed agricultural fields. AMF communities are richer and more diverse across organically managed fields and are more similar to those of natural, undisturbed grasslands. In addition, the mycorrhiza richness increases significantly with the time since conversion to organic management [62,63]. The positive effect of organic management on AMF diversity could be explained by higher frequency of crop rotation with a grass–clover mixture as a forage crop. The inclusion of legumes in crop rotations has been shown to have a positive effect on overall soil

parameters. On the other hand, some authors report that the differences in AMF richness and community structure appear to be most pronounced late in the growing season, which indicates that organic farming may select for AMF with long life cycles [62,64,65]. Organic farming may thus sustain the mycorrhizal component of soil fertility and agroecosystem functioning. Future progress in the knowledge of the organically managed soil–plant–mycorrhiza interactions, practical implications for effective biological control, the identification of markers associated with induced resistance, as well as the generation of predictive models for the result of these interactions are an important challenge for the organic farming R&D. For example, the results from a multidisciplinary study on comparison between conventional and organic tomato agro-ecosystems showed that the microbial activities are higher in the soil of organic agroecosystem, (due to the increased lability of carbon stock), which contributes to the suppression of root pathogens. The authors suggest that this is very likely a result of microbial antagonism [66].

It is known that the availability of nitrogen in the soil is one of the most important yield-determining factors [67]. In organic farming, nitrogen is derived only from the leguminous plants, crop residues, manure and compost, which usually do not supply enough nitrogen and this causes lesser crop yield in comparison to the conventional farming. Graham et al. [68] discuss the possibility for improvement of the soil nutrient content through integrated nutrient management (combined application of organic, inorganic and biological nutrient sources). On the other hand, synthetic nitrogen fertilizers provoke depletion of organically bound nitrogen and organic carbon, which consequently reduces the soil fertility [49]. Badgley et al. [12] evaluated the nitrogen content potentially available from leguminous cover crops fixation, used as fertilizer in both temperate and tropical agroecosystems. The authors concluded that leguminous cover crops could fix enough nitrogen, allowing replacement of the necessary amount of synthetic fertilizer. Conversion from conventional to organic management systems requires a transition period which is needed for adaptation of the soil ecosystems to the new conditions. For long-term sustainability, Mulvaney et al. [49] proposed a gradual transition from synthetic nitrogen fertilizers to their replacement with legume species and crop rotations typical of organic farming. Overall, during the periods of rapid plant growth, the insufficient nitrogen content in organic fields usually causes stress, which negatively influences the crop yield. In comparison to the conventional systems, with high inputs of synthetic nitrogen fertilizers, the productivity in organic farms is generally lower (by 20%–25%), more frequently during

the first several years [69]. According to Goklany [70], the reduction of crop yield in organic farming could be compensated with almost the same percent more arable land to ensure the necessary yield. There is evidence that the reduced yield in organic systems vs. conventional ones is not so significant after several years (over 5 years) [67,71]. The yield could be even similar, according to other reports [11,72]. The yield difference is not so remarkable particularly in the developed countries where organic farming has traditions and the society can support these farm systems by technological novelties [72,73]. Vice versa, the yield gap between the two systems is significant in the developing countries where the production system is not intensified and farmers have limited access to the natural resources and their buying capacity is relatively low [12].

Organic farming and relevant plant breeding

Research and innovation are expected to play a very important role in solving the existing technical gaps in organic production, processing and marketing. Siderer et al. [74] suggest that research studies should embrace not only food content and nutritional effects, but also farming methods, in order to support all stakeholders in organic agricultural systems. The value of farmer experience, validated by scientific findings in this field, could be a stimulus to design future organic practices. The use of innovative methods and technologies in organic farming depends not only on purely technical aspects, but also on the effective interaction between creativity and diversity in the perspectives of researchers and farmers, social networks and institutions involved. It is therefore necessary for organic farmers and the organic sector as a whole to promote a bold spirit of innovation and a culture of intensive learning and communication with regard to new solutions and innovative practices [75,76]. In order to meet the challenges of organic production, smart technologies have to be used towards organic genotypes with enhanced productivity and resource-use efficiency, with low impact on the environment. At present, around 95% of organic production in modern societies is based on crop varieties that were bred for the conventional high-input sector where mineral nitrogen fertilization and synthetic chemical pest, disease and weed control are not a limiting factor [77]. Often the high yielding varieties cannot express their productive capacity and disease resistance at low-input farming, where mineral fertilizers are replaced with organic sources. Therefore, they are inappropriate for low-input agriculture with all the related negative consequences [78]. Because high productive crops bred for conventional agriculture are usually grown as monocultures of

homogeneous cultivars [79], numerous local varieties, possessing properties suitable for organic and low-input practices have been lost [80]. Some of them are more adaptable to the different environmental conditions and management practices [81], which push breeders to start new programmes for producing new varieties that meet the criteria of organic practices. The inclusion in the breeding programmes of local varieties and landraces that are carriers of valuable traits should not be limited by the organic seed regulations [82].

Genetic variation for nitrogen use efficiency has been reported for crops relevant to organic agriculture, including potato [83], wheat [84] and barley [85]. This proves that the nitrogen use efficiency in organic farming systems could be improved by breeding. It has also been shown that the applied agronomic practices can additionally enhance the nitrogen use efficiency [86]. Dawson et al. [87] suppose that the good productivity of the newly bred crops at the lower nitrogen content in the soil of organic fields is probably a result of the beneficial association between plants and soil microorganisms. Boyhan and Stone [88] discuss the techniques involved and some social and philosophical concerns about crop improvement intended for low-input farming. Targeting plant breeding for organic agriculture can contribute to reduce the yield gaps between the conventional and the organic agriculture production systems. However, it is not clear if the latter aims at yields comparable to conventional agriculture or just being higher than they are today. As reviewed by Crespo-Herrera and Ortiz [15], the breeding goals for both organic agriculture and conventional agriculture converge are aimed at higher productivity, incorporation of resistance or tolerance to biotic and abiotic factors and higher resource-use efficiency (water, nutrients, light, etc.). The genotype-by-environment interaction ($G \times E$) is a common situation that plant breeders have to deal with and, if exploited correctly, it is still possible to make important progress in crop improvement. Hence, from the pure plant breeding perspective, organic agriculture can be considered as a separate environment with a strong component of local adaptation, in which the necessary traits and selection methods should be incorporated [15]. Although many breeding goals are identical for conventional and organic production, the priorities nevertheless can be different for both production systems. This is mainly due to the fact that conventional agriculture is able to compensate for the lack of certain traits via inputs, including inorganic fertilizers and synthetic crop protection chemicals that are not available for use in organic agriculture farming systems [89]. The traits that are specifically important for organic agriculture include: nutrient use efficiency, weed competitiveness, the ability to establish

symbiotic relations with micro-organisms in the soil and tolerance to mechanical weed control [90]. Scientific reports showed that genetic variation for weed competitiveness is also present in cereals [91,92], and that early vigor and allelopathy can be useful traits in breeding for enhanced weed suppression [91,93]. Participation of the organic sector in the European Innovation Partnership (EIP), would be essential for boosting innovation and improving cooperation between the farm, science and industry at regional, national and European levels (Action Plan of EC 2020). In this Action Plan for the future of Organic Production in the European Union [94], the EU Commission refers to research and innovation to overcome challenges in organic rules. Research into protein crops has remained limited compared with other production sectors, with the result that protein crop yields have fallen behind in the last decades. The Action Plan underlines that renewed investment in research into protein crop production could help narrow the gap again, leading to greater yield stability and product quality (protein content, digestibility, etc.) so as to make protein crops more profitable for farmers and the entire supply chain. Another point that is made is that research could also lead to improvements in animal nutrition, feed efficiency, breeding and husbandry in organic production if it focuses on increased sustainability.

Since organic plant breeding is considered part of the whole production chain, it should comply with the underlying principles of health, ecology, fairness and care. Hence organic plant breeding is restricted to specific conventional breeding practices; in general, the crossing methods should not break the reproductive barriers between species and evaluation and selection should be done on the basis of whole plant performance [15]. Therefore, remote hybridization, protoplast fusion and *in vitro* selection are not allowed, leaving meristem culture as a single *in vitro* method allowed in organic plant breeding. In addition, the technologies or methods that directly change the DNA or those operating at sub-cellular level are also considered to be incompatible with organic plant breeding [90]. This excludes genetically modified organisms (GMOs), the application of synthetic hormones and colchicine treatments, as well as both physical and chemical mutagenesis as sources of genetic variation in organic plant breeding. According to the latest evaluation of plant breeding methods for organic agriculture [95], the critical issues with experimental mutagenesis with organic agriculture are the use of synthetic chemicals in chemical mutagenesis and violation of the genome integrity by chromosome breakage caused by radiation. However, a mutagenesis protocol termed 'accelerated ageing of seeds' needs to be re-evaluated for its compatibility with organic agriculture

principles. It is based on a phenomenon termed 'ageing of seeds during storage.' The main difference of this protocol compared to other experimental mutagenesis methods widely employed in plant breeding is that it simply speeds up the mutation process naturally taking place in the farmer's granary, breeding collections and even in the gene banks by storing seeds at elevated temperature and humidity. Therefore, the genetic variation generated by this method should be the same as the one found in natural populations and in the farmers' fields. It is noteworthy that the applied physical factors are also natural and such situation may occur by chance with the farmer's saved seeds if they are not properly stored. Since the efficiency of accelerated ageing of seeds for generating useful genetic variation for breeding [including variation in important quantitative traits], have already been proved in conventional maize breeding programmes [96], adoption of this method in organic plant breeding can greatly speed-up the breeding process by allowing induction of new genetic variation in elite cultivars already adapted for organic agriculture. All varieties of which seeds or other plant material have been propagated under organic growing conditions are currently allowed in organic agriculture, given that they are not declared as genetically modified varieties [89,97]. To this end, it is important to emphasize that the plant tissue culture methods and the experimental mutagenesis techniques have significant advantages in comparison with the genetically modified organisms: they are much less expensive and can be used from every public unit and the intellectual property rights (IPR) are much less restrictive. As recently highlighted by Nuijten et al. [97], according to derogation rules, the situation seems to be slightly improved for organic seeds, where there is an exception allowing the use of conventional non-treated seeds, if no suitable varieties from organic propagation are available. Among the currently available varieties, the following categories can be distinguished [97,98]:

- (1) Varieties derived from conventional plant breeding that are suitable for organic farming with the exception of genetically modified varieties (conventional breeding, organically propagated, or, if necessary, derogations are made for conventionally propagated but post-harvest untreated seeds).
- (2) Varieties derived from plant-breeding programmes with a special focus on the breeding goals or selection environments for organic farming and organic seed propagation (product-oriented breeding for organic farming, organically propagated).

- (3) Varieties derived from organic breeding programmes or organic on-farm breeding, which have been bred under organic farming conditions considering the above-mentioned criteria (process-oriented organic plant breeding, organically bred and propagated) [97].

It is important to enrich the information intended for producers on the availability of organic seeds throughout the EU, with a seed database at a European level [94].

Organic farming and new OMICS technologies

Genomics

Many authors are of the opinion that organic farming in the twenty-first century needs to be more flexibly innovative to solve the existing problems, even if it has to find new 'avenues' for it [99–103]. Undoubtedly, innovative techniques can be beneficial to the traditional selection, but a serious barrier to this is a number of sometimes mildly controversial safety assessment restrictions at the highest possible standards. For example, 5 years ago, the European Food Safety Authority (EFSA) confirmed that cisgenic plants carried the risks similar to those of plants obtained with conventional breeding [104–106], but up to now, cisgenesis is still considered transgenesis in the European Union [100]. Acceptance of plants resulting from these modern techniques in organic agriculture is seen as probably a 'bridge' too far [106]. The different positions have to converge in compliance with the principles of coexistence and preservation of food and food safety [102]. More efficient, innovative and evidence-based communication between science, business and public administration in the organic farming sector is the only meaningful way to help farmers obtain good healthy harvest without chemicals and maintain healthy soil in line with flexibly up-to-date with the organic farming principles [105].

The United States recently released the first products, an anti-browning mushroom and a waxy corn, genetically modified with the gene-editing tool CRISPR-Cas9, for commercialization without the oversight of the US Department of Agriculture with the justification that these products do not contain genetic material from plant pests such as viruses or bacteria [107]. New high throughput sequencing approaches combined with an increase in identification of candidate genes and the new breeding techniques (NBT) like CRISPR-Cas9, transcription activator-like effector nucleases (TALENs) and Zinc finger nucleases will have large impact in conventional plant breeding. These new genomics assisted techniques provide breeders with handy tools for cost- and labour-effective precise gene editing at a resolution

of a single base substitution with little or no off-target effects on the rest of the genome [108]. Although, these techniques show great promise for revolutionizing plant breeding, the debate on whether they should be allowed in plant breeding for organic agriculture is still ongoing with many publications advocating [109–113] or opposing [114] their adoption in organic plant breeding. However, considering the draft position paper of International Federation of Organic Agriculture Movements (IFOAM) on the New Plant Breeding Techniques [115], most of these techniques are considered GMO and incompatible with organic agriculture and organic plant breeding, respectively. Nevertheless, some recent papers [97,110] attempted to define a clear set of criteria to evaluate the available breeding techniques including NBTs for compatibility with the IFOAM's four basic principles of Health, Ecology, Fairness and Care [115]. Using these criteria, the authors concluded that molecular marker assisted selection is fully compatible with organic plant breeding because it is a diagnostic tool based on the analysis of DNA and does not interfere physically at the genome or cell level [97]. It does not overcome species specific crossing barriers, and does not affect breeder's privilege or farmers' right to produce farm saved seeds. By comparing marker assisted recurrent selection (MARS) with the pedigree method in tropical maize breeding, Beyene et al. [113] found that the observed differences in genetic gains between the two evaluated methods were much higher under drought stress conditions than under well watered conditions, indicating that MARS can be more efficient and effective than phenotypic selection, and could improve genetic gains for complex traits like drought and low nitrogen tolerance in tropical maize breeding programmes. Some fractions in the organic sector still have concerns on the use of hazardous chemicals and recombinant enzymes in marker development and application. However, these could be overcome by the use of native enzymes and employment of laboratory automation. Although marker assisted selection is the single genomics aided tool currently available to organic plant breeders that can significantly speed-up the breeding programmes and increase the genetic gain per cycle, its application in organic plant breeding is still limited. Currently, there are few reports describing the application of molecular marker systems in organic plant breeding. Significant changes in allele frequencies of markers located close to the quantitative trait locus (QTL) for grain yield in barley were found by comparing sets of landraces, historical and modern cultivars of barley [116]. It was found that the frequency of some alleles with positive effect on grain yield in high input environments increased up to 56% in modern cultivars compared to 36% in old cultivars and 15% in

landraces. Conversely, no such enrichment in allele frequencies was observed near the QTLs for grain yield in low input environments. The authors suggested that modern breeding may have increased the frequencies of marker alleles close to QTLs that favour production under high yield potential environments at the expense of yield under low input conditions. Since landraces adapted relatively better to low yield potential environments than old and modern cultivars, it was concluded that landraces should be included in breeding programmes aiming at improving the yield under organic and low input systems, as they may provide variation at genetic regions responsible for adaptation to low input conditions that may have been unintentionally negatively selected by modern breeding [116]. In another study, an association mapping population consisting of 154 spring barley genotypes contrasting for traits that are important for organic agriculture was established in an attempt to develop molecular markers useful in breeding for organic farming [117]. The mapping population was genotyped at 3072 single-nucleotide polymorphism (SNP) loci and traits important for organic agriculture were evaluated in field trials in two organically and two conventionally managed locations during three seasons. The evaluated traits essential for organic farming included: plant morphological traits ensuring competitive ability against weeds, grain yield in organic farming, yield stability/adaptability to organic conditions, nutrient use efficiency and prevalence of diseases. The preliminary results showed that genotype and location significantly influenced most of the analysed traits and, for traits related to weed competitiveness, the average trait values tended to be higher in conventional farming locations, but the coefficients of variation were higher in organic locations in most of the cases. However, the final marker-trait association results of this study have not been published yet. In spring wheat, a bi-parental population genotyped at 579 DArT (diversity arrays technology) markers was used for mapping QTLs for various agronomic traits in both conventional and organic management conditions [118]. Most QTLs detected in this study were specific to either the organic or the conventional management system. However, some QTLs for grain yield, grain volume weight, kernel weight and days to flowering on chromosomes 6A, 1B, 3A and 5B were co-located in both systems. It was also found that Rht-B1 had no effect on other traits except for plant height in conventional systems, while in organic management, recombinant inbred lines carrying the wild-type allele were taller, produced more grain yield with higher grain protein content and suppressed weed biomass to a greater extent than those carrying dwarfing alleles. Based on these results, the authors suggested that

indirect selection of superior genotypes from one system to another will not result in advancement of best possible genotypes and concluded that selection of spring wheat for organic farming should be done in organically managed lands. Re-analysis of the same phenotype data set with 1200 SNP markers allowed detection of more QTLs not detected in the previous study, suggesting that higher marker density improved the power of QTL detection [119]. One of the newly mapped moderate-effect QTLs on chromosome 5A affecting both flowering time and maturity was mapped close to the *Vrn-A1* gene, while a moderate-effect QTL on chromosome 4B that reduced plant height by 7.2 cm but increased maturity by 2 d was mapped 27 cM apart from the *Rht-B1* gene. The increased employment of molecular marker systems and marker assisted selection in the future organic plant breeding programmes could improve both the speed and genetic gain. There are two main strategies to assist breeding with molecular selection: to use molecular markers that map near or within specific loci with known phenotypic effects (marker-assisted selection, MAS) or to exploit all available markers as predictors of breeding value (genomic selection, GS). MAS is used to drive the selection of a relative small set of genes having large phenotypic effects [110]. Marker assisted backcross selection (MABC) has been extensively used in conventional plant breeding to transfer qualitative traits and QTLs with large effect [mainly disease resistance genes], which often reduces the required backcrosses from six to three [120]. Therefore, many molecular markers, tightly linked to disease resistance genes are readily developed and available for use in organic plant breeding. For example, information on linked molecular markers is available for almost all known rust resistance genes in wheat [121] and those could be readily transferred to build durable rust resistance in varieties suitable for organic agriculture. In the last few years, substantial progress has been made in association and QTL mapping and marker assisted breeding strategies for complex traits such as tolerance to drought and low nitrogen stress that are also desired in varieties bred for organic agriculture. For example, the differences in the genetic gains observed between MARS and the pedigree method in tropical maize breeding were much higher under drought stress conditions than under well-watered conditions, indicating that MARS can be more efficient and effective than phenotypic selection, and could improve genetic gains for complex traits like drought and low nitrogen tolerance in tropical and perhaps temperate maize breeding programmes [113]. In GS, the marker effects of all loci are estimated across the entire genome to calculate the genomic estimated breeding values (GEBVs) in a population of individuals

representative of the breeding programme in question [often referred to as training populations] for which both phenotypic and genotypic data are known [110]. In a recent study, Vivek et al. [122] demonstrated that GEBV-enabled selection of superior phenotypes, without the target stress, resulted in rapid genetic gains for drought tolerance in tropical maize. With the availability of abundant cost-effective markers provided by genotyping by sequencing (GBS) or microarrays for almost all major crops, similar marker assisted approaches could be utilized in organic plant breeding. However, the QTLs and the phenotype data of training populations should be validated in organic agriculture conditions prior to use in MAS or GS. On the other hand, the employment of MAS or GS techniques in the breeding of certain crops for organic agriculture strongly depends on the availability of funding for the organic breeding programme of this crop. Perhaps, such scientific results will in the future lead to the revision of some of the requirements for the selection of varieties suitable for organic farming.

Metabolomics

A study carried out on organic food with respect to current legislation, inspection and certification, gives details about the accepted food safety standards, which allow organic and conventional products to be easily distinguished by customers [74,123]. Organic products are generally more expensive than their conventional counterparts, which is why the increased prices generate the risk of fraud. Therefore, proper analytical techniques are required to assess the true organic origin of these foods (reviewed in [124]). As a rule, organic products are considered more safety and beneficial than conventional ones, but sometimes they could be more contaminated by microorganisms and biogenic amines as a result of application of manure for soil fertility improvement, and traces of antibiotics and fungicides could be detected as well. Therefore, proper analytical approaches and techniques are required to determine the authentic composition and origin. This is usually done by comparing organic and conventional food products, using target analyses of specific macronutrients (carbohydrates, lipids, proteins) or micronutrients (minerals, vitamins, amino acids, bioactive compounds, etc.). Another approach is isotope-based analysis in order to verify the soil of cultivation and fertilizers used. However, these techniques often result in unreliable data for the classification of farming procedures, unless they are combined with other multivariate approaches [124,125].

Key aspects of recent research focus on metabolomic differentiation of organic and conventional agricultural products [126]. Since organic and conventional farming practices and processes influence complexly the plant

cellular response, a metabolomics approach allows the identification of variations in the plant metabolome. Untargeted analyses is promising for generating clear and robust results, and metabolomics is a powerful tool for identifying and quantifying molecules for the comparison of different products [127]. Organically and conventionally grown crops could be effectively differentiated by mass spectrometry (MS) coupled with other separation techniques. Some examples include flow injection electrospray ionization time-of-flight mass spectroscopy (FI-ESI-TOF-MS) and flow injection electrospray ionization ion trap mass spectroscopy (FI-ESI-IT-MS) in grapefruit [128], gas chromatography with mass spectrometry (GC-MS) in wheat grains [129] and winter wheat cultivars [130]. With the help of statistical analysis, e.g. Tukey's test, analysis of variance (ANOVA), principal component analysis (PCA), linear discriminant analysis (LDA) etc., the metabolomics approach is generally able to reveal that a metabolic modification exists between the foodstuff cultivated with different protocols, although in some cases, it may not be able to identify the exact metabolites that account for these differences [124,128,129]. Ambient MS is another effective tool capable of fingerprinting low-molecular-weight metabolites (<1 kDa), with very little sample preparation and no need of separation procedures prior to spectral analysis (reviewed in [129]). For example, ambient MS including direct analysis in real time (DART) might be suitable for rapid discrimination of organically or conventionally grown tomatoes and sweet bell peppers, although it attributes greater metabolomic differences to the production year and needs a large number of samples to provide reliable differentiation [131].

Interestingly, the type of farming process may not have much impact on the nutritional value of the products, i.e. on the content of sugar and sugar alcohols [129]. In maize hernels, for example, the farming mode (organic vs. conventional) reportedly causes minor variation of the metabolome compared to other major factors such as the cultivar or environmental factors [132]. Nevertheless, discrimination between locations/cultivation systems could be achieved based on the relative amount of some analytes, e.g. myo-inositol, malic acid and phosphate, which show higher levels in the organically grown maize kernels [132]. Similarly, higher myo-inositol and malic acid content, but lower levels of free amino acids [e.g. aspartate, asparagine and alanine], have been reported in organic wheat grains compared to conventionally grown ones [130]. Although myo-inositol is known to play a role in many biochemical pathways involved in stress response and osmoregulation, its increased expression in organic kernels has not yet been explained. On the other hand, phosphate is very

important for plant growth and its content changes in various organically grown plants, depending on the farming procedures [133].

Other attempts to differentiate between organic or conventional farming origin based on metabolomic analysis concern processed food, e.g. ketchup [134] or wine [135,136]. In organic ketchup samples [134], LC coupled to MS in tandem mode (LC–ESI/QQ) and statistical analysis showed significantly higher amounts of some compounds: caffeoylquinic and dicaffeoylquinic acids, caffeic and caffeic acid hexosides, kaempferol-3-O-rutinoside, ferulic-O-hexoside, naringenin-7-O-glucoside, naringenin, rutin and quercetin. On the other hand, the conventional products contained typical compounds (glutamylphenylalanine and N-malonyltryptophan) that were not present in the organic samples. These differences in the metabolite profiles could be due to the secondary metabolism and self-defence mechanisms of plants [137]. In red wines produced from either organic or biodynamic grapes [135], nuclear magnetic resonance (NMR) spectroscopy and ANOVA revealed significant variation in the metabolic fingerprints. The major source of distinction was the concentration of tyrosine-related metabolites, which was high in organic wines. Organic grapes also showed a greater concentration of resveratrol and a lower amount of transcaffeic acid, whereas the concentration of transcaffeic acid was higher in biodynamic wines. Melgarejo et al. [136] suggested that some polyphenols might target biogenic amine-producing enzymes. The spectral variations in wines from successive years showed that switching from organic to biodynamic farming modifies the phenylpropanoid pathways, thus supporting the hypothesis that the decrease of glutamine concentration is related to an antagonistic effect of polyphenol biosynthesis [124,136].

The metabolomic approach highlights the patterns of metabolites that discriminate between plants produced according to different cultivation protocols, and gives evidence of possible distinctive characteristics in organically produced foods (reviewed in [124]). Multivariate data analyses, such as PCA, provide combinations of compounds useful for classification, suggesting that patterns of metabolites, rather than single molecules, may be used as quality biomarkers.

Proteomics

Proteomics in organic agriculture is still in its infancy with only a relatively small number of publications available in the scientific literature. Several studies have reported changes observed in potato proteome when comparing organic vs. conventional farming. In 2007, Lehesranta et al. [138] studied the protein profile of potato tubers grown under organic and conventional

farming conditions. The protein samples were subjected to 2D-gel electrophoresis and identification was carried out following HPLC-ESI-MS/MS. One hundred and sixty of the 1100 detected tuber proteins were differentially expressed. The results showed that only the fertilization regime (organic matter vs mineral fertilizer) had a significant impact on protein composition but not the crop protection treatments (organic vs conventional) and the nature of the previous crop in the rotation (different combinations of wheat, grass and clover). One hundred and forty three of the 160 differentially expressed proteins were more abundant in the tubers grown under an organic fertilization regime. The identified differentially expressed proteins were involved in protein synthesis and turnover, carbon and energy metabolism and defence responses. Based on these results, the authors suggested that organic fertilization leads to increased stress response in potato tubers. In a later study, Rempel et al. [139] analysed the response of the potato leaf proteome to contrasting fertilization regimes (mineral vs. composted cattle manure) and to changes in the protection regime (omitting pesticide-based crop protection). Again, the protein profiles were more influenced by switching to organic fertilizer than by the omission of chemosynthetic crop protection. Proteins involved in photosynthesis, like the large subunit of RuBisCO, RuBisCO activase, the photosystem I reaction centre as well as proteins in response to stress including dehydroascorbate reductase and glutathione S-transferases showed higher expression levels in potato leaves grown under mineral fertilizer regimes. The authors explained the higher abundance of proteins involved in photosynthesis by the higher leaf nitrogen and phosphorus content, while the increased level of stress response proteins was attributed to higher cadmium levels. At the same time, proteins involved in biotic stress as 1,3- β -D-glucan glucanohydrolase and putative Kunitz-type tuber invertase inhibitor were more abundant in compost fertilizing conditions. In another study published in 2013, Tetard-Jones et al. [140] analysed the effect of previous crop management (conventional vs. organic), organic fertilization type (cattle vs. chicken manure) and rate (85 kg N ha⁻¹ and 170 kg N ha⁻¹, plus a control – 0 N) on the potato tuber proteome. The study included a total of 302 protein spots following 2D-gel electrophoresis. The results showed that 21 proteins were significantly influenced by the previous crop management, 33 by the fertilization regime whereas 9 proteins were influenced by both factors. Sixteen proteins showed to be significantly affected by the interaction of the two factors. The majority of identified proteins which were significantly influenced by the analysed factors were related to energy-glycolysis, disease/defence, protein

destination and storage and stress response. The main reason for differential protein expression was attributed to the different nitrogen supply by the different fertilization regimes. The previous crop management (organic vs. conventional) also influenced significantly the potato proteome. Upregulation of members of different protein functional groups (e.g. defence, glycolysis) was not restricted to a single plant treatment [previous crop management/fertilization] as different members of one and the same functional group were differentially upregulated in contrasting previous crop management/fertilization treatments. According to these reports, the potato proteome appears to be significantly influenced by switching between conventional and organic fertilization and by the previous crop management (organic vs. conventional) and less influenced by the plant protection regime (organic vs. chemosynthetic) and the nature of the previous crop in the rotation. The type of the used organic fertilizer can also have significant influence on the potato proteome. Switching from conventional to organic fertilization can lead to altered expression of proteins involved in protein synthesis and turnover, carbon and energy metabolism and defence responses. Further studies including different potato genotypes as well as comparison of samples from one and the same type of tissue will help to reveal to what extent the genetic background influences the proteome response to different fertilization regimes and treatments. Nawrocki et al. [141] performed proteome analysis of cabbage (*Brassica oleracea* L. var. 'capitata') and carrot (*Daucus carota* var. 'sativus') under conventional farming and two types of organic farming conditions (O1 and O2) which differed in the type of nutrient delivery (slurry for O1 and autumn green manures for O2). The results showed that for cabbage, 58 out of 1300 and for carrot 68 out of 1800 observed proteins on 2D-gel electrophoresis were differentially expressed in O1 or O2 respectively compared to the conventional farming condition. The results also showed that the differences between any of the organic schemes and the conventional scheme were much higher compared to the differences between the two organic schemes. Identification of the differentially expressed proteins by MALDI (matrix-assisted laser desorption/ionization) tandem mass spectrometry showed that proteins from the glycolytic pathway and Krebs cycle as well as proteins related to amino acid and protein metabolism were overexpressed in organically farmed cabbage, while proteins related to detoxification were overexpressed in conventional cabbage. In carrots, proteins related to the metabolism of carbohydrates, polypeptides and secondary metabolites were differentially expressed between organic and conventional growing conditions. Lee and Lim [142] attempted to

identify protein biomarkers allowing to differentiate between organic and conventional rice. The authors compared rice varieties grown in three different organic rice farms located in different regions of Korea. The proteins were separated by 2D-gel electrophoresis and spots of interest were subjected to MALDI-TOF identification of the respective proteins. The authors found that 13, 12 and 8 proteins were differentially expressed between organic and conventional farming conditions depending on the three respective farm locations. Finally, three proteins were found to be differentially expressed in all three farms, including B3 domain-containing protein, cellulose synthase A catalytic subunit 3 and 1-cys peroxiredoxin A. The meta-analysis performed by Baranski et al. [143] on the differences in composition between organic and non-organic crops/crop-based foods revealed that protein, amino acids and nitrogen content are negatively influenced by organic farming practices, which positively correlates with the lower nitrogen inputs in organic crop production systems. The authors concluded that in spite of this, the lowered protein and amino-acids concentrations are unlikely to have significant health impact on European and North-American consumers who typically consume enough amounts of proteins and essential amino acids in their diet.

Proteomics is a key research tool, whose application in organic farming will make it possible to improve the quality of organic grown plants and respectively the food produced thereof in several aspects. First, improving fertilization and plant protection in order to obtain plants with optimal protein composition will make it possible to improve the yield as well as the resistance of plants to environmental conditions and diseases. Secondly, the ability to track changes in relative amounts of individual health-beneficial proteins allows for optimization of the growing conditions in order to obtain healthier food from organic plants. Last but not least, proteomics in organic farming also contributes to the accumulation of knowledge about plant physiology and its influence by the conditions of cultivation. Future results in this area, complemented by genomics and metabolism research, will be essential for the development of organic farming in the near future.

Conditions for development of the organic sector

Important preconditions

Organic production systems are already recognized and generally supported by authorities. As a result, many farmers, in spite of the assured income with conventional agriculture, have changed their attitude and have

converted to the environmentally and socially friendly organic systems. Of significant importance for the further development of this sector, is undoubtedly the availability of relevant bulletins, handbooks and data of research studies illustrating the specific aspects and benefits of organic farming as well as the prospects for market expansion for their products. The important preconditions for this could be summarized as follows:

- suitable climate and soil conditions;
- political will for implementation of organic farming, and sufficient financial support;
- the necessary know-how;
- availability of the respective legislation for organic farming (regulation system); control and certification of organic products;
- conditions for development of the internal and external market;
- good reputation as an exporter of conventional agricultural products;
- professional education (management training for farmers adopting this type of production system); expanding the secondary school curriculum with specific subjects for organic production and farming;
- the attitude of consumers;
- availability of enterprises for processing of organic products;
- availability of certified seeds and other plant material suitable for organic and low-input farming.

The shortage of organically produced seeds on the market is a considerable challenge for farmers, thus becoming an obstacle to the quicker expansion of the organic sector. With regard to this, the European Commission notes that the situation seems to have slightly improved owing to the exception that allows the use of conventional, non-treated seeds, instead of organically produced ones [144].

Consumer attitudes

Consumers are generally concerned about the way food is produced and look for products with proven quality. Due to the wide use of agro-chemicals and the growing awareness of foodborne diseases, environmental pollution etc., customers are losing trust in the foodstuffs produced by intensive agro-systems and begin to prefer buying organic food, in most cases regardless of its higher price. Buyers believe that organic food contains lower levels of artificial chemicals and higher levels of nutrients and beneficial phytochemicals, together with having better sensory characteristics [145–147].

According to some surveys on consumers' attitudes, consumers fall into two categories: either 'internal' ones, i.e. those who control their own life, or 'external' ones, who rely on the decision made by persons in charge. Those from the second group very rarely buy organic food in contrast to the 'internal' ones. It seems that this distinction is useful in guiding the choice of correct strategy for advertisement of particular foodstuffs in order for them to be accepted by consumers [148,149]. Some studies on the correlation between the age of consumers and their attitude to buying organic products show that younger buyers have a higher attitude to purchasing organic products [137,150]. However, other surveys make the opposite conclusion [151–153]. The higher prime cost of certified organic products compared to those from conventional production systems is often a barrier for some buyers. A survey conducted in two regions in Spain shows that the organic market is segmented due to the different purchasing power of the people. The inquired consumers expressed readiness to pay a higher price for perishable organic products, which could be identified easily like meat, fruit and vegetables [154]. For young consumers, the price is also a main barrier, but they believe that their behaviour will change at a later stage of their life [155]. Siderer et al. [74] suppose that achieved economies in the processing and distribution systems of organic products may bring about a reduction in their price in future. A study of the consumer's perception of organic food in an emerging market (Saint Petersburg, Russia) and factors influencing positively or negatively the public opinion, proved that one of the main confusions regarding the organic food consumption growth is the ability to recognize such products. It is beyond doubt that the ease of access to information for production and processing of organic food and feed commodities could positively influence the attitude of the purchaser. The confidence in the strict application of organic standards, food labelling and availability of respective control systems, (a result of a coherent legislative framework), are very important factors for the development of the organic sector [156]. Thus, managing consumer trust is increasingly seen as a prerequisite for the development of a market for green products [150], whereas, interestingly, personality traits appear to influence consumers' preferences for some locally produced, but not for organic food products [151].

Organic market

The demand for health foods, which surpasses those offered for sale, stimulated the expansion of the market for organic products in the late 1980s [148].

Nevertheless, even in Denmark, where the organic market is mature, and supermarkets offer a relatively broad spectrum of organic foods, the market growth is unfortunately still moderate. Every supplier to the organic market needs to follow strict quality standards for each commodity, which is a prerequisite if it is to be offered as organically certified. The dynamics of the organic quality system are presented as a relationship between the processing conditions, the product characterizations, the product performance and the customer requirements [157]. An earlier survey on the organic food market in Germany and the UK, showed that both countries are seeking to create a broad consumer base [158]. The conclusion was that the UK has greater opportunities in this direction if small markets expand, while in Germany, it seems more appropriate to include supermarkets as well [158]. Although, the demand for regional organic food in Germany is now higher than the regional supply [159] and the market for organic goods is large [160], organic farming reportedly still faces obstacles in limited access to land, increasing renting prices, insufficient processing capacities and unsupportive political environment [159]. The above-mentioned factors are obstructive for a quicker development of the market, which is a key issue for organic producers. The market conditions prompt farmers to pay special attention to the adaptation of the traditional processing methods to the organic requirements, to diversify the produced foodstuffs, to use innovative approaches, even new packaging systems, and to apply different ways of communication with consumers, in order to advertise their output. Producers as a rule seek information and recommendations not only for the local, but also for the globalized marketplace. Green marketing is expected to encourage consumers to purchase environmentally friendly organic products [161]. Depending on the country, product developers and marketers could potentially use different elements of the consumers' preferences for organic food to better meet organic consumers' wishes and expectations [162].

Standards and regulations in organic farming

Promoting the benefits of organic farming and marketing of organic products has led to the rapid spread of this agricultural sector in many countries in the world. The number of organic producers and respective production area in the EU has grown significantly over the past two decades. In Europe, organic agriculture began to spread in the 1980s [163,164] and currently, it is one of the active organic producing regions in the world (27% of the world's organic agricultural land belongs to

Europe). The certified and policy supported organic production area in the EU plus Norway and Switzerland in 1985 was less than 0.1% of the total agricultural area [165], while today in Europe it is 2.4%. In the EU, the percent of organic farmland is 5.7%, but some of the countries reach higher quota, such as Liechtenstein (30.9%), Austria (19.4%), Sweden (16.4%) and Estonia (16.2%) [165]. This situation forces authorities to pay more attention on food safety – production, processing and monitoring via respective standards, procedures and risk management programmes. The International Federation of Organic Agriculture Movements (IFOAM) released in 2002 an initially developed basic standard for organic production [166]. EC Council Regulation (EEC) No. 2092/91 [100] was the primary regulation governing organic agriculture in Europe and determines how it needs to be applied by individual member states. Today, all EU Member States have regulations for organic agriculture and national production standards [167]. European law in its predominant part is harmonized with the basic standards of IFOAM. The organic products imported into the EU need to correspond to the EU standards. Regulation 2092/91 requires third country certification – accreditation, audit traits, annual inspections, material lists, defined conversion periods and sustainable farm plans. In other words their standards and control measures need to be similar to those in the EU. Australia, Israel, New Zealand and Switzerland have their own regulations [168], but they are also holders of such certificates [74]. According to the FiBL survey on organic rules and regulations, the total number of countries with organic standards worldwide as of 2016 is 87 [169]. Since its introduction in 1991, Regulation (EEC) 2092/91 has had several additions, including a set of guidelines for livestock production (Regulation No. 1804/99) [170] and establishment of a community logo (EC Regulation No. 331/2000) [171], which could be used for agricultural products and foodstuffs obtained according to the standards. The EU pays special attention to the quality of the organic products offered for sale; they need to comply with the strict definitions of organic food and farming. The logo and labelling rules, which are a substantial part of the organic regulations, make organic products easier to recognize by consumers and facilitate the control by authorities. The protection of the EU organic logo is achieved by registering it as a collective trade mark in the European Office for Harmonisation in the Internal Market and in a limited number of neighbouring countries like Switzerland and Norway (Action Plan for the future of Organic Production in the European Union, 2014) [94]. Organic regulations compile all the legislation of the *acquis communautaire* concerning the organic

production of agricultural products. It is applicable for all EU member states and refers to crop and animal products for human consumption and animal feed, and contains rules valid for production, processing, marketing (labelling and advertising) and trade of both raw and processed products. Regulation 2092/91 [100] requires individual member states to designate a Competent Authority to approve and supervise certification bodies, implement procedures for inspection and certification of imports, and generally oversee all activities related to organic production, processing and marketing. These measures contribute to improving the consumer confidence in the produced organic commodities. In addition to these broad EU programmes, many countries have developed their own programmes aiming at promoting organic agriculture. Most of the programmes offer partial reimbursement of certification and inspection fees. In Denmark, certification has been free for producers since 1996 [172]. Council Regulation (EC) No. 1804/1999 [76] introduced some modifications for crop growing and conditions for organic animal production. In Article 6, it states that genetically modified organisms (as defined in Directive 90/220/EEC) or GMO derivatives (produced from GMO, but which do not contain GMO's themselves) are not allowed in organic farming, except the use for medication and veterinary purposes [7]. Since 2007, a new Council Regulation (EC) 834/2007 [173] regarding the organic production and labelling of organic products is enacted. Commission Regulation (EC) No. 889/2008 [174] gives detailed description for the application of Regulation (EC) 834/2007 and of organically produced seeds. There are, however, some concerns that, under the common EU agricultural policy, the organic farming community in Central and Eastern European countries is reportedly losing influence over the development of the organic sector due to the need to increasingly react to changes in mainstream agricultural institutions. The mainstream agricultural sector sees organic farming as a way to address current problems the regime is dealing with, rather than providing a role model for future farming development [175]. Van Bruggen et al. [176] assume that the regulations, especially those for plant disease management in organic farming, will undergo changes, but considering the views of all stakeholders.

Although organic agriculture has an untapped role to play in the establishment of sustainable farming systems, it is largely recognized that no single approach will safely feed the planet [177]. Rather, a blend of organic and other innovative farming systems is needed. Significant barriers exist to adopting these systems, however, and a diversity of national and international policy instruments will be required to facilitate their future development and implementation [103,177].

Conclusions

Organic farming has increased tremendously in importance over the past 20 years, including in developing countries, and the global market for organic products has grown. Organic agriculture, in general, is recognized to produce lower yields compared to conventional agriculture, but at the same time, to be more profitable and environmentally friendly, providing equally or more nutritious pesticide-free foods, and additional agroecosystem and social benefits. However, due to the yield gap between organic and conventional farming, the differences in the cost effectiveness are deep, so organic agriculture continues to be a minor alternative to conventional agriculture. The much more important debate now must be over how to get enough sustainable healthy food all in the right places at the right times and the right price. Therefore, it is necessary for organic farmers and the organic sector to promote a bold spirit of inclusivity in innovation and a culture of intensive learning and communication regarding new solutions and innovative practices. Strategic planning is imperative.

Disclosure statement

No potential conflict of interest was reported by the authors.

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