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Human health implications of organic food and organic agriculture

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Human health implications of organic food and organic agriculture

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Abstract

This report reviews the existing scientific evidence regarding the impact of organic food on human health from an EU perspective and the potential contribution of organic management practices to the development of healthy food systems.

Very few studies have directly addressed the effect of organic food on human health. They indicate that organic food may reduce the risk of allergic disease and obesity, but this evidence is not conclusive. Consumers of organic food tend to have healthier dietary patterns overall. Animal experiments suggest that identically composed feed from organic or conventional production has different impacts on early development and physiology, but the significance of these findings for human health is unclear.

In organic agriculture, the use of pesticides is restricted. Epidemiological studies point to the negative effects of certain insecticides on children's cognitive development at current levels of exposure. Such risks can be minimised with organic food, especially during pregnancy and in infancy, and by introducing non-pesticidal plant protection in conventional agriculture. There are few known compositional differences between organic and conventional crops. Perhaps most importantly, there are indications that organic crops have a lower cadmium content than conventional crops due to differences in fertiliser usage and soil organic matter, an issue that is highly relevant to human health. Organic milk, and probably also meat, have a higher content of omega-3 fatty acids compared to conventional products, but this is not likely to be nutritionally significant in light of other dietary sources.

The prevalent use of antibiotics in conventional animal production is a key driver of antibiotic resistance. The prevention of animal disease and more restrictive use of antibiotics, as practiced in organic production, could minimise this risk, with potentially considerable benefits for public health.

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Contents

Executive summary

This report reviews existing scientific evidence regarding the impact of organic food on human health from an EU perspective, with a focus on public health. The development of environmentally sustainable and healthy food systems is an international priority and in this report we discuss how organic food and organic agriculture can contribute to this in relation to public health. Human and animal studies directly addressing the health effects of organic food are reviewed. Furthermore, evidence linking principles and rules of organic production to human health effects is also discussed.

Studies on the health effects of organic food in humans

To date, very few studies have been performed that directly investigate the effect of organic food on human health. There are indications from these studies that organic food consumption is associated with a lower risk of childhood allergies. Adult consumers who frequently eat organic food are also less likely to be overweight or obese compared to other consumers. However, the evidence for this effect is currently not conclusive as no long-term studies have yet been carried out. Furthermore, it is inherently difficult to separate organic food consumption from other associated lifestyle factors that may affect human health.

Organic food consumption and sustainable diets

It is known, however, that consumers who regularly buy or consume organic food have healthier dietary patterns, such as a higher consumption of fruit, vegetables and wholegrain products and a lower consumption of meat, compared to other consumers. These dietary patterns are associated with various health benefits, which include a reduced risk of chronic diseases such as type 2 diabetes and cardiovascular diseases. These patterns also coincide with patterns that are favourable from the perspective of environmental sustainability, such as greenhouse gas emissions and land use. Further evaluations need to be undertaken on the extent to which the organic agro-food system, comprising production and consumption, can serve as an example of a sustainable food system with respect to health and environmental effects.

Experimental *in vitro* and animal studies

A small number of *in vitro* studies point to different biological activities of organic and conventional crops on human cell lines. However, it is unclear whether any of the observed activities are preferable. Several animal experiments using feed composed from the same ingredients, but from organic or conventional production, suggest that the feed production system has a different impact on the development of animals. Specifically, two-generation animal studies indicate an effect of the feed production system on the offspring's immune system. However, it is currently unclear how these observations translate into effects for humans, if at all.

Pesticides

Organic farming largely relies on preventive measures for plant protection, therefore the use of pesticides is low and potential risks to human health are largely avoided. A small number of pesticides are approved as curative measures but, with some exceptions, these are generally of low toxicological concern. Overall, consumption of organic food substantially decreases the consumer's dietary pesticide exposure, as well as acute and chronic risks from such exposure.

Pesticides undergo a comprehensive risk assessment before market release, but important gaps remain. Of major concern, these risk assessments disregard evidence from epidemiological studies that show negative effects of low-level exposure to organophosphate insecticides on children's cognitive development, despite the high costs of IQ losses to society. While the intake of fruit and

vegetables should not be decreased, existing studies support the ideal of reduced dietary exposure to pesticide residues, especially among pregnant women and children.

Organic agriculture provides both a source of food with low pesticide residues and an environment in which agronomic techniques for pesticide-free plant protection are developed. These techniques can be adopted in conventional production, thereby aiding a transition towards integrated pest management and overall lower pesticide exposure of the population and the environment.

Production system and composition of plant foods

Organic farming mainly relies on animal and green manure for crop fertilisation; water-soluble mineral fertilisers are generally not approved. The total amount of plant nutrient fertilisation, specifically nitrogen, is lower in organic agriculture. The difference in the amount and plant availability of plant nutrients has some effect on plant development and overall plant composition. However, the nutritional value of plant foods is only slightly affected by organic vs. conventional management and, based on what is currently known, is limited to a moderately higher content of phenolic compounds in organic foods. Although phenolic compounds are believed to mediate protective effects against certain chronic diseases in humans, it is not currently possible to translate such differences into specific health benefits from crops in either system. The minerals and vitamins content is generally similar when conventionally and organically produced crops are compared. Crop variety, soil type, weather, climatic conditions and other factors also affect crop composition.

The long-term use of mineral phosphorus fertiliser has contributed to increased cadmium concentrations in agricultural soils. There are indications that crops produced by organic farming, specifically cereal crops, have comparatively low cadmium concentrations, although this is not certain. This is highly relevant to human health because food is the dominant route of human exposure to cadmium in non-smokers. The population's current cadmium exposure is close to, and in some cases above, tolerable limits. There have been no studies comparing the effects of long-term organic *vs.* conventional farm management on cadmium concentration in crops. However, long-term experiments over more than 100 years indicate that cereal crops fertilised with mineral fertiliser tend to have a higher cadmium content compared to cereal crops fertilised with animal manure. This issue is highly relevant to human health and deserves further investigation. For other toxic metals, current evidence suggests that the production system has no influence on metal concentration in crops.

Animal-based foods

Animals in organic husbandry have plenty of access to forage and receive comparatively low amounts of concentrate feeds. It is well established that the fatty acid composition of the feed affects the fatty acid composition of milk, eggs and meat. As grass and clover have a high content of omega-3 fatty acids, organic milk has been found to have an approximately 50 % higher content of omega-3 fatty acids on average compared with conventional milk. A similar effect has been observed for organic meat, although there is less supporting evidence of this. While a higher omega-3 content in itself represents an advantage from a nutritional point of view, milk, dairy products and meat account for only a minor proportion of dietary omega-3 intake in the human diet. Based on current knowledge, the calculated additional human omega-3 intake from organic animal products cannot be extrapolated to any specific health benefit. Another group of fatty acids, ruminant fatty acids, are found in higher concentrations in organic compared to conventional milk. However, the effects of these fatty acids for human health are unclear. Most other fatty acids are not or only slightly affected by the production system.

Antibiotic resistance

Globally and in the EU, more antibiotics are used in animal production than for human health. The World Health Organization has identified the overly prevalent use of antibiotics in animal production to be one of the contributing factors to increased antibiotic resistance in bacteria. However, the restricted use of antibiotics in organic systems could minimise this risk. Organic broilers and pigs, but not dairy cows, are less likely to develop diseases related to intensive production compared to animals in conventional production. As a consequence, less use of antibiotics for treating clinical diseases is required. However, there are considerable differences in use between species and countries.

Furthermore, the preventive use of antibiotics is heavily restricted in organic husbandry where the maintenance of animal health instead relies on preventive management factors, such as hygiene measures and decreasing stocking density. The use of antibiotics has been clearly linked to the risk of developing antibiotic resistance in bacteria. Consequently, there is a lower risk of the development of antibiotic resistance in organic animal husbandry. There are several routes for resistant bacteria and resistance genes to move from farm animals to humans.

Knowledge dissemination between conventional and organic production may be an important step in decreasing the use of antibiotics in animal production overall. However, hypothetically, a transition to organic production for the whole livestock sector would, on its own, be only part of a solution to the antibiotic resistance issue, because factors outside animal production, such as their use in humans, will be unaffected.

Policy options

Based on the science reviewed in this report, five policy options have been developed.

Policy option 1: No action

The health of citizens is a core EU priority. Pesticide exposure, bacterial antibiotic resistance and cadmium exposure are major public health issues. Organic agriculture and organic food might be one way of addressing these issues. If no action is taken, an opportunity to address some important public health issues would be missed.

Policy option 2: Pursue and intensify EU policies for food safety

A reduction in the cadmium influx to soils and thereby a reduction of the population's exposure to cadmium, reduced use of and exposure to pesticides, and countermeasures to meet increasing challenges with bacterial antibiotic resistance are the aims of existing EU policies or policies under discussion. Organic products compare favourably to conventional products with regard to pesticide residues, antibiotic-resistant bacteria and probably cadmium concentrations in crops. For fruits and vegetables that frequently contain pesticide residues, member states may choose to generate advisories aimed at pregnant women and children to prefer organic products, while maintaining a high overall fruit and vegetable intake. These issues suggest synergies and interactions between EU food safety policies and organic agriculture. Within organic agriculture, crop and livestock management strategies have been developed that may eventually be adopted by the entire agricultural system, thereby supporting EU policies for food safety. Political support for organic agriculture may to some extent also be looked upon as political support for EU food safety policies.

Policy option 3: Support organic agriculture by investing in research, development, innovation and implementation

Some plant diseases and pests cannot be satisfactorily managed with contemporary organic approaches and there is a need for new plant protection methods in organic agriculture. For animal production, varieties that are bred for less rapid growth and that remain productive, yet are resistant and robust, are needed. Furthermore, there are bottlenecks in the implementation of best practices in organic plant production; specifically, some approaches to plant protection are fairly knowledge intensive. Investments in the further development of organic agriculture may improve its capabilities to serve as a provider of high-quality food and as a laboratory for sustainable and healthy agricultural practices.

Policy option 4: Improve the business environment of organic agriculture through fiscal instruments

Cadmium exposure, pesticide residues and antibiotic-resistant bacteria all result in costs to society that are not typically included in the price of the fertiliser, plant protection product, or antibiotic drug. Although difficult to estimate accurately, these costs may be substantial and represent negative production externalities. They could provide motivation for the use of fiscal instruments in favour of practices that help avoid these costs. Taxes or fees could be imposed on practices that result in costs to society or the use of alternatives could be subsidised.

Fiscal instruments that aim to internalise such external costs into production costs are likely to serve public health and improve the competitiveness of organic agriculture due to its low use of pesticides and antibiotics. Such instruments could either be directed towards organic agriculture or towards the practices to be avoided or preferred, or in combination.

Policy option 5: Support sustainable food consumption patterns

Current average European food consumption patterns are characterised by higher meat consumption and lower consumption of whole grains, fruit and vegetables compared to healthy and environmentally-sustainable diets. The promotion of healthy and sustainable food consumption is in line with central EU policies on public health and sustainability.

The consumption patterns of organic food consumers tend to be healthier compared to the general population. Likewise, due to the higher costs of organic food, public kitchens that serve a high proportion of organic food tend to serve food with a comparatively high content of plant proteins and vegetables, which is desirable from the perspectives of human health and environmental sustainability. EU institutions set the rules for public procurement in the region and through this can support sustainable food consumption patterns.

Ongoing negotiations and international agreements

A new EU regulation on the labelling of organic products is currently being negotiated. Of relevance to this report, a more rigorous policy regarding pesticide residues in organic products is under discussion. From a human health perspective, risk assessments of acute and chronic exposure reviewed in this report demonstrate that risks from pesticide exposure are far lower for organic food than for conventional food, indicating that pesticide residues on organic food are currently a very small issue. Although action should be taken against fraudulent pesticide use and labelling, overly rigorous action on pesticide residues in organic food carries the risk of making farmers responsible for factors beyond their control, such as the volatilisation and ubiquity of certain pesticides in the agricultural landscape.

Growing international trade in agricultural goods may lead to the increased import of organic products from outside the EU, where different rules apply for organic production, often including less strict regulation of pesticides approved for organic agriculture. It is unclear whether such uses lead to residues on imported foods. There is little specific cause for concern for human health, but there is some uncertainty associated with this development that the EU may wish to address.

1. Introduction

In the public debate, discussions regarding organic food often become polarised and simplified down to the question of which of organic or conventional food is "better". This perspective may be relevant from a narrow consumer perspective because the consumer's choice is often focused on products with or without an organic label. However, most scientists instead are aiming to understand the impact of different farm management systems on human health, animal wellbeing, food security and environmental sustainability, with the long-term goal of developing sustainable food systems, rather than deciding which of the currently existing systems is "better".

Several intergovernmental organisations have made the development of sustainable food systems a high priority [1-3]. Sustainable food systems will not be created *de novo*. Policymakers should support the increase in sustainability of existing food systems by new developments and learning from other food systems around. Research funds, subsidies and other instruments should be directed towards supporting this goal. Scientists should understand, develop and evaluate these systems with the objective of creating future sustainable food systems. In this regard, contemporary organic and conventional systems will serve as real-world large-scale laboratories.

The present report has been initiated after a workshop entitled "The impact of organic food on human health" held at the European Parliament in Brussels, Belgium on 18 November 2015, in which several of the authors participated.

The aim of the present report is to give policymakers access to a review of current knowledge concerning how organic farming and food can contribute to human health improvements, and to discuss related policy options. Therefore, where appropriate, an EU perspective was taken. The authors of the present report are currently preparing the publication of a review paper with a similar scope in a scientific journal.

There is not just one conventional agro-food system or just one organic agro-food system, but a variety of different forms with some overlap. The term "conventional agriculture" in this paper generally refers to the predominant type of intensive agriculture in the European Union, *i.e.* intensive agriculture with high inputs of synthetic pesticides and mineral fertilisers, and a high use of antibiotic drugs as well as a high proportion of conventionally-produced concentrate feed in animal production. "Organic agriculture" refers to farming that is in accordance with EU regulations or similar standards for organic production, comprising the use of organic fertilisers such as farmyard and green manure, a predominant reliance on ecosystem services and non-chemical measures for pest prevention and control, and livestock access to open air and roughage feed.

As the focus of this report is on the effect of organic food on human health, studies that directly measure health effects as a function of organic or conventional food consumption are generally of greatest relevance so human and animal studies with this scope are summarised and discussed first. However, few such studies have been undertaken, and they all have considerable limitations. Therefore we also discuss studies that have been performed in relation to potential causal links between organic production and consumption as causes and human health as the effect. Topics were prioritised and selected by their potentially large relevance for public health, by the availability of a substantial evidence base and by initial expert judgement. Figure 1 gives a schematic overview of the various links between organic food and health that are discussed in this report. Several other topics, including microbial contamination of food and the effect of food processing, are not or only briefly touched on.

Aspects of environmental sustainability, such as biodiversity and greenhouse gas emissions, may also be affected by the agricultural production system [4] and may affect human health *via* food security [5, 6], for example, but such indirect links are outside the scope of this report, although they are briefly touched on in the "food systems" section in Chapter 3. Also, the focus of this report is on public health. The health effects of pesticide exposure on agricultural workers and residents are briefly discussed because such studies form an important evidence base for pesticide effects.

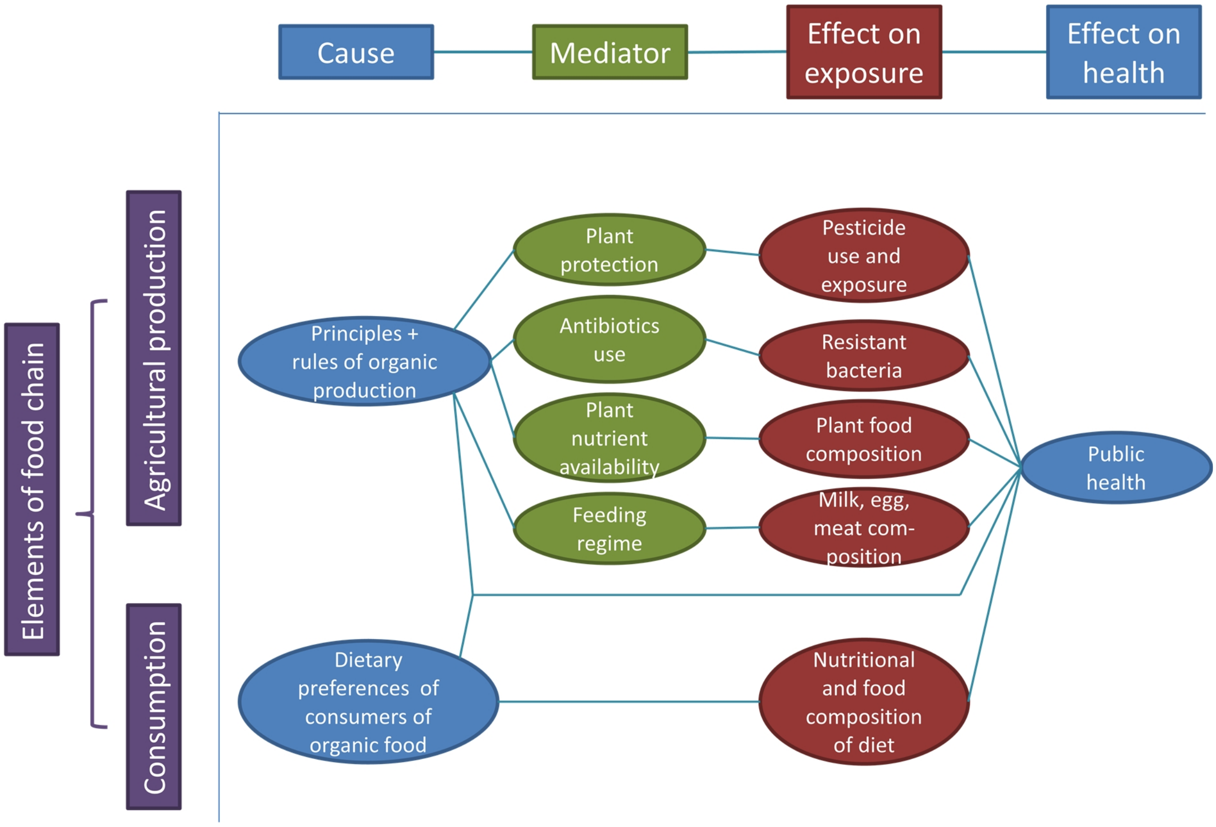

Figure 1. Potential causal links between organic food (blue, left) and human health (blue, right) that are reviewed in this report

2. Studies on the health effects of organic food in humans

2.1. Types of epidemiological studies

Epidemiological studies are conducted to determine possible associations between health outcomes and various factors and to establish scientific evidence. There are two main types of epidemiological studies, experimental (*e.g.* randomised clinical trials) and observational, and both of these can be divided into several subgroups.

These different study designs provide different levels of evidence. One way of evaluating whether associations in observational studies are likely to be causal relationships are the Bradford Hill guidelines [7, 8] (see Table 1).

1. Strength of association

A strong association is more likely than a modest association to have a causal component

2. Consistency

A relationship is observed repeatedly

3. Specificity

A factor specifically influences a particular outcome or population

4. Temporality

The factor must precede the outcome it is assumed to affect

5. Biological gradient

The outcome increases monotonically with an increasing dose of exposure or according to a function predicted by a substantive theory

6. Plausibility

The observed association can be plausibly explained by substantive (e.g. *biological) explanations*

7. Coherence

A causal conclusion should not fundamentally contradict present substantive knowledge

8. Experiment

Causation is more likely if evidence is based on randomised experiments

9. Analogy

For analogous exposures and outcomes an effect has already been shown

Table 1. Bradford Hill's guideline for causality assessment.

In that context, interventional trials and cohort studies, which are experimental and observational studies respectively, display the highest level of evidence. Cohort studies are prospective and collect exposure data (such as food consumption) before health outcomes are measured [9]. Case-control and cross-sectional studies provide only suggestive information. However, such studies are relevant for depicting behaviours, in particular those related to diet.

In interventional studies, organic food consumption can be measured and controlled, however the cost of such studies is high and compliance presents a key challenge. In turn, observational long-term prospective cohort studies offer a good compromise for studying the effect of organic food consumption on health issues. Nonetheless, this implies the precise estimate of dietary exposure by using validated methods such as food-frequency questionnaires or dietary records, both of which present some limitations [10].

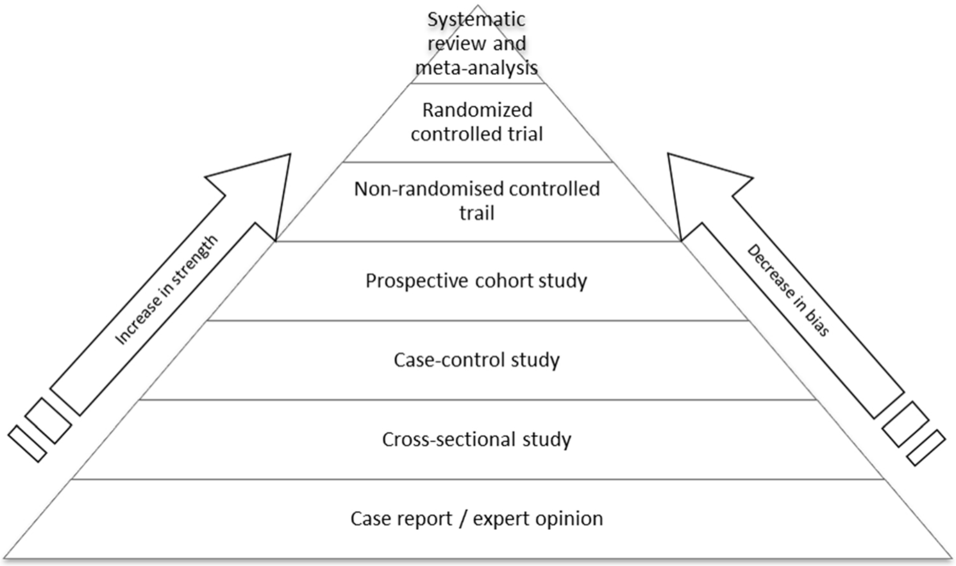

Figure 2. Types of epidemiological studies and grades of evidence

There is growing scientific literature based on cross-sectional studies aiming to describe organic food consumers' profiles [11-18]. These studies provide new insight into the individual characteristics, motivations and dietary patterns that differ according to the level of consumption of organic food. Most of these studies define different types of organic consumers using frequency of consumption (regular, occasional and non-consumption) as a reflection of preferences for such foodstuffs. For the most part, the proportion of organic food across food groups and in the whole diet is not considered.

Furthermore, one of the key challenges when considering the potential effect of organic food consumption on health is to disentangle the potential effect of organic food consumption and overall nutritional quality. Indeed, it has been shown that organic food consumers exhibit healthier dietary patterns [12].

The link between pesticide exposure and health has been investigated in many studies, but a limited number of studies directly address the effects of the consumption of organic food on health.

However, existing data have recently been compiled in some reviews focusing on organic food and health consequences [19-23].

2.2. PARSIFAL, KOALA, ALADDIN: Effects of an organic diet on allergies and atopic diseases in children

The most convincing results are based on studies carried out on a large sample of children in the past decade focusing on allergies and atopic diseases.

The PARSIFAL study [24] was carried out with a cross-sectional design and included about 14,000 children aged between 5 and 13 in five European countries (Austria, Germany, the Netherlands, Sweden and Switzerland). The children were selected from farming families, from families with an anthroposophic lifestyle (in Steiner schools) that included an organic and biodynamic diet, and from a control group. An anthroposophic lifestyle is characterised by the restrictive use of vaccinations and antibiotics, but also by specific dietary patterns.

The children from Steiner schools exhibited a lower prevalence of allergic symptoms and sensitisation, although this finding was not consistent across all the countries. The authors emphasised that it was rather difficult to attribute such findings to organic food consumption since there was a potential variation in the level of adoption of an organic diet among families with an anthroposophic lifestyle. The whole lifestyle may be more responsible for this kind of protective effect than organic food consumption. However, even though it was not possible to make a causal inference because of its cross-sectional design, this study offers an important hypothesis that warrants further investigation.

The KOALA study [25] is a longitudinal birth cohort study conducted in the Netherlands following about 2,700 mothers and babies. In this study, the consumption of organic food (including meat, eggs, fruit and vegetables) or the proportion of these foods in the diet, was not associated with a risk of eczema or atopic sensitisation, and hence did not support the findings observed in the PARISFAL study. However, exclusive consumption of organic dairy products by the mother during pregnancy and during infancy was associated with a 36 % reduction in the risk of eczema at the age of two. It has been hypothesised that such findings could be due to a higher content of some fatty acids, such as vaccenic acid or conjugated linoleic acid, in organic milk. Indeed, a study conducted on the same cohort has shown that the content of these components in human milk may be modified by replacing conventional animal products with those of an organic origin [26].

The ALADDIN prospective birth cohort was developed in Sweden and included 330 children from families with an anthroposophic (including a preference for organic food) or conventional lifestyle to investigate allergic disease during infancy. Children were followed from the foetal period to the age of two years. In this study, children from families with an anthroposophic lifestyle had a significant 75 % reduction in risk of sensitisation during the first two years of life compared to children from families with non-anthroposophic lifestyles [27]. More recently, it has been shown that an anthroposophic lifestyle is associated with a reduction in the risk of self-reported food hypersensitivity and recurrent wheezing. No association was observed between lifestyle and risk of eczema. It should be noted that it is difficult to disentangle the role of organic food and other characteristics of an anthroposophic lifestyle in this study. Overall the findings of the ALADDIN study document that an anthroposophic lifestyle has a greater effect on allergen sensitisation during the first year of life [28].

In summary, human observational studies have demonstrated that an organic diet is associated with a lower risk of childhood allergy but, based on these studies, it is not possible to identify whether it is organic food or other lifestyle factors related to the preference for organic food that account for these associations.

2.3. Norwegian mother and child cohort study

The MoBa study is a Norwegian cohort study that initially included more than 28,000 pregnant women with their first child born between 2002 and 2008. Organic food consumption was estimated as the frequency of its consumption. Women who reported frequent consumption of organic vegetables (but not other food groups) exhibited a 21 % reduction in the risk of pre-eclampsia [29]. Pre-eclampsia is a disorder that occurs during the third trimester of pregnancy and is characterised by high blood pressure and a large amount of protein in the urine. Cases can be severe, threatening both the mother and the foetus and leading to premature birth. Despite a small number of cases, this study also provided some evidence of a link between organic food consumption and lower risk of hypospadias, but not cryptorchidism (both birth defects in male genitals) (odds ratio for hypospadias =0.42; 95 % confidence interval= 0.25, 0.70) [30]. These findings are consistent with previous results observed in a Danish case-control study including more than 600 subjects [31].

As no urine or blood samples were analysed, there was no biomonitoring of pesticide exposure in these studies. Therefore it was not possible to investigate whether the observed significant associations were related to lower pesticide exposure or might be explained by other factors correlated with organic food consumption.

2.4. The Million Women Study

There are very few prospective cohort studies being carried out among adults that focus on the effect of organic food consumption and health. A recent study has investigated the association between organic food consumption and the risk of cancer in 623,080 middle-aged UK women over a 9.3-year follow-up period. Participants reported their consumption of organic food using a simple frequency questionnaire with three modalities (never, sometimes or usually/always). The overall risk of cancer was not associated with organic food consumption, but a significant reduction (-21 %) in the risk of non-Hodgkin lymphoma was observed. A marginal increase (+9 %) in the risk of breast cancer was also detected [32].

To the best of our knowledge, this study is the first to provide findings about a potential link between organic food preference and health events in a long-term prospective cohort study among adults on a large scale. Health data were validated through the National Health Service Central Registers. It should be noted that the consumption of organic food was grouped as "never, "sometimes" or "usually/always", *i.e.* with three modalities. This enabled a limited dose-response investigation. Analyses were partially adjusted for dietary pattern through some confounders such as dietary fibres or red meat and processed meat, but the nutritional quality as a whole was not accounted for, which may represent a major confounding factor.

The potential link between preferences for organic food and non-Hodgkin lymphoma may be interpreted in light of the findings of a recent meta-analysis based on 44 original studies, reporting that occupational exposure to pesticides, including phenoxy herbicides, carbamate insecticides, organophosphorus insecticides and lindane, an organochlorine insecticide, was positively associated with the risk of non-Hodgkin lymphoma [33]. The subtype B cell lymphoma was also positively associated with glyphosate and phenoxy herbicide exposure.

In summary, the lack of investigations on this topic among adults argues prospective studies to be undertaken with well-designed methodologies and a specific focus on organic food consumption.

2.5. The NutriNet-Santé study and the Bionutrinet research programme

The NutriNet-Santé Study is a web-based prospective observational cohort investigating the relationship between nutrition and health, as well as the determinants of dietary patterns and nutritional status. It was launched in May 2009 in France with a scheduled followed-up of at least 10 years [34] during which health events are collected. At the start of the study and yearly, participants are asked to complete a baseline set of self-administered web-based questionnaires on dietary intake, health and anthropometric status, and sociodemographic and lifestyle characteristics. In follow-ups, participants are also invited to complete extensive questionnaires relating to determinants of dietary behaviour and nutritional and health-related characteristics. In particular, volunteers are invited to complete questionnaires with the aim of assessing a wide range of data on organic food consumption (motivations, attitudes, consumption *etc.*).

For instance, participants were asked *via* an optional questionnaire to provide information about organic products. For 18 organic products – fruit, vegetables, soya, dairy products, meat and fish, eggs, grains and legumes, bread and cereals, flour, vegetable oils and condiments, ready-to-eat meals, coffee/tea/herbal tea, wine, biscuits/chocolate/sugar/marmalade, other foods, dietary supplements, textiles and cosmetics – the frequency of consumption or reasons for non-consumption were assessed. The eight possible answers were: 1) most of the time, 2) occasionally, 3) never (too expensive), 4) never (product not available), 5) never ("I'm not interested in organic products"), 6) never ("I avoid such products"), 7) never (for no specific reason) and 8) "I don't know". A typology of consumers was identified among about 54,000 participants, leading to five groups of subjects. Compared to non-consumers, regular consumers of organic foods exhibited a healthier overall nutritional quality of diet (reflected by a better adherence to the French nutritional recommendations score) and a lower probability of overweight and obesity in a cross-sectional design [12] (see also Chapter 3).

This is consistent with findings observed in the German National Nutrition Survey II (NVS II), a nationwide food consumption study conducted among 13,074 adults. German buyers of organic food exhibited healthier characteristics compared with non-buyers, particularly in respect of smoking, physical activity and body weight [13].

Individual health history was described across these groups after extensive adjustment for confounding factors such as the nutritional quality of the diet. In men and women, regular consumers of organic foods were more likely to declare that they have food allergies. Organic food consumers (occasional and regular) declared more often a history of cancer (in women). In both genders, occasional and regular organic food consumers exhibited hypertension, type 2 diabetes and hypercholesterolemia less often than non-consumers. A similar association was observed for cardiovascular disease in men [35].

Given the cross-sectional design of the study, these findings should primarily be interpreted in terms of a change in dietary behaviours in favour of organic foods after a health event (disease). As regards cardiovascular disease and metabolic disorders, for which fat and sugar are more often perceived as risk factors, modification in favour of an organic diet may be less relevant. A recent small, cross-sectional study carried out in the Netherlands reported that general health benefits among organic food consumers include, among other things, an improvement in energy levels, better resistance to illness, psychological wellbeing and improved satiety [15].

Further prospective investigations will therefore improve understanding of the potential benefits of organic food in the aetiology of cardiometabolic disorders.

For a better assessment of the association between organic food consumption and health in future, an organic food frequency questionnaire focusing on the preceding year was used in June 2014 to collect accurate data about conventional and organic food intake, as well as the proportion of organic food in the whole diet, among participants of the NutriNet-Santé cohort study [36].

A prospective association between organic food consumption, using accurate and detailed data, and health indicators is currently being studied.

2.6. Clinical studies in humans

Investigations to evaluate directly the potential effects of consumption of organic products in humans are scarce and are mostly based on very small samples and of short duration [19, 21, 22]. For instance, Smith-Spangler *et al.* concluded that no clinically meaningful differences in *in vivo* health-related biomarkers or nutrient levels were found when comparing subjects who consume organic or conventional food [22].

2.6.1. Effects of organic vs. conventional diet on health

There have been no clinical human studies evaluating the direct impact of an organic diet on health. The probable reason for this is that any effects on human health would be likely to be long-term effects, and it is methodologically difficult and expensive to perform long-term dietary interventions.

2.6.2. Effects of organic vs. conventional diet on health-related biomarkers

An alternative to studying health outcomes is to study levels of health-related intermediate biomarkers that may respond to an intervention more quickly. Some published clinical studies or controlled trials have investigated the differences between organic *versus* conventional food consumption on health-related biomarkers (including antioxidant activity and status, LDL oxidation or plasma triacylglycerol, semen quality, homocysteine, glycaemia *etc*.). Most of them reported null findings, but it should be noted that there have been very few of these studies and they have mostly been based on a limited number of subjects, are of very short duration, and feature a very specific change in diet (one food item for example), and are therefore likely to lead to poor statistical power.

A small Italian cross-over study was conducted on 150 men (100 healthy male individuals + 50 male chronic kidney disease (CKD) patients) [37]. Mediterranean diets composed of foods from organic or conventional production were successively administered for 14 days each. The authors reported a statistically significant improvement in fat mass and homocysteine in all subjects, and in weight and body mass index in CKD patients only. However, a number of limitations should be highlighted, including the absence of permutation in the order of the diets.

2.6.3. Effects of organic vs. conventional food on pesticide exposure

Pesticide residues are important food contaminants. Several studies have been conducted to assess the impact of an organic diet on pesticide residues in humans using urine biomonitoring. They consistently report a markedly lower concentration of pesticide residue metabolites in urine among children or adults (for more information, see Chapter 5).

2.6.4. Effects of consumption of organic vs. conventional food on nutritional biomarkers

Some clinical trials have investigated the nutritional plasma biomarkers of participants who were offered organic food compared to the control [19, 21, 22]. The nutritional biomarkers included polyphenol excretion, carotenoids (in particular flavonoids), phosphorus and vitamin C. Overall no differences were reported except for a randomised controlled cross-study reporting higher quercetin and kaempferol excretion after a three-week organic diet [38]. No difference in antioxidant capacity was detected.

Recently a small double-blind, cross-over intervention trial (OrgTrace) (three dietary periods of 12 days with a two-week-long wash-out) was conducted among 33 men. This study reported no difference in intake or bioavailability of zinc, intake or bioavailability of copper, or plasma status of carotenoids between the organic and conventional diets [39, 40].

Here again, due to potential shortcomings concerning statistical power and design, these studies are too limited to conclude the absence of a link. In particular, experimental designs mostly pertain to a restricted introduction of organic foods (fruit juice or tomatoes), which probably does not reflect the subjects' actual organic diet and thus leads to a limited magnitude effect.

2.7. Conclusions

Overall, there is a scarcity of studies investigating the potential beneficial effects of organic compared to conventional food consumption on health through a direct estimation of the consumption of organic food. It should be noted that large observational prospective cohort studies developed during the 1980s and 1990s did not include a data assessment of organic food consumption. Therefore, such relationships cannot be investigated in these cohorts.

Some limited scientific arguments are available. A link between organic food consumption and a decreased risk of allergic diseases is suggested, and there are indications of a potential beneficial effect on overweight/obesity among adults.

Some questions remain open and as yet there is no conclusive evidence, despite some new and interesting findings from a rather small number of studies and novel epidemiological studies that are in progress. It should be noted that the concept that individual resilience could be amplified under an organic diet has been proposed based on a laboratory animal study [41].

In conclusion, there is a lack of data from well-designed studies (prospective, long-term duration, accurate data in particular for dietary factors and sources, *i.e.* conventional or organic) involving a sufficiently large population.

3. Organic food consumption and sustainable diets

3.1. Organic food consumption patterns – environmental sustainability and health

3.1.1. Consumer attitudes and food choices

Consumers buy organic foods because they associate this kind of food with a healthy and sustainable lifestyle [42-49]. Some consumers are willing to pay a higher price for organic products with additional ethical attributes [50]. They choose the food either in relation to values (such as environmental protection, animal welfare, fair trade) or due to safety concerns (such as pesticide residues or antibiotics). Several studies have underlined this behaviour [51-54].

3.1.2. Preference for organic food and dietary choices

Three large European studies report that consumers who buy organic food consume significantly more fruit (+17 % [13], +25 % [12] (both average men/women)), more vegetables (+23 % [13], +27 % [12] (both average m/w)), more whole grains (+200 % [12] (average m/w)) or dietary fibres (+17% [32] (w)), more legumes (+ 68 % [12] (average m/w)) and less red and processed meat [32] (w), -25 % [13], -32 % [12] (both average m/w)) than other consumers – these figures refer to a comparison of regular consumers *vs.* non-consumers of organic food, if reported. Accordingly, consumers who often buy organic food have a higher adherence to a healthy food pattern [12, 29]. While regular organic consumers are generally ethically motivated, occasional buyers tend to be driven by food safety concerns [42, 44]. Regular and occasional consumers of organic food associate the term "organic" first with fresh vegetables and fruit, which are commonly the first food group that consumers buy organic [47]. They associate a healthy diet with organic products [47]. Moreover, organic consumption patterns [12, 13, 35, 36] seem to align well with the sustainable diet concept of the FAO [2] as consumers who regularly buy organic food tend to choose more vegetables, fruit and fresh food than highly processed food, including sweets *etc.*, or meat. These food choices are also very much in line with healthy dietary patterns. Consumers who regularly buy organic food seem to include essential elements of a healthy lifestyle as they are more physically active and less likely to smoke [12, 13, 32], although in one study women with an organic food preference were more likely to smoke during pregnancy [29].

3.2. How consumption patterns of consumers with an organic food preference are linked to risks of chronic disease

These consumption patterns may be associated with a reduced risk of non-communicable diseases. Diet-related non-communicable diseases such as diabetes cause millions of premature deaths worldwide every year [55, 56]. Promoting healthy and sustainable lifestyles is a major policy goal [2]. Healthy diets as part of a healthy lifestyle may prevent chronic diseases [55]. This is underlined by studies demonstrating a reduced risk of type II diabetes [57-61], cardiovascular disease [60, 62, 63], some cancers [60, 64-66] and mortality [60, 67] in people with healthy diets. There is also a lower mortality in people who report an overall healthy lifestyle, where a healthy diet is one factor [68]. In terms of food, as examples with relevance in the context of this chapter, wholegrain and dietary fibre intake are inversely associated with the risk of cardiovascular disease [69, 70] and all-cause mortality [71, 72]. Consumption of fruit and vegetables is inversely associated with all-cause and cardiovascular mortality [73], and there is convincing evidence that increased consumption of fruit and vegetables reduces the risk of hypertension, coronary heart disease and strokes [74]. The consumption of red meat is positively associated with cardiovascular mortality [75] but not all-cause mortality [75, 76].

The consumption of red meat and processed meat is also associated with the risk of colorectal cancer, where causal relationships are regarded as established (processed meat) or probable (red meat) based on epidemiological and mechanistic evidence [77]. It should be noted that a comprehensive review of associations between food and disease lies outside the scope of this report.

3.3. Sustainable diets

Dietary patterns worldwide are undergoing changes [78]. These changes have important impacts on the environment, societies and human health as diets link environmental sustainability and human health [79]. For the development of healthy and environmentally-sustainable food systems in future, it is therefore not sufficient to focus solely on production; instead production and consumption need to be considered in an integrated manner as a food system [2, 80]. The sociocultural context of food consumption and dietary patterns, in particular, has been recognised as an essential part of a sustainable food system. Sustainable diets have been defined as “those diets with low environmental impacts which contribute to food and nutrition security and to healthy life for present and future generations. Sustainable diets are protective and respectful of biodiversity and ecosystems, culturally acceptable, accessible, economically fair and affordable; nutritionally adequate, safe and healthy; while optimizing natural and human resources” [2]. Currently, the overall sustainability of a food system cannot be easily measured. However, it is possible to compare food systems with respect to environmental or health indicators.

3.3.1. The Mediterranean Diet and the New Nordic Diet – two examples of sustainable diets

The Mediterranean Diet (MedDiet) concept provides one of the models for sustainable diets [81]. It has in the first instance been described and documented as a model for healthy diets, as adherence to the MedDiet is negatively associated with a risk of major chronic diseases, including a reduction in all-cause mortality and risk of cardiovascular disease and cancer [82]. The MedDiet is characterised by a comparatively high intake of fruit, vegetables, legumes, cereals, fish and olive oil, a comparatively low intake of meat and dairy products, and a moderate intake of alcohol [82]. The MedDiet concept has been expanded by aspects of environmental sustainability and developed further towards a model for sustainable diets [81, 83-85]. For example in Spain, if a Mediterranean dietary pattern were adopted by the entire population, greenhouse gas emissions from diets would be reduced by 72 %, land use by 58 %, energy by 52 % and water use by 33 % compared to current consumption patterns [86].

The transformation of the MedDiet concept to northern European regions has resulted in the New Nordic Diet concept [87, 88]. While the MedDiet is a traditional diet, the New Nordic Diet has been developed by scientists and chefs, integrating environmental sustainability and health from the outset. The New Nordic Diet is characterised by a high intake of fruit, vegetables, legumes, whole grains, nuts and fish, and a low intake of meat compared to the average consumption [88]. The development of the New Nordic Diet has been followed by the development of educational tools such as cookery books. Adoption of this diet would save 18,000 disability-adjusted life years (DALY) by preventing non-communicable diseases per year in Denmark, which is reported as a cost-effective prevention [89]. Compared to the average Danish diet, the adoption of the New Nordic Diet would improve all 16 environmental indicators in a lifecycle analysis (disregarding the production system). If conventionally produced food were also replaced by organic food, only 10 of the 16 environmental indicators would improve, while the environmental impact of the remaining six would increase [90]. Apart from health and environmental issues, the New Nordic Diet takes into account issues of food origin (*e.g.* local production, growing wild), cultural identity (connecting to Scandinavian traditions) and food processing [87].

3.4. Potential contribution of the organic agro-food system to sustainable diets

In contrast to the wealth of studies on the nutritional value and environmental performance of organic products, there has so far been no evaluation of whether the organic food system, understood as comprising agricultural production according to organic standards and dietary patterns of consumers who prefer organic food, has distinct health and environmental sustainability characteristics [91].

With respect to human health, it is apparent that the dietary preferences of consumers who prefer organic food have similarities with the Mediterranean Diet and the New Nordic Diet [88], including a comparatively low consumption of meat and a comparatively high consumption of fruit, vegetables, legumes and wholegrain products. According to the discussion above, these dietary preferences are likely to imply health benefits for the consumer.

With respect to environmental sustainability, organic agriculture performs favourably for many but not all indicators; importantly, the yields are generally lower compared to conventional production systems, implying greater land use to generate the same amount of food [4]. However, the dietary preferences of consumers who regularly choose organic food, specifically the comparatively low meat consumption and comparatively high legume consumption, may imply favourable dietary land use and greenhouse gas emission footprints. It remains to be investigated how the organic agro-food system compares to other food systems with respect to these important indicators.

3.5. Conclusions

Much of the research regarding the health effects of organic food has focused on the potential dependence of the nutritional composition of foods on the production system. Recent large studies show that certain dietary patterns are associated with the preference for organic food. These patterns, including a comparatively high intake of fruit, vegetables and wholegrain products and a low intake of meat, are likely to have a beneficial effect on human health. They also coincide with patterns that are favourable from the perspective of environmental sustainability, such as greenhouse gas emissions and land use. Further evaluations need to be undertaken around the extent to which the organic agro-food system, comprising production and consumption, can serve as an example of a sustainable food system with respect to health and environmental effects.

4. Experimental *in vitro* and animal studies

4.1. Studies of health effects: *in vitro* studies

The focus on single plant components in the comparison of crops from organic and conventional production, discussed in Chapter 6, neglects the fact that nutrients do not exist and act in isolated forms, but in their natural contexts [92]. *In vitro* experiments on cell lines are one way of studying the biological effects of entire foods.

In a small and early study using a bacterial assay for antimutagenic activity, it was found that the juice of five organically grown vegetables (Welsh onion, sweet pepper, carrot, spinach and Japanese radish) in most cases have a stronger antimutagenic effect against some mutagenic compounds than the same types of vegetables grown on a neighbouring conventional farm [93]. Another small study compared the cytoprotective activity of Sicilian red oranges from organic *vs.* integrated production, purchased on four occasions from one retailer. Despite a slightly higher antioxidant activity in organic orange extracts, no significant differences in the protection of cells against oxidative damage between samples from organic and integrated production were observed [94]. Furthermore, the antioxidant activity of organic and conventional grape leaf extracts was studied in a series of *in vitro* assays using rat heart, liver and kidney tissue. All grape leaf extracts provided protection against oxidative damage to lipids and proteins to a varying degree, but neither the organic nor the conventional extracts offered overall better protection [95]. A common weakness of these three studies is their reliance on samples obtained from a single farm pair or retailer, without taking the actual agricultural practices into consideration.

Two studies have investigated the effect of organic and conventional crops on cancer cell lines, both using crops produced under well-documented agricultural practices. In one study, extracts from organically grown strawberries exhibited stronger antiproliferative activity against one colon and one breast cancer cell line, compared to extracts from conventional berries [96]. Furthermore, the activity of naturally fermented beetroot juices on a cancer cell line has been investigated. Juice from organically and conventionally grown beetroots differed in the extent to which various types of cell death were induced. These findings were reported as the organic fermented beetroot juice having a stronger anti-cancer activity [97]. Both studies demonstrated sizeable differences in the biological activity of organic *vs.* conventionally produced crop extracts, which may serve as a rationale for continued research efforts or for the effects observed in animal or human studies. However, none of the studies included any measure of non-specific cell toxicity, *e.g.* using healthy control cell lines. In other words it is not possible to determine whether the cytotoxic activities observed are specific to the respective cancer cells or rather constitute non-specific toxicity against any cell. Accordingly, from these two studies, it can be concluded that the organic and the conventional extracts had differential *in vitro* biological activities, but it is not possible to determine which of the organic and conventional extracts, if any, had the preferable biological activity.

In summary, four of the five *in vitro* studies cited have revealed different biological potency or activity of the organic plant extracts/juices compared to the conventional ones. The authors of these studies speculate or conclude that a higher content of antioxidants, namely various phenolic compounds, in organic fruit and vegetables is responsible for the observed effects.

4.2. Animal studies of health effects

Animal studies are performed as models for humans where studies on humans are not feasible. Animal studies have several advantages over studies of health effects in humans: researchers can fully control the environment and animal feed over a long time, and it is possible to conduct studies over several generations. However, results from animal studies are not easily translatable to humans: observed effects may be specific for the species, and for any extrapolations to humans care must be taken in the choice of a suitable animal model for the outcome of interest. Furthermore, the diversity of genotypes, environments and lifestyles is typically much larger in natural human populations than in animal studies.

The history of animal studies that compare the health effects of organically and conventionally produced feed goes back almost 100 years. A large number of studies with varying designs have been published. These have been reviewed elsewhere, with the overall conclusion that positive effects of organic feed on animal health are suggested by existing studies, but confirmatory research is still needed in animals and ultimately in humans [98]. Here, we focus on health outcomes related to the immune system and to fertility/fecundity, both of which have received attention in a substantial number of studies.

4.2.1. Immune system

In one of the best-designed animal studies, chickens were raised on feed identically composed from ingredients obtained from organic and conventional farm pairs. In the second generation, chickens receiving the conventionally grown feed displayed a faster growth rate. Upon exposure to an immune challenge by the injection of a protein foreign to the body at nine weeks of age, chickens receiving organic feed displayed a more pronounced immune reaction and recovered more quickly from the challenge, as manifested in a more pronounced “catch-up growth” [41]. Although all the chickens in the study were healthy in terms of “absence of disease”, the observed robustness against a challenge in the chickens that received organic feed has subsequently been interpreted as a sign of better health [99, 100].

A one-generation rat study was based on feeds produced in field trials under highly controlled conditions, using four crops grown for two years in three production systems (one conventional, two organic) in two to three locations, each with two field replicates per location. Overall, the production system had an effect on plasma IgG levels in rats; however this effect was inconsistent with an opposite effect observed in earlier studies. Other factors (location and year) also had effects on some of the reported nutritional and health parameters, to a degree that may outweigh any effect of the production system [101]. A two-generational rat study, using four experimental feeds produced under controlled conditions using organic *vs.* mineral fertiliser and organic *vs.* conventional plant protection, demonstrated that the production system influenced several physiological, endocrine and immune parameters in the offspring [102]. Most of the observed effects were caused by the fertilisation regime.

Several other studies, mostly in rats, have investigated the effects of the feed production system on various aspects and parameters of the immune system. Most, but not all, of these studies have found some effect of the feed production system on some immune system parameter(s) [102-105]. However, it is not easy to judge whether the effects observed in the various studies are consistent with one another. Furthermore, the relevance of these findings for human health is not clear due to general limitations in extrapolating results from studies in small mammals and birds to humans.

4.2.2. Reproduction: fertility/fecundity

In one recent study, fruit flies were raised on feed prepared from organic *vs.* conventional potatoes, raisins, bananas or soybeans obtained from a retailer. The fertility of flies was evaluated as daily egg-laying, and was significantly higher in flies raised on organic feed for each of the four feedstuffs. In addition, the lifespan was longer for the flies eating organic feed for three of four feedstuffs, and unchanged for the fourth. For tolerance to starvation and oxidative stress, no clear trends in favour of feed from any of the production systems were observed [106].

Several older animal studies from the 1970s and 1980s also investigated the effects of the feed production system on reproductive performance and have been reviewed elsewhere [98, 107]. Some studies report beneficial effects of organic feed, while others do not. As an overall conclusion of these studies, no clear effect of the production system on reproductive performance can be demonstrated. For older studies, it is important to bear in mind that relevant agricultural management practices may have undergone changes.

4.3. Conclusions

In vitro studies have given some indications of differential biological activities in organic and conventional foods in various cell models, but the methods employed do not at this point allow for strong conclusions to be made as to whether any of the observed effects favour any of the production systems.

A small number of well-designed animal studies point to an effect of feed production system on some aspects of the immune system and its development. However, to date the relevance and implications of these findings for humans are unclear and these findings have not been translated into hypotheses to be tested in humans.

5. Pesticides

5.1. Plant protection in organic and conventional agriculture

Plant protection in conventional agriculture is largely dependent on the use of synthetic pesticides, whereas organic farming largely relies on agricultural and biological means for plant protection, such as crop rotation, intercropping, resistant varieties, biological control employing natural enemies, hygiene practices and other measures [108, 109], although certain materials classified as pesticides are approved for use in organic agriculture. In the EU, pesticides (in this context, more specifically chemical plant-protection products) are approved after an extensive evaluation, including a range of toxicological tests in animal studies [110]. Acceptable residue concentrations in food are calculated from the same documentation and from the expected concentrations in accordance with approved uses of the pesticides. Currently, 389 substances are authorised as pesticides in the EU (Table 2). Of these, 35 are also approved for use in organic agriculture [111-113], as evaluated in accordance with the same legal framework.

Most of the pesticides approved for organic agriculture are of comparatively low toxicological concern for consumers because they are not associated with any identified toxicity (*e.g.* spearmint oil, quartz sand, some microorganisms), they are part of a normal diet or are human nutrients (*e.g.* iron, potassium bicarbonate, rapeseed oil) or because they are approved for use in insect traps only and therefore not applied to soil or plants (the synthetic pyrethroids lambda-cyhalothrin and deltamethrin, pheromones). Two notable exceptions are the pyrethrins and copper (Table 2). Pyrethrins, a plant extract from *Chrysanthemum cinerariaefolium,* share the same mechanism of action as the synthetic pyrethroid insecticides, but are less stable. Copper is an essential nutrient for plants, animals and humans, but toxic when chronically ingested in higher concentrations and of ecotoxicological concern due to accumulation in soils and sediments and due to toxicity to algae and daphnia.

	Approved in EU agriculture [1]	Of these, also approved in EU organic agriculture [1]
Total number of EU-approved active substances [1, 2]	389	35
Of these:		
No identified toxicity [3]	49	24
Classified as [4]		
Acutely toxic class 1+2+3+4, total [5]	5+17+26+78, 102	0+0+2+2, 3 [6]
Carcinogenicity category 2 [7]	28	0
Germ cell mutagenicity category 2 [8]	2	0
Reproductive toxicity category 1B + 2 [9]	5+23	0
Candidate for substitution [10]		
Low ADI/ARfD/AOEL	20	0
Two PBT criteria fulfilled [11]	57	1 [12]
Reproductive toxicity 1B [9]	5	0
Endocrine disruption	5	0

Table 2. Active substances approved in the EU and important toxicological properties according to risk assessments by EFSA. Data compiled from the EU pesticides database [112] and from Commission Regulation 889/2008 (consolidated version 2016-05-07) Annex II Sections 1-3 [113]

[1] Following the practice of [113], the groups of copper compounds, pheromones, repellents by smell of animal and plant origin, microorganisms, fatty acids C7 to C20 (only potassium salts approved for organic agriculture) and paraffin oils are counted as one substance per group. In deviation from [113], plant oils are counted as four substances due to different toxicologicahl properties

[2] Active substance approved in the EU and at least one plant-protection product based on this substance approved or approval in progress in at least one member state (including basic substances; for organic agriculture including five basic substances that are classified as foodstuffs and are of plant/animal origin)

[3] No identified chronic (ADI – acceptable daily intake) or acute toxicity (ARfD – acute reference dose) or an identified acceptable operator exposure level (AOEL)

[4] According to Regulation 1272/2008. Only classifications that relate to human health effects and to at least one of the criteria for "candidates for substitution" are included in the table (*e.g.* skin sensitisation not included). These classifications relate to a compound's intrinsic hazardous properties, irrespective of its use. Classifications without any compound are not included (*e.g.* carcinogenicity class 1 A + B)

[5] Class 1 referring to the highest acute toxicity. Some substances have multiple classifications for different endpoints therefore the total number of compounds is lower than the sum

[6] Pyrethrins, extract from *Chrysanthemum cinerariaefolium*, are classified as acutely toxic class 4. In addition, two acutely toxic synthetic pyrethroids are approved for use in insect traps in organic agriculture: lambda-cyhalothrin (class 3 + 4) and deltamethrin (class 3)

[7] Category 2: "Suspected human carcinogens". (Category 1A/B: known/presumed to have carcinogenic potential for humans. No substances in this class)

[8] Category 2: "Substances which cause concern for humans owing to the possibility that they may induce heritable mutations in the germ cells of humans". (Category 1A/B: "Substances known to/to be regarded as if they induce heritable mutations in the germ cells of humans". No substances in this class)

[9] 1B: "Presumed human reproductive toxicant", 2: "Suspected human reproductive toxicant". (1A: "Known human reproductive toxicant". No substances in this class)

[10] Refers to approved substances that should be replaced when less hazardous substances/products are available. The criteria "Carcinogenous 1A/1B" (no compound), "Nature of critical effects" (no compound, no criteria defined) and "Non-active isomers" (two compounds, none approved in organic agriculture) are not included in this table

[11] PBT criteria: persistent, bioaccumulative and toxic according to criteria specified in [110]

[12] Copper. PBT classification based on accumulation in freshwater/estuarine sediment (P) and toxicity to algae and daphnia (T)

According to the EU directive on the sustainable use of pesticides [114], since 2014 all pesticide applicators (occupational users) in the EU must apply the principles of integrated pest management (IPM), which implies that all available plant-protection measures, including non-chemical ones, need to be considered. In particular, methods supporting natural pest control mechanisms have to be prioritised. The objective is to reduce the risks to human health and the environment. Although full implementation is likely to take many years, plant protection in conventional agriculture in the EU is thereby moving towards the practices applied in organic farming. Conversely, organic agriculture today essentially fulfils the principles of IPM and is mentioned in the directive as one form of low-pesticide input agriculture. Several national action plans [115] (*e.g.* Sweden, Germany, Italy) to implement this directive therefore explicitly include targets to increase the agricultural area under organic certification.

Agro-ecological approaches to plant protection have the potential to reduce pesticide inputs [116, 117]. Diverse organisations argue that practices developed in and for organic agriculture may be of benefit to the entire agricultural system [118-122], which is of specific value for the transition towards integrated pest management in the EU. Here, we give a few different examples of what this can look like in practice. The Swedish Board of Agriculture provides leaflets with information for conventional plant producers to assist in the mandatory transition towards integrated pest management. These leaflets make several references to existing information for organic producers [123]. The “Bicopoll” project and its predecessors have developed the use of bees to deliver spores of a beneficial fungus to strawberry flowers in order to prevent the development of grey mould in strawberries, thus providing an alternative to synthetic fungicide treatments. This approach has been developed for organic agriculture, but is now being adopted by some conventional strawberry growers [124]. Steam treatment of cereal seeds for the prevention of several fungal diseases [125] has been developed in organic agriculture as an alternative to chemical seed treatments [126, 127]. These methods are now also being marketed for conventional agriculture, specifically for integrated pest management as well [128]. The “System Cameleon” is a camera-steered machine for seeding, hoeing and precision fertilisation for use in several arable crops. It has been conceived and developed by an organic farmer, motivated by the lack of machinery developed for the needs of organic farming [129]. This machine is now being marketed for “crop production with reduced or no pesticides” [130], and its mechanical weeding capabilities have been successfully combined with reduced herbicide applications to control weeds in spring rapeseed cultivation [131, 132].

5.2. Pesticide use – exposure of consumers and producers

One main advantage of organic food production is the restricted use of synthetic pesticides [111, 113, 133], which leads to low residue levels in foods and thus lower pesticide exposure for consumers [22, 23, 134, 135]. It also reduces the occupational exposure of farm workers to pesticides and drift exposures of rural populations. According to the latest EFSA report on pesticide residues in food samples in the EU, pesticide residues were detected in 44.4 % of conventional food products (2.7 % above the maximum residue level (MRL), the legal limit) and in 15.5 % of the organic products (0.8% above MRL) indicating that pesticide exposure *via* organic foods is comparatively low [134]. Although there are few comparisons of the risks from dietary pesticide exposures *via* conventional and organic products, based on residues found in foods, pesticide residues in 18,747 samples of 12 foods were screened for potential exceedance of the acute reference dose (ARfD) for high consumers of these specific foods. At least 586 of these samples were of organic origin. A total of 218 samples (=1.2 %) exceeded the ARfD for at least one dietary scenario, with the organophosphate chlorpyrifos accounting for two thirds of these cases. None (0 %) of the organic samples exceeded the ARfD for any dietary scenario [134]. This risk assessment was based on 96 of the 202 pesticides approved in the EU that have identified acute toxicity (*i.e.* specified ARfD), including three of the four pesticides authorised for organic agriculture that have identified acute toxicity (pyrethrins, deltamethrin, lambda-cyhalothrin (the latter two to be used in insect traps only; azadirachtin was not included). It should be noted that ARfD does not provide any information on the potential risks of long-term exposure. Furthermore, MRL can be exceeded due to high residues or due to a very low MRL in cases where no use of the specific substance for the particular crop is approved.

One cumulative chronic risk assessment comparing organic and conventional products has been performed in Sweden. Using the hazard index (HI) method [136], adults consuming 500 g of fruit, vegetables and berries per day in average proportions had a calculated HI of 0.15 under the assumption of imported conventional products, an HI of 0.021 when assuming Swedish conventional products and an HI of 0.0003 under the assumption of organic products [137]. This work was based on Swedish food monitoring data of 173 of the 331 pesticides approved in the EU that have identified chronic toxicity (*i.e.* specified ADI), including five of the nine pesticides authorised for organic agriculture that have identified chronic toxicity (azadirachtin, pyrethrins, spinosad, deltamethrin, lambda-cyhalothrin (the latter two to be used in insect traps only)). Copper, iron, citronella oil and clove oil were not included in the monitoring.

Even though the scope of this observation is limited, it is apparent that both pesticide exposure and the calculated health risks are far lower for organic products than for conventional products. This indicates that current systems for the certification and control of organic products are suitable, although they still can be improved [138].The following section reviews the evidence on human pesticide exposure in the EU and the epidemiological data on adverse health effects.

The general population's exposure to pesticides can be measured by analysing blood and urine samples, as is routinely done in the US [139] although not yet in Europe. As the pesticides in use today are metabolised and excreted within a few days and hundreds of single active ingredients are used, methods that measure common metabolites for groups of pesticides with similar chemical and toxic properties are often more useful and efficient than measurements of specific pesticide metabolites for estimating pesticide exposure at a population level. Established methods are available for dialkyl phosphates (DAPs), which are common metabolites of multiple organophosphate insecticides [140], 3-phenoxybenzoic acid (3-PBA), which is a common urinary metabolite of several pyrethroid insecticides [141], and for a range of specific pesticides or their metabolites. Exposure levels of specific pesticides are mainly relevant if they are frequently detected in food items and if they are of special concern with regard to adverse health effects. Examples are the widely-used organophosphate chlorpyrifos with the specific metabolite trichloro-2-pyridinol (TCPY) and the herbicide 2,4-dichlorophenoxyacetic acid (2,4-D) [141].

A few scattered European studies from France [142-144], Germany [145], the Netherlands [146], Spain [147], Belgium [148], Poland [149] and Denmark [150] have shown that EU citizens are commonly exposed to pesticides. It should be noted that the exposure levels of organophosphates found in most of the European studies are similar to or higher than in the US studies in which neurobehavioral deficits have been associated with DAP concentrations in urine samples, as described below. A general observation has been higher urine concentrations of pesticides in children compared to adults, most likely reflecting children's higher food intake in relation to body weight and maybe also more exposure-prone behaviours.

Although exposure to pesticides can originate from occupational operations or from home and garden use, pesticide residues contained in conventional foods constitute the main source of exposure for the general population. This has been illustrated in intervention studies where the urinary excretion of pesticides reduced markedly after one week of limiting consumption to organic food [151-153]. Similar conclusions have emerged from studies investigating associations between urinary concentrations of pesticides and questionnaire information on food intake, frequency of different foodstuffs and organic food choices. Thus a high intake of fruit and vegetables is positively correlated with pesticide excretion [154] and frequent consumption of organic produce is associated with lower urinary pesticide concentration [155].

In addition to dietary pesticide exposures, conventional farming might result in the exposure of farm workers and their families, as well as rural populations living near sprayed agricultural fields, as demonstrated in several studies [156-158].

5.3. Pesticide exposure and health effects

The regulatory risk assessment of pesticides currently practised in the EU is comprehensive, as a large number of toxicological effects are addressed in animal and other experimental studies. Nonetheless, there are concerns that this risk assessment is inadequate at addressing mixed exposures, specifically for carcinogenic effects [159] as well as endocrine-disrupting effects [160, 161] and neurotoxicity [162]. Furthermore, there are concerns that test protocols lag behind independent science [163], studies from independent science are not fully considered [164] and data gaps are accepted too readily [165]. These concerns primarily relate to effects of chronic exposure and to chronic effects of acute exposure, which are generally more difficult to discover than acute effects. However, this report is not meant to provide a discussion of the regulatory risk assessment of pesticides. Instead, this section focuses on epidemiological studies of pesticide exposure and human health effects. There is also a discussion of how findings from these epidemiological studies relate to organic food and to regulatory pesticide risk assessment.

The overall health benefits of high fruit and vegetable consumption are well documented [73, 74], but these benefits might be compromised by the adverse effects of pesticide residues, as recently indicated for effects on semen quality [166]. The potential negative effects of dietary pesticide residues on consumer health should not be used as an argument for reducing fruit and vegetable consumption. Instead, this discussion may serve as a rationale for individual choice and political action to decrease dietary pesticide exposure while maintaining a high consumption of fruit and vegetables. From a regulatory point of view, there is no basis for offsetting the potential adverse effects of residual contamination against the benefits of fruit and vegetable consumption. (In this context, it is worth noting that people who choose organic food also consume more fruit and vegetables (see also Chapter 3), despite the concern that the higher prices of organic produce could result in lower fruit and vegetable consumption [23]).

Synthetic pesticides comprise a variety of bioactive chemical substances, and a considerable proportion of these possess neurotoxic, endocrine-disrupting, carcinogenic and/or other toxic properties. Exposures related to the production of conventional crops (*i.e.* occupational or drift exposure from spraying) have been related to an increased risk of some diseases including Parkinson's disease [167-169], type 2 diabetes [170, 171] and certain types of cancers including non-Hodgkin lymphoma [33] and childhood leukaemia or lymphomas, *e.g.* after occupational exposure during pregnancy [167, 172] or residential use of pesticides during pregnancy [167, 173] or childhood [174]. Foetal life and early childhood are especially vulnerable periods for exposure to neurotoxicants and endocrine disruptors. Even brief occupational exposure during the first weeks of pregnancy, before women know they are pregnant, have been related to adverse long-lasting effects on their children's growth, brain functions and sexual development [175-179].

Chronic adverse health effects related to occupational exposure may be caused by peak acute exposure or chronic exposure to certain pesticides. Without detailed knowledge of which exposure patterns may cause a disease, the direct relevance of these studies for consumers' dietary exposure levels must therefore be carefully evaluated.

In order to assess the potential health risk for consumers associated with exposure to dietary pesticides, epidemiological studies of sensitive health outcomes and their links to exposure measures have to be relied on. The main focus so far has been on cognitive deficits in children in relation to their mother's exposure level to organophosphate insecticides during pregnancy. This line of research is highly appropriate given the known neurotoxicity of many pesticides in laboratory animal models [162] and the substantial vulnerability of the human brain during early development [180].

Most of the human studies have been carried out in the US and have focused on assessing brain functions in children with different levels of prenatal organophosphate exposure. In a longitudinal birth cohort study among farmworkers in California (the CHAMACOS cohort), maternal urinary concentrations of organophosphate metabolites in pregnancy are associated with abnormal reflexes in neonates [181], adverse mental development at two years of age [182], attention problems at three and a half and five years [183], and poorer intellectual development at seven years [184]. In accordance with this, a birth cohort study from New York reported impaired cognitive development at the ages 12 and 24 months and six to nine years related to maternal urine concentrations of organophosphates in pregnancy [185]. In another New York inner-city birth cohort, concentration of the organophosphate chlorpyrifos in umbilical cord blood has been found to be associated with delayed psychomotor and mental development in children in the first three years of life [186], poorer working memory and full-scale IQ at seven years of age [187], structural changes, including decreased cortical thickness, in the brain of the children at school age [188], and mild to moderate tremor in the arms at 11 years of age [189]. Based on these studies, chlorpyrifos has recently been categorised as a human developmental neurotoxicant [190]. Several reviews of neurodevelopmental effects of organophosphate insecticides in humans have been conducted and most of them conclude that exposure during pregnancy, at levels found among groups of the general population, may have negative effects on children's neurodevelopment [191-193]. A few reviews find the evidence for such effects less convincing [194, 195]. The discrepancy in conclusions is probably related to the large variability in study designs and the methodologies used to assess exposure and neurodevelopmental outcomes across studies, as well as differences in the procedure used for including studies in the reviews.

Since growth and functional development of the human brain continues during childhood, it is assumed that the postnatal period is also vulnerable to neurotoxic exposures [180]. Accordingly, five-year-old children from the CHAMACOS cohort had higher risk scores for development of attention deficit hyperactive disorder (ADHD) if their urine concentration of organophosphate metabolites was elevated [183]. Based on cross-sectional data from NHANES in the US, the risk of developing ADHD increases by 55 % for a ten-fold increase in urinary concentration of organophosphate metabolites in children between eight and 15 years [196]. Also based on the NHANES data, children with detectable concentrations of pyrethroids in their urine are twice as likely to have ADHD compared with those below the detection limit [197]. In addition, associations between urinary concentrations of pyrethroid metabolites in children and parent-reported learning disabilities, ADHD or other behavioural problems in the children have recently been reported in studies from the US and Canada [198, 199]. Nevertheless, although current exposures may also reflect past exposures, these cross-sectional studies cannot rule out reverse causality, *i.e.* that the ADHD children somehow acquired higher exposures.

So far only two prospective studies from the EU addressing associations between urinary levels of pesticides and neurodevelopment in children from the general population have been published. Both studies are based on the PELAGIE cohort in France and present results for organophosphates and pyrethroids respectively [142, 143]. While no adverse effects on cognitive function in six-year-old children were related to maternal urine concentrations during pregnancy of organophosphate or pyrethroid metabolites in this cohort, the children's own urinary concentrations of pyrethroid metabolites in particular were related to decrements in verbal and memory functions. Thus, this sole European study did not appear to confirm the results from birth cohort studies from the US showing that exposure during pregnancy to organophosphate insecticides at levels found in the general population may harm brain development in the foetus. However, the exposure levels measured in the PELAGIE cohort were considerably lower for both organophosphates and pyrethroids than those measured in other European studies as well as in studies from the US and Canada. The median urine concentration of organophosphate metabolites in pregnant women in the PELAGIE cohort was two to six times lower than for pregnant women in other studies [146, 183, 200] and the concentration of the common pyrethroid metabolite 3-PBA was only detectable in urine samples from 30 % of the women compared to 80-90 % in other studies [149, 201]. Thus, more studies that include more representative exposure levels for EU citizens are desirable.

Although exposure levels found in European countries are generally similar to or slightly higher than concentrations found in the US studies, the risk of adverse effects on neurodevelopment in European populations needs to be further characterised. The organophosphate insecticides contributing to the exposure might differ between the US and the EU. In the EU chlorpyrifos is probably one of the most important contributors to health risks due to its widespread use and frequent detection in commodities on the European market. Furthermore, according to the European Food Safety Agency (EFSA), this pesticide is the one that most often exceeds the toxicological reference value (ARfD) [134]. As yet, no European studies have measured chlorpyrifos exposure in population-based studies to determine the potential effects on neurodevelopment after foetal or early life exposure. Such studies, as well as studies including other pesticides widely used in agriculture in the EU, *e.g.* pyrethroids, dithiocarbamate fungicides and selected herbicides, and developmental health effects are warranted to obtain better data for a risk assessment for the European population. Nonetheless, a recent report utilised the US data on adverse effects on children’s IQ levels to calculate the approximate costs of organophosphate exposure in the EU. The total number of IQ points lost due to these pesticides was estimated to be 13 million per year, representing a value of about € 125 billion [202], *i.e.* about 1 % of the EU’s gross domestic product. Although there is some uncertainty associated with this calculation, it most likely represents an underestimation, as it focused only on one group of pesticides. As discussed above, a diet based on organic food has been shown to strongly reduce the consumer’s exposure to organophosphates. Thus, population groups at high risk, such as pregnant women and children, could minimise their exposures by avoiding the kinds of conventional fruits and vegetables that show the highest residue levels. Which kind of fruits and vegetables that have highest residues depends on the approved uses of specific pesticides in each member state, and on the degree specific crops are produced domestically in that member state or imported. Also, the need for pest control and therefore the level of pesticide residues generally varies by crop type.

It is worth noting that in no case known to us has any epidemiological study linking pesticide exposure and human health effects been regarded as reliable in the regulatory risk assessment by EU authorities. For example, in the case of chlorpyrifos, the relevant epidemiological studies are discussed with the conclusion that an association of prenatal chlorpyrifos exposure and adverse neurodevelopmental outcomes is likely. However, it is stated that the contribution to this observation of other neurotoxic agents (including other pesticides) cannot be ruled out, and that animal studies only show adverse effects at 1,000-fold higher exposures. Therefore, the results of the epidemiological studies were disregarded when setting the toxicity reference value [203]. The recent decrease of the maximum residue limit for chlorpyrifos in several crops [204, 205] was still based on animal studies [206]; the limits for the sister compound, chlorpyrifos-methyl were not updated. Given the apparent inability of current pesticide toxicity tests to predict adverse effects that have been documented in epidemiological studies, a concern may be raised that the toxicity tests and the way the results are interpreted need to be reconsidered. For example, very few pesticides have been properly tested for developmental neurotoxicity.

The statement that the epidemiological data on chlorpyrifos cannot be used for regulatory risk assessment because other neurotoxic agents might have contributed to the observed effects is a good illustration of one of the major obstacles to effective protection of the general population being exposed to a broad variety of neurotoxic agents simultaneously. In addition, health effects other than cognitive deficits may be of relevance, *e.g.* disturbances of the endocrine system, but the authorities still do not require testing of endocrine-disrupting effects.

5.4. Conclusions

Recent insight into the toxic effects of pesticide exposure suggests that early-life exposure is of greatest concern, especially prenatal exposure that may harm brain development. Most insecticides are designed to be toxic to the insect nervous system, but living creatures depend on similar neurochemical processes and may therefore all be vulnerable to these substances. Besides insecticides, experimental studies have suggested the potential of adverse effects on the nervous system for many herbicides and fungicides as well [162]. However, no systematic testing is available since testing for neurotoxicity – especially developmental neurotoxicity – has not consistently been required as part of the registration process, although it may be required for more substances in future. Nevertheless, at least 100 different pesticides are known to cause adverse neurological effects in adults [162], and all of these substances must therefore be suspected of being capable of damaging developing brains as well. Such adverse effects are likely to be lasting and one main outcome is cognitive deficits, often expressed in terms of losses of IQ points. The combined evidence suggests that current exposures to certain pesticides in the EU may cost at least € 125 billion per year, as calculated from the loss of lifetime income due to the lower IQs associated with prenatal exposures [202]. This calculation is almost certainly an underestimation, and it does not take into account the possible contribution made by pesticides to the development of other prevalent diseases such as Parkinson’s disease, diabetes and certain types of cancer.

Although the scientific evidence is incomplete, substantial data point to the developing brain being extremely vulnerable to pesticide exposure [162]. The recent estimate of the costs to society due to organophosphate exposure [202] is somewhat uncertain and likely underestimated, but this calculation emphasises the need to generate better and stricter safety information on pesticides, especially with regard to adverse effects on the brain, limit human pesticide exposure further through regulation and public information, obtain better exposure assessments for population-wide pesticide exposures, and acquire better documentation on the adverse health effects associated with current pesticide exposure.

Increased production and consumption of organic food in the EU is likely to substantially reduce the pesticide exposure of both consumers and producers. This effect is both direct, *via* a low use of pesticides in organic agriculture, and indirect, *via* the development of non-chemical plant protection practices that may eventually be adopted in conventional agriculture as part of a transition towards integrated pest management. As a consequence of reduced pesticide exposure, organic food consequently contributes to the avoidance of health effects and associated costs to society, as well as other hidden and external costs related to pesticide use, as recently reviewed [207] and suggested to be greatly underestimated.

6. Production system and composition of plant foods

6.1. Fertilisation in conventional and organic crop production

The principles of organic agriculture [208] and EU regulations [113, 209] set the rules for the fertilisation regime in organic plant production. Generally, only natural fertilisers such as farmyard manure, compost and green fertilisers are allowed while several mineral fertilisers of natural origin are also permitted as supplements. The intention is to improve or at least maintain soil fertility by returning plant residues, animal manure and other organic material to the soil, preferably in the form of on-farm or local nutrient cycles. In contrast, conventional agriculture largely relies on mineral fertilisers that are generally highly water soluble and easily plant accessible, although farmyard manure is also a common fertiliser on conventional farms in some countries.

In most cases, there is no specific limit for nitrogen fertilisation in conventional agriculture, while it is limited to 170 kg N/ha in organic agriculture in the EU. The typically fertilisation rates of main plant nutrients are higher in conventional compared to organic crop production, although actual uses are generally not well documented.

A few examples are given for illustrative purposes. According to Swedish national statistics, for all crops harvested in 2013, the average nitrogen fertilisation was 64 kg N/ha in organic and 115 kg N/ha in conventional production. For organic production 94 % of N originated from farmyard manure, while in conventional production 67 % N originated from mineral fertilisers. Specifically for cereal production in the same year, organic cereal fields received on average 69 kg N/ha from different kinds of organic fertiliser, predominantly farmyard manure, while conventionally managed fields received 24 kg N/ha from farmyard manure and 94 kg/ha from mineral fertilisers. These numbers have been adjusted for ammonia losses during fertiliser handling and application [210].

For phosphorus, the corresponding numbers for all crops are 16 and 15 kg P/ha for organic and conventional production; 97 % /65 % of P originated from farmyard manure in organic/conventional production. For cereals, P fertilisation was 18 and 14 kg P/ha, with 80 %/52 % from farmyard manure in organic/conventional production [210].

These data are not suitable for a systematic comparison: soil types, regional differences and differences in cultivated crops are disregarded. All these factors may affect the fertilisation strategy and introduce bias into the comparison. Also, nitrogen fixation from legume crops was not included in these data. Nonetheless, these data can serve as an illustration of different fertilising strategies in organic and conventional crop production.

One meta-analysis of lifecycle assessment studies points to a slightly lower P input per area in organic systems based on 12 individual studies from various countries, although between-study variation is substantial [211].

6.2. Effect of fertilisation on plant composition

It is well known that different types and levels of fertilisation affect plant nutrient uptake and plant quality [212, 213]. It is therefore plausible that systematically different fertilisation strategies in organic and conventional production may cause differences in the chemical composition of the crop. On the other hand, plants (like all living organisms) are homeostatic, *i.e.* they are able to maintain their functions over a range of environmental conditions. Both organic and conventional producers generally strive for good plant growth and development by maintaining an optimal plant nutritional status and avoiding deficiencies.

Specifically, it is sometimes argued that a high plant nutrient availability will emphasise the primary plant metabolism, comprising plant functions such as growth and reproduction, over secondary plant metabolism, which is responsible for functions such as defence and appearance. The distinction between primary and secondary metabolism is not clear. Primary metabolites include lipids, carbohydrates, sugars and many vitamins. Secondary plant metabolites include plant defence compounds such as phenolic compounds.

Specifically for plant defence, it is well known that in many cases environmental factors, among them plant nutrient availability and pathogen/herbivore pressure, may affect the chemical composition of plants [214]. It has been hypothesised that a high availability of plant nutrients, specifically nitrogen, may shift plant metabolism towards more pronounced growth and less pronounced defence [215]. This has served as a rationale for hypothesising a higher content of plant defence compounds, specifically phenolic compounds, in crops from organic production compared to crops from conventional production.

6.3. Studying crop composition

Three types of study designs are available for comparing the composition of organic and conventional crops, each with their own advantages and drawbacks. In controlled field trials, researchers have full control over all agronomic factors of crop production. However, long-term field trials are expensive and do not always reflect the range of agronomic practices that are actually used by farmers. In farm-pairing studies, samples are collected from neighbouring organic and conventional farms. Care needs to be taken in the choice of crop varieties: in many cases, different varieties perform differently in organic and conventional systems, and there is a risk of comparing compositional differences between crop varieties, rather than the effects of conventional *vs.* organic production. In market-basket studies, samples are taken from the food supply chain, *e.g.* supermarkets. This is of relevance if a consumer perspective is of interest. However, typically, not much is known about the origin, climatic conditions, soil type, variety or supply chain, all of which may affect sample composition and change over time. It is therefore difficult to generalise findings from such studies.

It is also worth bearing in mind that a fruit or vegetable may consist of 10,000 compounds, while most studies measure only a few dozen compounds. It is not a straightforward process to translate differences in the concentration of single plant components into differential health effects for humans. In the absence of nutrient deficiencies, focusing on single nutrients may not be an adequate way of evaluating the impact of a food or diet on human health [92]; studies of actual health effects, discussed in other sections in this report, are generally more informative than studies of single nutrients.

6.3.1. Effect of production system on overall plant composition

A small number of studies have investigated whether production system has a measurable effect on overall plant or crop physiology. In these “omics” studies, hundreds or thousands of plant metabolites [216-220], proteins [221, 222] or expressed genes [223, 224] are measured in conventional and organic products in controlled experiments. Notably, almost all these studies have found that production system has an overall effect on crop composition. However, from currently available data it is generally not possible to understand whether such differences in crop composition are of any relevance for human health. It is also worth noting that the overall effect of other factors, such as the production year, can be greater than the effect of the production system. Furthermore, based on the available data, it is not easy to establish whether the findings from these studies are consistent with each other. Nonetheless, these studies support the view that organic and conventional management practices differentially affect plant composition.

The lower crop yields in organic production [225] also constitute evidence that management strategies affect plant development.

6.3.2. Effect of production system on the concentration of single compounds

Several hundred studies have been performed that compare the content of various plant components in various crops as a function of the (organic or conventional) production system in a wide range of experimental designs, crops and crop varieties, management practices, soils, climates and weather conditions. These have been summarised in several systematic reviews and meta-analyses [22, 135, 226, 227] with different scopes, inclusion criteria and statistical methods. Findings and conclusions from these systematic reviews are partially consistent and partially contradictory. Here, we summarise the consistent results and discuss inconsistent findings and uncertainties. We also discuss the biological plausibility of the findings, and their relevance for human health or for meeting nutritional guidelines. We generally focus on compounds that have either been extensively studied in this context or are of high relevance for human health. Pesticide residues are dealt with in Chapter 5.

It is important to bear in mind that any effect of crop, cultivar, soil, climate or weather on the concentration of a specific compound may far outweigh differences due to organic or conventional production. When discussing any potential relevance for human health, it is necessary not only to focus on the statistical significance of any differences by production system, but also the magnitude of such differences.

It should also be noted that in a summary of a large number of highly diverse studies, there is a risk of heterogeneous effects being overlooked, such as an effect of production system on the concentration of a certain compound only in some but not in all crops, or in some but not in all soils or under some but not all climatic conditions.

6.3.3. Brief overview of recent systematic reviews focusing on plant composition in relation to production system

A systematic review by Dangour *et al.* [226] included 46 studies on crop composition from organic and conventional production, published between 1958 and February 2008, that fulfilled several quality criteria. A pooled analysis of 11 components studied revealed 7 % higher total nitrogen content in conventional as well as 8 % higher phosphorus content and 7 % higher acidity in organic crops. Other compounds, including phenolics, vitamin C and several minerals, were found in similar concentrations in crops from both systems.

A meta-analysis by Brandt *et al.* [227] included 65 studies that were published between 1992 and October 2009 and met several quality criteria. It had a specific focus on vitamins and secondary metabolites in fruits and vegetables. Overall, plant defence compounds were found to be present in 16 % higher concentrations in organic crops, while there were small or no differences in vitamin C and beta-carotene concentrations.

A meta-analysis by Smith-Spangler *et al.* [22] included 153 studies of crop composition in organic and conventional agriculture, published between 1966 and May 2009 and fulfilling basic reporting criteria. Compositional parameters of interest included nutrients and contaminants. Overall, no differences between production systems were detected as regards nutrient content, with the exception of higher phosphorus and total phenolics contents that were found to be higher in organic crops. Among the contaminants, no differences between production systems were found for heavy metals and bacteria, but among the fungal toxins in cereals, one of two investigated toxins (deoxynivalenol, DON) was found in lower levels in organic cereal crops. This was the only one of the discussed meta-analyses that used a statistical correction for testing multiple outcomes, making it more conservative in the detection of differences between production systems compared to the other meta-analyses.

A meta-analysis by Barański *et al.* [135] included a total of 343 original peer-reviewed studies published between 1977 and December 2011, with inclusion based on the reporting of relevant data, without further quality criteria. The scope of this meta-analysis was broad, but a specific focus was placed on secondary plant metabolites. Among the main findings was a 19-69 % higher content of some, but not all, (groups of) phenolic compounds in organic crops, as well as a 48 % higher cadmium content in conventional crops, while vitamins and minerals were generally found in similar concentrations in crops from both systems. In this report, we refer to the weighted meta-analysis, which is the primary type of meta-analysis in Barańskis article.

6.3.4. Nitrogen and phosphorus

Existing systematic reviews have consistently found lower total nitrogen (7 % [226], 10 % [135]) and higher phosphorus (significant [22], 8 % [226]) in organic compared to conventional crops. This appears plausible in light of the fertilising strategies discussed above, but lacks direct relevance for human health. However, this finding does lend some plausibility to other observed differences in plant metabolism and composition, considering the central importance of N and P availability for plant development.

The higher N content in conventional crops is [135] or is not [22] reflected in a higher protein content. Nitrate and nitrite concentrations in crops appear not to differ significantly between production systems, although the variation between studies is particularly high for these compounds [135].

6.3.5. Vitamins

Vitamins are a group of compounds with diverse biological functions, which are all essential for humans. In the context of organic and conventional agriculture, the most frequently investigated vitamin is vitamin C. The available meta-analyses conclude differently on the question of whether there is significantly more vitamin C in organic products. Nonetheless, disregarding the question of statistical significance, all meta-analyses consistently conclude an approximately 6 % higher vitamin C content in organic crops [135, 227], with similar standardised mean differences [22, 135, 227], based on a large number of studies. This means that if there is any systematic difference in vitamin C content in organic and conventional crops, then this difference is fairly small. To meet the dietary guidelines on vitamin C intake, the amount, type and processing of consumed fruit or vegetables is therefore far more important than the production system. The situation is similar for the other frequently measured vitamins, β-carotene/vitamin A (similar or slightly higher in organic foods) [22, 227] and α-tocopherol/vitamin E (similar or slightly higher in conventional foods) [22, 135]. Some vitamins have only rarely been measured in this context, without any clear trends [135].

6.3.6. Minerals

For the minerals calcium, zinc, magnesium, iron and copper, which have been reported in at least two of the systematic reviews discussed here, the overall conclusions are that their concentration is not significantly affected by the production system.

6.3.7. Phenolic compounds

This group consists of several thousand compounds. Although (poly)phenolic compounds are not essential nutrients for humans, they have attracted considerable interest due to their potential health benefits. Phenolic compounds, and foods rich in phenolic compounds, are believed to play an important role in preventing several non-communicable diseases, including cardiovascular disease, neurodegeneration and cancer [228]. The detailed mechanisms may be complex and in most cases are not fully understood [228]; this may be one reason why dietary guidelines advocate an intake of fruit and vegetables, but not an intake of fruit and vegetables rich in some specific group of phenolic compounds.

Several environmental and agronomic practices affect the phenolic composition of the crop, including light, temperature, availability of plant nutrients and water management [229]. Under conditions of high nitrogen availability, many plant tissues show a decreased content of phenolic compounds, although there are examples of an opposite relationship [229].

All four systematic reviews discussed above report data on phenolic compounds. While Dangour finds no differences in the content of phenolic compounds between organic and conventional crops based on 13 studies including 80 comparisons, Brandt reports a 14-20 % higher content in organic crops based on 89 comparisons. Smith-Spangler reports a significantly higher content of total phenols in organic crops based on 34 studies comprising 102 comparisons. However, based on fewer studies, the concentrations of the single compounds quercetin and kaempferol, as well as the total flavonoids, were not found to be different in crops from the two systems. Barański reports a 19-61 % higher concentration of some (groups of) phenolic compounds in organic crops, while other (groups of) phenolic compounds have been found in similar concentrations in crops from the two systems, based on several hundred comparisons. In most cases, however, the heterogeneity between studies is high and there are indications of publication bias.

The most "global" result is the content of "total phenolics", which is reported by a relatively large number of original studies and by three meta-analyses, and which also constitutes some kind of summary measure for a large number of compounds. Brandt reports 14 % significantly more "total phenolics" in organic crops based on 39 studies, Smith-Spangler reports significantly higher "total phenols" in organic food, with a reasonably large effect size (standardised mean difference SMD = 1.03) based on 22 studies, and Barański reports a 26 % higher content of "phenolic compounds (total)" in organic crops based on 58 comparisons from 40 studies (SMD=0.52), however not statistically significant. In a subgroup analysis, Barański reports significantly more (34 %) total phenolics in organic fruit, but not in organic vegetables, compared to the conventional products. Both Barański and Smith-Spangler report a statistical heterogeneity in these results, which currently is not understood. As an average of these meta-analyses, the concentration of phenolic compounds is apparently approximately 20 % higher in organic crops compared to conventional crops. In parallel with this, another related "global" parameter has been reported in a large number of original studies: the Barański meta-analysis reports a 17 % higher antioxidant capacity in organic compared to conventional crops, based on 66 comparisons from 33 studies.

With respect to single phenolic compounds or narrower groups of phenolic compounds, Barański reports differences ranging from non-significant to a 69 % higher content in organic crops (for flavanones). However these estimates are less certain than the "total phenolics" results discussed above because in many cases they are based on relatively few studies, and single studies may contribute a lot of weight to the "percentage difference".

In summary, collectively the published meta-analyses indicate a modestly higher content of phenolic compounds in organic crops, which is plausible. These compounds are believed to play a role in preventing several non-communicable diseases in humans, although the detailed mechanisms are not generally well understood. It is important to bear in mind that in many cases the variation in the concentration of phenolic compounds is greater between different types and varieties of crops and between years, climates, soils *etc.* than between production systems. According to current knowledge, a slightly higher content of phenolic compounds in organic food does not constitute a strong basis for the inference of positive effects of organic compared to conventional plant products for human health.

6.3.8. Toxic metals

Cadmium (Cd) is toxic to the kidneys, can demineralise bones and is carcinogenic. The general population's Cd exposure is close to, and in some cases above, the tolerable intake and therefore their exposure to Cd should be reduced. For non-smokers, food is the primary source of exposure, with cereals and vegetables being the most important contributors [230].

The Cd content of crops is therefore of immediate relevance to human health. Cd is present naturally in soils, and is also added by fertilisers, atmospheric deposition and sewage sludge. Several factors, including soil structure and soil chemistry, humus content and pH, have important effects on the plant availability of Cd [231]. The application of Cd-containing fertilisers increases Cd concentrations in the crops [230, 231]. Low soil organic matter generally increases the availability of Cd for crops [232], and organically managed farms tend to have higher soil organic matter than conventionally managed farms [4].

Two meta-analyses have summarised existing studies on the Cd content of organic and conventional crops, with conflicting results. Smith-Spangler [22] reported 15 studies totalling 77 comparisons (data pairs). Of these data pairs, 21 show a significantly lower Cd content in the organic crop, one shows a higher Cd content in the organic crop, and the remaining data pairs do not show significant differences between conventional and organic crops. When only those 11 studies providing sufficient statistical information are included in a formal meta-analysis, no significant differences between organic and conventional crops are observed. Barański [135] reported 27 studies totalling 62 data pairs. Of these data pairs, 45 show numerically lower Cd concentrations in organic crops, while 16 show numerically lower Cd concentrations in conventional crops. When only those 25 data pairs from 17 studies that provided sufficient statistical information were included in a formal meta-analysis, conventional crops show a significantly 48 % higher Cd concentration compared to organic crops. It should be noted that a higher Cd concentration in conventional crops has been observed in cereals, but not in other types of crops in this meta-analysis.

Due to the very high relevance of Cd concentration in crops and of a potential effect of the production system on Cd concentration, these conflicting results are discussed here in some detail. For this report we contacted the authors of these meta-analyses in order to understand the discrepancies between them and enquired whether they would be able to provide updated analyses because some inconsistencies were found in the two meta-analyses. Both rely to a large degree on the same underlying original study base, albeit with different inclusion criteria. The Barański meta-analysis provides more detail by presenting summary statistics for each data pair included in the meta-analysis, and by providing the extracted raw data in a database. An updated version of this meta-analysis, in which some inconsistencies have been addressed and which has been provided by the original authors for the present report [233], shows a significant 30 % (95 % confidence interval 14 %, 47 %) higher Cd content in conventional compared to organic crops. The Smith-Spangler meta-analysis has somewhat stricter inclusion criteria. Apparently, two large well-designed studies with tendencies towards a lower Cd content in organic crops have not been included, although they apparently fulfilled the inclusion criteria [234, 235]. Furthermore, a conservative statistical "multiple testing adjustment" has been imposed, which appears inappropriate in this case because it is well understood that mineral fertilisers are an important source of Cd in soils. It is unclear how these points would affect the results of this meta-analysis. No updated analysis was available for this meta-analysis.

The source of Cd in mineral fertilisers is the raw material phosphate rock. Two studies report the European average Cd content in mineral fertilisers as 68 mg Cd/kg P [236] or 83 mg Cd/kg P [237]. The content of Cd in farmyard manure is variable but apparently in many cases lower. In a collection of fertilisers sold in Germany, the average Cd content in various mineral P fertilisers ranged between 56 and 133 mg Cd/kg P [238]. Organomineral fertilisers (composites of organic and inorganic fertilisers, in some cases approved in organic agriculture) averaged 61 mg Cd/kg P [238], and various types of animal manure averaged between 14 and 37 mg Cd/kg P in samples from the same collection [239]. There are limitations to the representativeness and generalisability of these data, but given the lower Cd content in P fertilisers approved in organic agriculture, it appears plausible that organic crops have a lower Cd content than conventional crops.

In a continental Cd balance, the import of Cd *via* mineral P fertiliser, feed and food represent influxes to the EU. Although on the local field scale, both mineral fertiliser and animal manure are Cd influxes, there is only a net influx to EU soils *via* animal manure when the animal feed is imported – for locally, regionally or domestically grown feed, Cd is cycled rather than accumulated at an EU level. Although organic agriculture has a focus on local and regional cycles, thereby offering a potential of cycling rather than importing Cd, some feeds, specifically protein feeds, are imported in substantial quantities from outside the EU in both organic and conventional agriculture. A full analysis on these Cd fluxes with respect to organic and conventional production is, to our knowledge, not currently available. Decreasing use of phosphate fertiliser, along with decreasing atmospheric deposition, is expected by some researchers to lead to a slight decrease in soil Cd concentration in Europe over the next 100 years under the assumption that current fluxes are constant [240]. However it is not clear how these fluxes are affected by a development towards a bio-economy or an increased re-cycling of plant nutrients.

There are short-term and long-term effects of Cd influx from fertilisers on the Cd content of crops [231]. Cd accumulation in soils is a slow process, and trends are typically seen after >40 years [241]. In order to properly address the question of whether long-term organic and conventional management have a different effect on soil and crop Cd content, long-term farm pairing studies or field trials appear to be most suitable. However, none of the farm-pairing studies included in the meta-analyses have collected data on the long-term history of the included farms, or have designed the study to include only pairs that have been in organic or conventional production respectively for a long time. No data from such long-term field studies are apparently available. Given the high relevance of Cd concentrations in crops, this represents an important research gap. In the absence of such direct evidence, the Rothamsted study may be considered. Rothamsted has been an experimental agricultural site since the 1840s and allows for a comparison of Cd concentrations in wheat and barley from long-term fertilisation with animal or mineral fertiliser in time series stretching from 1877 until 1984. Wheat fertilised with mineral fertiliser had an increasing Cd content during this time, from 50 to 76 µg Cd/kg dry weight (dw), while wheat fertilised with farmyard manure had a long-term decreasing Cd concentration, from 61 to 33 µg/kg dw. Barley had somewhat lower overall Cd concentrations and did not show similar trends [242]. Limited documentation indicates that the Cd concentration in the mineral fertilisers used was lower than the current European average [243]. In another long-term growing experiment in Askov (Denmark), after 120 years, the Cd concentration was higher after mineral fertilisation compared to animal manure fertilisation for all six crops. This effect was most pronounced for cereal crops, with approximately twofold higher Cd concentration in mineral-fertilised barley and wheat [244].

Although some national legal limits for Cd content in mineral fertilisers are in place, there is still no common legal limit in force for the EU. A limit of 137 mg Cd/kg P, which may be gradually decreased further to 92 and 46 mg Cd/kg P, is under discussion [245]. Such a limitation will eventually also decrease the Cd content of animal manures *via* a decreased Cd content in feedstuffs.

For inorganic fertilisers that are approved for organic agriculture, the legal limit is currently 206 mg Cd/kg P [113]. This limit is likely to be decreased once EU-wide Cd limits for fertiliser are in place.

In summary, current data indicate a lower Cd content in organic crops, but this has not been demonstrated unequivocally. A lower Cd content of organic crops is plausible due to a lower Cd content in the fertilisers used in organic farming, and potentially due to higher soil organic matter in organic farmland.

For other toxic metals including lead, mercury and arsenic, no differences in concentration in organic and conventional crops are reported [22, 135]. Uranium is also present as a contamination of concern in mineral P fertilisers [246], but apparently less so in organic fertilisers [247]. Uranium is accumulating in mineral-fertilised soils. No data are available comparing the uranium content of organic and conventional products.

6.4. Conclusions

Most aspects of crop composition, including vitamins and minerals, are not affected by the agricultural management system. If they are it is only to a limited extent. From the perspective of nutritional guidelines, which are generally concerned with macronutrients, vitamins and minerals, there is no reason to prefer organic over conventional plant foods or *vice versa*. There is some evidence that the concentration of phenolic compounds is approximately 20 % higher in organic crops. However, the relevance of this moderate increase in phenolic compounds for human health is at present unclear. Several "omics" studies indicate global effects of the production system on crop composition; the relevance of these findings for human health is currently unknown. There are indications that organic crops, specifically cereal crops, contain less cadmium than conventional crops. This effect is plausible, mainly due to the presence of cadmium in mineral phosphorus fertilisers. Current cadmium exposure of the general population *via* crops is of direct relevance for human health and a decreased cadmium exposure is desirable.

7. Animal-based foods

7.1. Feeding regimes in organic and conventional animal production

Organic herbivore production systems should make as much use of grazing as possible, depending on the seasonal availability of pastures. 60 % of the daily feed intake (as dry matter) of herbivores must be roughage, as fresh, dried or silage in most circumstances. According to regulations, omnivores in organic production also get roughage as part of their daily feed. Poultry should have access to pasture (e.g. 4 m^2/laying hen) during at least a third of their lifetime [113].

Minimum requirements for access to pasture and to forage do not exist for animals in conventional production in most EU countries. Current intensive conventional production generally tends to favour concentrate feeds because these allow for a higher energy and protein intake per kg dry weight, and therefore faster growth or higher milk production. Accordingly, rules of organic production and the logics of intensive production together give rise to different feeding regimes in organic and conventional production. There is little data available on actual feed statuses in organic compared to conventional production. One recent study on 22 dairy farm pairs in Germany reports significantly different feeding regimes with respect to concentrate feed (14 % in organic *vs.* 24 % in conventional herds as percentage of dry matter), maize silage (7 % *vs.* 31 %), and pasture (30 % *vs.* 5 %), hay (12 % *vs.* 3 %), straw (1 % *vs.* 3 %), with the remaining feed constituents similar between production systems (other 8 % *vs.* 6 % and grass silage 29 % *vs.* 28 %) as averaged over one to three years [248]. One systematic review on milk quality found on average over four studies 33 % fresh forage in the feed of conventional dairy cows and 60 % fresh forage in the feed of organic cows (in g per g dry matter) [249].

7.2. How feed determines the composition of the animal product

The focus here is on omega-3 fatty acids because of the high interest in these fatty acids with respect to human health. Table 3 lists the omega-3 polyunsaturated fatty acid (PUFA) content of selected feeds.

Feed	Alpha-linolenic acid content, weight-% of total fatty acids
Grass, grass silage	46-49
Red clover	34-46
White clover	4
Soy	7
Corn, cereals	4-7
Corn silage	5
Palm kernel cake	2
Rapeseed	9
Linseed	54

Table 3. Omega-3 content of selected feeds, expressed as g alpha-linolenic acid (ALA, C18:3 n-3) per 100 g total fatty acids. Data are assembled from [250], except for palm kernel cake [251] and corn silage [252]

It is well demonstrated that the feeding regime of livestock is reflected in the milk, egg and meat fatty acid (FA) composition [250, 253]. A feeding regime containing a high proportion of forage will therefore result in a comparatively high content of omega-3 fatty acids in the meat, egg or milk. This relationship is not linear but monotonous [253]. Furthermore, legume forages such as clover have a specific effect of increasing the omega-3 content of milk and of beef and lamb meat [254, 255]. This is of interest because clover is commonly part of grassland cultivation in organic farms due to its nitrogen-fixing effect.

Like humans, farm animals turn a small part of dietary alpha-linolenic acid into long-chain omega-3 fatty acids with the help of elongase and desaturase enzymes.

7.3. The effect of production system on fatty acid composition

7.3.1. Milk fatty acid composition

Cow milk is the most thoroughly researched animal product in this context. Almost 200 studies from a range of countries (*ca.* 75 % from Europe) have reported various composition parameters in organic and conventional milk using a variety of study designs. These have recently been summarised in a meta-analysis [256]. Generally confirming earlier reviews [22, 249], this meta-analysis has found a significantly higher content of omega-3 PUFA and of ruminant fatty acids in organic compared to conventional milk, while the content of saturated fatty acids, mono-unsaturated fatty acids and omega-6 PUFA was similar in organic and conventional milk. Ruminant fatty acids are a group of naturally-occurring trans fatty acids produced in the rumen of ruminants. With respect to omega-3 fatty acids, total omega-3 fatty acid levels were found in 56 % higher concentrations in organic milk. For single omega-3 fatty acids, this figure was 69 % for alpha-linolenic acid (ALA, C18:3 n-3), 67 % for eicosapentaenoic acid (EPA, C20:5 n-3) and 45 % for docosapentaenoic acid (DPA, C22:5 n-3). Related to these results, the ratio of omega-6/omega-3 fatty acids was lower in organic milk. Furthermore, the ruminant fatty acids vaccenic acid (VA, C18:1 n-7 trans) and conjugated linoleic acid (CLA, C18:2 c9, t11) were found in 66 % and 24 % higher concentrations in organic milk. These are formed in the cow's rumen from ALA in the feed.

It is worth noting that there is a considerable statistical heterogeneity between studies. Individual differences described above are based on results from between five and 21 studies. However, the observed differences are plausible, because they are directly linked to differences in feeding regimes. Also for omega-3 fatty acids no study reported a higher concentration in conventional milk [256]. Therefore a higher content of omega-3 and ruminant fatty acids in organic milk must be regarded as well established. It should also be noted that several other factors influence the fatty acid composition in milk [257]. Specifically, the season (indoor *vs.* outdoor) has an impact on the feeding regime [248] and therefore on the omega-3 content of milk. However, the content of omega-3 fatty acids is higher in organic milk during both the outdoor and indoor seasons [249].

7.3.2. Egg fatty acid composition

Very few studies have addressed the fatty acid composition of organic and conventional eggs. As with milk, it is known that the fatty acid composition of the feed affects the fatty acid composition of the egg. It is also clear that not just the availability, but also the attractiveness of pasture determines how much time hens spend grazing. In one study from Italy, researchers investigated how different housing systems affected the intake of feed and the fatty acid composition of eggs. Hens in a regular organic experimental system with access to 4m^2 pasture per hen with trees, bushes and hedges in the area had approximately 15 % of their feed intake from grass (fresh weight) and the remainder from concentrate feed. Hens in an "organic plus" system with 10 m^2 pasture had a twice as high grass intake. Compared to their conventional counterparts (no grazing), "organic plus" eggs had a markedly higher content of omega-3 fatty acids [258]. There is not enough evidence on the composition of organic and conventional eggs to determine any compositional differences.

7.3.3. Meat fatty acid composition

A total of 67 studies that report compositional aspects of meat (mainly beef, chicken, lamb, and pork) from organic and conventional husbandry have recently been summarised in a meta-analysis [259]. Based on 23 and 21 studies respectively, the content of total PUFA and omega-3 PUFA was found to be significantly higher (23 % and 47 % respectively) in organic compared to conventional meats. These findings are plausible, especially in the case of omega-3 PUFA, in light of the known differences in feeding regimes in organic and conventional production and the known effect of feed fatty acid composition on meat composition discussed above. However, few studies were available for each analysis, leaving many analyses with poor statistical power. The variation between studies and between species was large, and the overall reliability of these results is therefore lower compared to milk above. Specifically, in some sensitivity analyses performed to investigate the extent to which the methodological aspects of meta-analysis affect the results, no significant differences in the omega-3 content of organic and conventional meats were observed. This meta-analysis therefore indicates a plausible higher omega-3 content in organic meats, but more well-designed studies are needed in order to confirm this effect.

7.3.4. Other compositional aspects of animal products

A recent meta-analysis points to a significantly higher content of iodine (74 %) and selenium (21 %) in conventional milk and of iron (20 %) and tocopherol (13 %) in organic milk based on six, four, eight and nine studies respectively [256]. For iodine, is not clear whether a higher content in milk generally is advantageous or disadvantageous; the differences are likely to be caused by feed additives used in conventional dairy farming [256]. For tocopherol, selenium and iron, a higher content is generally desirable, and in the case of selenium milk is an important source. These results should be interpreted with caution, however, because they are based on just a few studies.

7.3.5. Significance of production system for meeting recommended omega-3 PUFA intake

Linolenic acid (LA, omega-6) and alpha-linoleic acid (ALA, omega-3) are considered essential fatty acids for humans. Other fatty acids can be synthesised from carbohydrates or from these essential fatty acids. EFSA has proposed an adequate intake (AI) of 0.5 energy-% (E %) for ALA, an AI for EPA+DHA of 250 mg/day for adults (for pregnant and lactating women: plus 100-200mg DHA, children: 100mg DHA), and an AI of 4E % for LA [260].

Although the population-average intake of these fatty acids generally appears to exceed AI in the countries for which data were available, sections of the populations in European countries tend to have a lower than recommended omega-3 PUFA intake [260]. Therefore, the higher omega-3 content in organic compared to conventional dairy and meat products may potentially be of nutritional relevance, and it is of interest to estimate what contribution a change from conventional to organic foods while maintaining an average diet might have for the intake level of omega-3 fatty acids.

Food group	Intake of Fats g/person*day, Europe	Intake of mg n-3/person*day	
		conventional	organic
Milk, cream, butter	27.5	184	281
Fish, seafood	2.0	347	
Meat (bovine, mutton + goat, pig, poultry)	28.5	613	(748)
Egg	3.3	35	
Soybean oil	8.4	570	
Rapeseed (canola) oil	7.3	667	
	Sum omega-3	2,415	2,512 (milk fat) (2,648) (milk fat + meat)

Table 4. Preliminary estimated average omega-3 FA intake per person per day in the EU. Estimates of fat intake per food group from food supply data in FAOSTAT [261] (data for 2011). Food composition data from [262] (fish: average of salmon, herring, mackerel, sardine, cod liver oil) except dairy products [256] and meat [259]. Note that differences between organic and conventional for dairy are well established, while differences for meat have lower reliability. Omega-3 PUFA in plant oils are 100 % ALA (C18:3 n-3), in fish and seafood <10 % ALA, in dairy approx. 70 %, in meats typically 50-75 %, in eggs 35 % ALA. The remainder is long-chain (LC) omega-3 PUFA. Note that there are limitations to the accuracy of this calculation, including the use of food supply data as food consumption data, and the unavailability of details for the food category "animal fats" in FAOSTAT. Nonetheless, a preliminary estimate of the effect size can be gained.

Table 4 shows an estimate of the dietary omega-3 sources for the average EU inhabitant. Such an estimate has so far not been available; it has been produced for this report and should be regarded as preliminary until it is repeated with greater rigour. Accordingly, switching from conventional to organic dairy products with an otherwise unchanged diet would increase the omega-3 intake by approximately 4 % on average. Switching from conventional to organic meat would accordingly increase the omega-3 intake by 6 %, although a higher omega-3 content in organic meat is less well established, as discussed above. The higher omega-3 intake from organic milk and meat is desirable but small in magnitude. It is worth noting that other dietary changes are available to increase omega-3 intake, such as increased fish or canola oil intake, which along with a high omega-3 PUFA content also have a higher total PUFA and lower saturated FA content than meat and milk, with benefits for cardiovascular health [263].

7.4. Is the differential fatty acid composition linked to health effects?

The KOALA study from the Netherlands (see also Chapter 2) has shown that the breast milk of women who prefer organic food has higher levels of ruminant fatty acids compared to mothers who prefer conventional foods [26]. Higher levels of these fatty acids are associated with a lower risk of allergic disease during infancy [264]. Furthermore, maternal preference for organic milk, but not organic meat or other food groups, is also associated with a lower risk of eczema up to the age of two [25]. These results suggest that organic dairy products could play a role in preventing childhood allergies *via* a higher content of ruminant fatty acids. However, an association between breast milk ruminant fatty acids and allergic disease in infants was not confirmed in another study [265]. Accordingly, at this point, there is no strong evidence available that would support the existence of health benefits of a higher ruminant fatty acid content in organic compared to conventional milk.

A higher dietary intake of omega-3 PUFA has been linked to a number of beneficial effects, *e.g.* related to anti-inflammatory activity [266] and to a decreased risk for some cardiovascular outcomes [267-269], although clinical trials do not confirm a cardioprotective effect of omega-3 supplementation [270]. It is therefore not possible to conclude any specific health benefit offered by a modest increase in omega-3 PUFA intake from a change from conventional to organic milk and meat.

7.5. Conclusions

For milk and dairy products, it has been conclusively demonstrated that organic products have a higher content of omega-3 PUFAs, across countries and seasons, due to a higher content of grass and roughage in the feed of organic cows. In a direct comparison, organic dairy products therefore have a more beneficial fatty acid composition. The same is apparently true for meat as well, although fewer studies have investigated this and therefore the evidence base is weaker. Dairy products make only a minor contribution to the omega-3 intake in humans. On average, replacing conventional with organic dairy products while keeping the diet constant will increase the intake of omega-3 PUFA by approximately 4 %. Replacing conventional meat products with organic meat products may increase the omega-3 intake by an additional 6 %. Policies aimed at increasing the omega-3 intake of the population are likely to be far more efficient if they are directed at increasing the intake of omega-3-rich plant oils (*e.g.* rapeseed/canola and linseed) and fatty fish, with the desirable side effect of simultaneously reducing the intake of saturated fatty acids.

8. Antibiotic-resistant bacteria

8.1. Maintaining health and treating disease in organic and conventional animal production

8.1.1. European use of antibiotics for food-producing animals

Farm animals are exposed to large quantities of antimicrobial drugs, *i.e.* agents that kill microorganisms or inhibit their growth. Antimicrobial drugs can be grouped according to the microorganisms against which they primarily act. The scope of this chapter is antibiotics, *i.e.* medical drugs that are used against bacteria. Antibiotics are an integral part of intensive animal production today, and farm animals may act as important reservoirs of resistant genes in bacteria [271, 272]. In the EU, 8 million kilograms of antimicrobial drugs were used for food-producing animals and 3.4 million kilograms were used for humans in 2012 [273]. It is reported that a substantial proportion (50 to 80 %) of antibiotics are used for livestock production worldwide [274]. On a "per kg biomass" basis, in 2012 the amount of antimicrobial drugs consumed by farm animals was slightly higher than the drugs used for humans in the 26 EU/EEA countries surveyed, with substantial differences between countries regarding volumes and types of substances [273].

8.1.2. Historic development of the use of antibiotics in food-producing animals

The development of antibiotics revolutionised human as well as veterinary medicine, as it then became possible to control and cure diseases caused by bacterial infections. Antibiotics have been favourable for treating diseases and improving the health of farm animals, *e.g.* cattle, pigs and poultry. Since the 1940s, antibiotics have been widely used in animal production in order to cure diseases. Shortly after the introduction of therapeutic treatment, antibiotic agents (bactericides as well as bacteriostatic drugs) were found to have a growth-stimulating effect in laboratory animals as well as in farm animals [275, 276]. In 1952 Weber *et al.* reported that tetracyclines, penicillin, bacitracin or combinations of these substances were widely used in commercial poultry and pig production for promoting weight gain and increasing feed conversion [275]. The effect on growth rate was reported to be substantial, *e.g.* pigs, broiler chickens and turkeys may increase their growth rate by an average of up to 30 % with feed additives of various antibiotics [275]. The precise mechanisms behind the growth-promoting effect are still not fully determined, however it has been suggested that some antibiotics suppress inflammatory reactions in the body that may reduce growth [277].

8.1.3. Use of antibiotics in food-producing animals today

An animal used for food production that is treated with antibiotics will have residuals in its meat and milk, for example, during the treatment and for a period after the treatment. In order to protect the consumer from eating food items with residual antibiotics, a defined withdrawal time for each drug used for food-producing animals has to be determined by the manufacturer. This is one reason why the use of antibiotics varies substantially between different farm animal species. In dairy and egg production, food products are delivered on a daily basis and eggs and milk within the withdrawal time must not be used for consumption. Thus, antibiotic treatment causes economic losses that have to be considered when the treatment decision is taken.

However, in beef, pork and poultry meat production, antibiotics can be used for treating both clinical diseases and subclinical diseases, as long as no residual is found in the food products. The prophylactic treatment of subclinical diseases is not easily distinguished from the use of antibiotics as growth-promoting agents, even if the purpose is not primarily to enhance body growth. Although the EU banned the use of antibiotics as growth-promoting agents in 2006 [278], the prophylactic use of antibiotics is still substantial. However, total veterinary antibiotics sales had declined by 11 % in 2013 compared to 2010 when antibiotics sales in EU member states had started to be consistently monitored [279].

8.1.4. The influence of housing and management on disease risk

The use of antibiotics in intensive livestock production is closely linked to the housing and rearing conditions of farm animals. Specific conditions for conventional livestock farming in different countries, as well as farmers' attitudes, may differ between countries, *e.g.* conventional pig production at above EU animal welfare standards and farmers' attitudes in Sweden [280, 281]. Large animal farms are often regionally concentrated and the space allowance for the individual animal is often very restricted, *i.e.* high stocking density in a confined space (in compartments and houses on the farm). Conventional production is typically aiming for high production levels with restricted input resources such as space, feed *etc.*, and these conditions may cause stress in the individual animal as it is unable to cope with the situation, *e.g.* in pig production[282, 283]. This means that higher stocking density, restricted space and barren environment are factors increasing the risk of the development of diseases, and therefore it is more likely that animals under these conditions need antibiotic treatments. Furthermore, young animals are separated from their mothers at an early age, and therefore the piglets are more likely to suffer from immunosuppression due to an underdeveloped immune system and social stress [284]. The separation may be followed by transfer (sometimes including transport) to an unfamiliar environment as well as by regrouping, factors that contribute to an increased risk of diseases needing antibiotic treatment.

8.1.5. Maintaining animal health in organic animal production

One of the guiding principles for the EU is that "organic stock farming should respect high animal welfare standards and meet animals' species-specific behavioural needs while animal-health management should be based on disease prevention" [285].

Organic production aims for less intensive animal production, which generally means that the animals have access to a more spacious and enriched environment, access to an outdoor range and restricted group sizes [113, 286]. Furthermore, the nursing periods for pigs, for example, are longer, *i.e.* 40 days compared to 21-28 days in conventional piglet production in the EU. It has been found that piglets weaned earlier have a more premature immune system and are more likely to catch infections, for example diarrhoea [284, 287]. Furthermore, sows that are not tethered at farrowing and have access to straw for nest building prior to farrowing, which is mandatory in organic production but not in conventional pig production in most countries, are less likely to develop disease peripartum and have improved piglet health [288, 289]. In organic poultry housing, the stocking density indoors in fixed housing is a maximum of six hens per m^2 compared to a maximum nine hens per m^2 of available area in the conventional housing of laying hens. For organic broilers the maximum is 10 broiler chickens per m^2 in fixed housing (with a maximum of 21 kg live weight per m^2), compared to up to 42 kg live weight per m^2 in conventional broiler production. In addition, organic hens and broilers have access to at least 4 m^2 outdoor area per animal, which may include a winter garden/veranda. The aim of the organic rules is that the birds should have access to a spacious, enriched and natural environment so they can perform more natural behaviours and have more opportunity to maintain a good health. This would ultimately decrease the need for preventive medication of the animals. However, in practice, the health status of organic livestock is complex and disease prevention needs to be adapted to the individual farm [290].

A report on the consequences of organic production in Denmark demonstrates that meeting the requirements of organic production has several positive consequences in relation to animal welfare and health [286]. The animals have opportunities to perform important natural behaviours, they are not confined and they have access to exercise in the barn as well as outdoors (including grazing), and more robust breeds can be used. As a consequence, the disease incidence is generally decreased for production diseases (*e.g.* respiratory diseases) and zoonoses (*e.g. Salmonella* infection), and antibiotic use is low (65 % for milk cows and 5-19 % for pigs) compared to its use for conventional livestock in Denmark [286].

8.1.6. The role of breeds adapted to organic production

Organic dairy and pig production commonly use the same breeds as conventional production, a practice that appears to work well since the health situation, including mortality, in organic dairy farming is generally equal to or better than that in conventional dairy production [286, 291]. A Norwegian study found that if the disease incidence in dairy herds were corrected for the level of production no difference was found, although the production level by itself may increase the risk of disease [292, 293]. Regarding fertility, maintaining good reproductive performance in cows on small farms during the winter in Scandinavia seems to be a challenge in organic production, although larger farms do not have these problems [294, 295]. A Swedish study found that the current breeding values for organic dairy cows were adequate for organic production and that a separate breeding programme for the organic sector was not needed [296].

In pig production there may be a need to develop pig breeds that are better adapted to organic conditions, *e.g.* to reduce the elevated risk of joint lesions found in free-range pigs [297]. Regarding egg production, productive commercial breeds are available that are well adapted to organic conditions, including tolerance for feed without synthetic amino acids that are not approved in organic production. However, there are still challenges regarding parasites and injuries from pecking [298, 299]. Beak trimming, which is commonly used to reduce feather pecking and cannibalism in conventional herds, is not allowed in organic production. Therefore, there is a need for both improved management practices and the development of less susceptible birds, and this is also necessary in conventional flocks if beak trimming is to be avoided [300].

Organic broiler production in particular seems to present a major challenge to maintaining good bird health and welfare. In studies comparing conventional and organic production, the same strains of animals have been used and in some studies, e.g. on broiler chickens, diseases such as foot pad dermatitis and parasites have been found to be more common in organic production due to the risk factors of a long rearing period and outdoor housing. The presence of parasites is associated with the chickens' contact with faeces and need special attention, *e.g.* hygienic measures and rotation of the outdoor area. Regarding foot pad dermatitis, a common lesion in intensive broiler production, the longer rearing period in organic production aggravates this problem when fast-growing hybrids (*e.g.* Ross 308) are reared, which is still common in organic broiler production. The risk of foot pad dermatitis is decreased when strains are used that genetically have a lower growth rate [301, 302].

In summary, breeding animal varieties that are adapted to the conditions of organic poultry and pig production may improve overall animal health in organic systems and thereby contribute to a further reduction in the need for antibiotics in organic production.

8.1.7. The link between animal welfare and animal health in organic husbandry

Several studies have shown that that disease patterns are usually slightly different in organic farms compared to conventional farms. Whereas conventional farm animals are more likely to get respiratory diseases, which are related to a higher stocking density and impaired indoor climate, *e.g.* poor ventilation, organically-reared animals are more susceptible to diseases related to parasites due to their outdoor housing [303].

8.1.8. Regulation and use of antibiotics in EU organic production

According to regulations, routine prophylactic medication of animals in organic production is not allowed and diseases should be treated immediately to avoid suffering [133]. For the treatment of diseases, the current EU regulation states that "veterinary medicinal products including antibiotics may be used where necessary and under strict conditions, when the use of phytotherapeutic, homeopathic and other products is inappropriate. In particular restrictions with respect to courses of treatment and withdrawal periods shall be defined" [133].

For non-therapeutic treatment, the relevant EU regulation [113] prohibits the use of antibiotics for disease prevention or for the promotion of growth or production in organic production.

This means that therapeutically the same antibiotics used in conventional farming may be used in organic farming, but under different conditions. Thus some antibiotics mainly used for sub-therapeutic treatment as prophylaxis are never considered in organic production.

On a more fundamental level, the precautionary principle is an element of the organic theoretical framework [208]. This principle has been discussed in relation to the use of antibiotics and the emergence of resistance in livestock production [304], contrasting a "principle of proof" where action is only taken once the presence of negative effects is proven [305]).

While the organic regulations aim for a low use of antibiotics in livestock production, the actual use of antibiotic drugs in European organic compared to conventional animal husbandry is not comprehensively documented. Scattered studies indicate that the antibiotic use generally is substantially higher in conventional compared to organic systems, especially for pigs (approximately 5- 15 times higher) [306, 307]. In studies from Denmark [291] and the Netherlands [308], the antibiotic use in dairy cows was 50% and 300% higher in conventional compared to organic systems, although a Swedish study found no differences in disease treatment strategies between organic and conventional dairy farms, *e.g.* for mastitis [295].

In conventional broiler production, antibiotics are in many EU countries commonly used prophylactically during most of the broilers' lifetime except for the withdrawal period before slaughter, whereas in organic broiler production this usage is prohibited. In practise, it is impossible to therapeutically treat individual birds. Therefore, there is virtually no use of antibiotics in EU organic broiler production.

8.2. The development of antibiotic resistance

8.2.1. Discovery of antimicrobial resistance and early restrictions in the use of antibiotics for food-producing animals

Soon after the introduction of antibiotics in the 1940s, it was found that the microorganisms developed resistance against specific types of antibiotics. In his Nobel lecture, Alexander Fleming warned that "there may be a danger (*with penicillin*), though, in under-dosage. It is not difficult to make microbes resistant to penicillin in the laboratory by exposing them to concentrations not sufficient to kill them, and the same thing has occasionally happened in the body"[309]. In 1966, the occurrence of multi-resistant strains of *E. coli* in healthy pigs and calves from commercial farms in the UK were found to be associated with the application of the types of antibiotics used as feed additives [310].

8.2.2. Mechanisms of the transmission of resistance genes

Recently, gene sequencing has revealed that the routes of transmission of resistance genes between human and farm animal reservoirs seem to be complex [271, 311, 312]. Nevertheless, a recent EFSA report found that "in both humans and animals, positive associations between consumption of antimicrobials and the corresponding resistance in bacteria were observed for most of the combinations investigated" [273]. For example, positive associations have been found regarding the use of macrolides and tetracyclines in food-producing animals and the occurrence of resistance to these drugs in *Campylobacter* spp. and some *Salmonella* spp. from cases of human infection [273]. In particular, the use of antibiotics as growth promoters (GP) in farm animals is considered to be a major threat to public health, as vast livestock populations are given large quantities of antibiotics in sub-therapeutic doses during the rearing period [16] which is why the EU banned the use of antibiotics for GP purposes in 2006 in all livestock production [8].

In addition to direct transmission between animals and humans *via* contact or *via* food, resistant strains and resistance genes may also spread into the environment. The existence of the colistin-resistant gene (mcr-1) is of even more concern considering that resistance genes are likely to be spread into the environment and not just be limited to livestock reservoirs, which makes control more difficult. The transmission can be regarded as pollution within ecosystems [313]. For example, in China the concentration of antibiotic-resistant genes has been found to be 28,000 times higher in soil and manure on Chinese pig farms compared to soil from other areas [20]. However, farm animal-related activities are not the only means of spreading resistance genes by pathogenic or commensal bacteria into the environment; there is also human input *via* wastewater and other effluents [314].

8.2.3. Emerging resistance to the last groups of antibiotics originating in animals

Since the start of the 21st century, the antibiotic colistin (polymyxin E) has experienced something of a renaissance in its use as a last resort in humans to treat infections with multi-resistant bacteria when no other options are available [315]. Although it was dropped from clinical use in the 1970s due to its negative side effects, *e.g.* toxicity to the kidneys and the nervous system [316], colistin has been used for decades in veterinary medicine, especially in swine and veal calves, mainly for oral group treatment targeting infections of *E. coli* and *Salmonella Spp.* [317]. In 2015, a transmissible colistin-resistant gene (mcr-1) was found in pig samples and a small number of patients in China, that was likely to have originated from animals and possibly from pig production, where colistin seems to be widely used [318]. These findings indicate that there is a major emerging threat to the use of colistin as a last resort in treating human patients with severe infections [318, 319]. The same resistance gene has subsequently been found in animals and patients in the EU [320].

8.2.4. Antibiotic resistance in pig production

In pig production, particular attention has been paid to methicillin-resistant *Staphylococcus aureus* (MRSA), and in Dutch and German studies, for example, MRSA has been isolated in 30 % and 55 % respectively of the pigs tested [321, 322]. Furthermore, it has been found that healthy French pig farmers are more likely to carry MRSA than control persons [323] and that they carry similar strains of MRSA to those found on their pig farms [324]. Similar findings are reported from the Netherlands [325], and MRSA strain exchanges between pigs and their farmers seem common.

In a meta-study, data on 12 management (risk) factors and MRSA prevalence at herd level were merged for 400 German fattening pig herds. Of the investigated management factors, the factor organic/non-organic was most strongly associated with the prevalence of MRSA in univariate analysis (*i.e.* largest effect size). The prevalence of MRSA was 55.2 % in conventional (n=373) farms, whereas it was 21.7 % in organic (n=23) pig farms; the difference was statistically significant in univariate analysis (p=0.004) [322]. However, when all risk factors were combined in the same multivariate model, organic/non-organic production was no longer significantly associated with MRSA prevalence. Instead, management factors such as herd size (smallest – lowest risk), herd type (farrow-to-finish – lowest risk), group treatment with antimicrobial drugs (none – lowest risk), slatted floor (none – lowest risk), and other livestock on farm (yes – lowest risk) were associated with the risk of MRSA on the farm. Several of these risk factors are associated with organic pig production [326] or required by regulation in organic pig production, but can of course be adopted by any farmer.

8.2.5. Antibiotic resistance in poultry production

In poultry production anthelmintics as well as antibiotics are commonly used, although a wide variation between countries is found. For example, broiler producers in Sweden used a minimum of antibiotics since antibiotics as a feed additive without veterinary prescription was banned in 1988 [278, 327]. Nevertheless, anti-parasitic drugs need to be widely used in order to prevent enteritis with coccidia, and some of these drugs also have an effect on bacteria, *e.g.* prophylaxis of clostridia infection (necrotic enteritis) [328]. The effects of coccidiostats in poultry are well-documented but little is known about the consequences of human exposure to coccidiostats-resistant bacteria or to coccidiostats themselves [329]. However, in most countries prophylactic antibiotics are used for specifically targeting bacterial diseases, *e.g.* clostridia [330]. Whereas resistant bacteria may be transferred within the production chain from farm to fork [331], it has been found that organic livestock products are less likely to harbour resistant bacteria in pork and chicken meat [22]. Furthermore it has been found that the prevalence of bacteria with extended spectrum beta lactamase (ESBL) is lower in organic chicken meat [332], and there are indications that performing a transition from conventional to organic practices may reduce the prevalence of resistant bacteria [333].

8.2.6. Antibiotic resistance in dairy and beef cattle

There are different patterns in the use of antibiotics in dairy cows compared to beef cattle, as milk within the withdrawal time must not be used for consumption. Furthermore, dairy products are generally pasteurised to restrict the spread of pathogens. Therefore, the risk of transmission of antibiotic-resistant bacteria is theoretically decreased in dairy products compared to that of meat, and there has been less focus on dairy production in research into antibiotic-resistant bacteria. However, dairy cow manure is commonly used in crop production, and discoveries of new and diverse antibiotic-resistance genes in cow-related bacteria imply that manure can be a significant reservoir of antibiotic resistance genes [334]. Through the contamination of crops, transmission to humans may occur either directly or indirectly through feeding of meat-producing animals. The reduced use of antibiotics in organic dairy production [286, 335] may theoretically decrease the risk of the transmission of antibiotic resistance genes, but scientific evidence is not conclusive [336].

In young calves, respiratory disease and diarrhoea are common, and these diseases are typically treated with antibiotics [337, 338]. Although the picture is complex, a meta-analysis found a trend over time for decreasing susceptibility of major respiratory pathogens to common antibiotics used for treatment [339]. Furthermore, associations have been found between levels of antibiotic use and occurrence of resistance in feedlot cattle, *e.g.* tetracycline and sulphonamide use increases the likelihood of finding antibiotic resistance [340]. With regard to the comparison between organic and conventional farms with beef cattle, the picture is complex; ampicillin-resistant *E. coli* has been found to be prevalent in a British organic herd with restrictive use of antibiotics [341], but in the US multiple antibiotics resistance was found to be higher in *E coli* isolates from cattle on conventional farms than on organic farms [342].

8.3. Antibiotic resistance as a threat to human health

In recent decades, there have been increasing concerns that the use of antibiotics in livestock would contribute to impairing the efficiency of antibiotic treatment in human medical care [343]. Despite the lack of detailed information on transmission routes for the vast flora of antibiotic-resistant bacteria and resistance genes, there is a global need for action to reduce the emerging challenges associated with the reduced efficiency of antibiotics and its consequences for public health, as well as for the environment more generally [313, 344].

The effect on public health of antibiotics usage in livestock production may be through residual antibiotics in food items, food contamination of pathogenic bacteria carrying antibiotic resistance genes and exposure of food with commensal (non-pathogenic) bacteria that have absorbed antibiotic resistance genes. Finally there can also be a transfer of antibiotic resistance genes in pathogenic or non-pathogenic bacteria to the environment where further transmission to the aquatic environment may occur, and it cannot be excluded that this may affect public health when water or aquatic food items are used [314, 345].

The use of antibiotics may increase the economic outcome of animal production [346, 347], but the spreading of multi-resistant genes is not just a problem for the animal production sector alone: negative effects are affecting parts of society not directly associated with livestock production. This means that the costs of side effects are borne by society in general and not primarily by the agricultural sector.

However, the generalisation cannot be made that all antibiotic treatment in farm animals represents a hazard to public health. For example, in epidemiological studies of antibiotics resistance in *Salmonella Typhimurium* DT104, the use of antibiotics in farm animals is unlikely to be a source of resistance in humans [312, 348].

8.4. The potential role of organic husbandry in counteracting antibiotic resistance

Although it is rare for conventional farms to adopt knowledge about management and housing from organic production except when converting farms in line with organic standards, there may be options to improve animal health and welfare by knowledge transfer to conventional farms in order to reduce the use of antibiotics [349]. Knowledge can also be picked up for future husbandry based on a prudent use of antibiotics.

In response to the public health threat of antimicrobial resistance in 2015, the European Parliament repeated its call from 2011 for a phase-out of the prophylactic use of antibiotics in livestock farming, stressing that the livestock and intensive fish-farming sectors should focus on preventing disease through good hygiene, housing and animal management, as well as strict bio-security measures, rather than the prophylactic use of antibiotics [350, 351]. The World Health Organization launched an action plan with a similar approach to the issue that aimed for a “reduction in the nontherapeutic use of antimicrobial medicines in animal health” [352, 353]. In contrast to most other current commercial animal husbandry in Europe and around the world, organic livestock production today essentially complies with this position. However, a general conversion from conventional to organic animal production would only be part of the solution to the resistance issue, as other factors (including human use patterns) have an important impact. It has been found that the withdrawal of prophylactic use of antibiotics when poultry farms are converted from conventional to organic production standards leads to a decrease in the prevalence of antibiotic-resistant *Salmonella* [354]. Furthermore, it has been postulated that a reduced need and use of antibiotics in organic livestock production will diminish the risk of development of antibiotic resistance [355], and this has also been demonstrated with regard to resistant E coli in organic pigs compared to conventional pigs [356].

In short, efficient antibiotics have been essential for the development of intense livestock production, thus the risk factors associated with intense production need to be tackled in order to achieve animal production with minimal antibiotics usage [349].

Although legislation on traceability in food production exists in the EU (European General Food Law) [357], *e.g.* fresh beef and lamb meat should be fully traceable from the farm to the shop, conventional food production has not yet achieved full transparency in all areas as there is not yet a full requirement to do so. Within organic production, labelling requires full traceability in all steps in order to guarantee the origin of the organic products being marketed [285]. This means that organic products are always certified according to rigorous standards, *i.e.* food products can always be traced back to the particular farm and particular unit of production. These requirements will offer an excellent way of handling disease control as well as developing hazard analysis critical control point (HACCP) systems for monitoring hazards at all stages of food production. Application of the general principle of organic regulations about transparency throughout the food chain can be used to mitigate against emerging problems of transmission of antimicrobial resistance.

8.5. Conclusions

Organic production may offer a way of restricting and even decreasing the prevalence of antibiotic resistance. Organic broilers and pigs, but not dairy cows, are less likely to develop diseases related to intensive production compared to animals in conventional production. As a consequence, the reduced use of antibiotics for treating clinical disease is required. However, there are considerable differences in use between species and countries. Furthermore, the preventive use of antibiotics is strongly restricted in organic husbandry where the maintenance of animal health instead relies on preventive management factors, such as hygiene measures and decreasing stocking density. The preventive use of antibiotics has been clearly linked to the risk of developing antibiotic resistance in bacteria. Consequently, there is a lower risk of the development of antibiotic resistance in organic animal husbandry. There are several routes for resistant bacteria and for resistance genes to move from farm animals to humans.

Furthermore, organic production is always certified according to rigorous standards, which means that transparency for consumers and authorities throughout the food chain should be guaranteed. This transparency may be useful for acquiring knowledge and methods to combat the rising issues around transmission of antimicrobial resistance within food production.

Today organic animal husbandry essentially fulfils the demands for the restrictive use of antibiotics made by WHO and the European Parliament to counteract the development and spread of antibiotic resistance. Knowledge dissemination between conventional and organic production may be important steps in the right direction. However, transition to organic production for the whole livestock sector would, on its own, be only part of a solution to the antibiotics resistance issue, because factors outside animal production, such as their use in humans, will be unaffected.

9. Conclusions

The few human studies that have directly investigated the effects of organic food on human health have so far yielded some observations, including indications of a lower risk of childhood allergies, adult overweight/obesity and non-Hodgkin lymphoma (but not for total cancer) in consumers of organic food. Owing to the scarcity or lack of prospective studies and the lack of mechanistic evidence, it is presently not possible to determine whether organic food plays a causal role in these observations. However, it has also been observed that consumers who prefer organic food have healthier dietary patterns overall, including a higher consumption of fruit, vegetables, whole grains and legumes and a lower consumption of meat. This leads to some methodological difficulties in separating the potential effect of organic food preference from the potential effect of other associated lifestyle factors. These dietary patterns have in other contexts been associated with a decreased risk of several chronic diseases, including diabetes and cardiovascular disease. It is therefore expected that consumers who regularly eat organic food have a decreased risk of these diseases compared to people consuming conventionally-produced food as a consequence of dietary patterns. The potential role of the production system has not yet adequately been investigated. These dietary patterns appear to be more environmentally sustainable than average diets.

To a large extent organic crop production relies on preventive measures for plant protection. As a consequence, consumers of organic food have a comparatively low dietary exposure to pesticides. Although chemical pesticides undergo a comprehensive risk assessment before market release in the EU, there are important gaps in this risk assessment. In some cases, specifically for cognitive development during childhood as an effect of organophosphate insecticide exposure during pregnancy, epidemiological studies provide evidence of adverse effects. However, epidemiological studies have a very low impact on regulatory risk assessment. The evidence reviewed in this report shows that a decreased exposure for the general population is desirable from a human health perspective in light of the findings from epidemiological studies that indicate very high costs to society of current levels of pesticide exposures. Organic agriculture supplies food with low pesticide residues, and may be instrumental in conventional agriculture's transition towards integrated pest management by providing a large-scale laboratory for non-chemical plant protection.

Organic milk, and probably also meat, have an approximately 50 % higher content of omega-3 fatty acids compared to conventional products. However, as these products only are a minor source of omega-3 fatty acids in the average diet, the nutritional significance of this effect is probably low (although this has not been proven). The nutritional content of crops is largely unaffected by the production system, according to current knowledge. Vitamins and minerals are found in similar concentrations in crops from both systems. One exception is the increased content of phenolic compounds found in organic crops, although this is still subject to uncertainty despite a large number of studies that have addressed this issue. Accordingly, although in general being favourable for organic products, the established nutritional differences between organic and conventional foods are small, and strong conclusions for human health cannot currently be drawn from these differences. There are indications that organic crops contain less cadmium compared to conventional crops. This is plausible, primarily because mineral fertiliser is an important source of cadmium in soils. However, notably, long-term farm pairing studies or field trials that are required for definitely establishing or disproving this relationship are lacking. Owing to the high relevance of cadmium in food for human health, this lack of research constitutes an important knowledge gap.

Most of the studies reviewed in this report have investigated the effects of agricultural production on product composition or health. Far less attention has been paid to the potential effects of food processing. Processing may affect the composition of foods and the bioavailability of food constituents. It is regulated [209] and recognised [358] that food additives are restricted for organic products compared to conventional products. It is also recognised that the degree of food processing may be of relevance to human health [359, 360]. In organic food processing, the processing should be done "with care, preferably with the use of biological, mechanical and physical methods" [209] but there are no specific restrictions or guidelines. With the exception of chemical additives, where organic products have specific restrictions, it is unknown whether certain food processing methods (*e.g.* fermentation of vegetables, pasteurisation of vegetables) are more prevalent in organic or conventional products or consumption patterns, or whether such differences are of relevance to human health. A discussion of the potential health effects of food additives lies outside the scope of this report.

WHO and other bodies have identified the overly prevalent prophylactic use of antibiotics in animal production as an important factor contributing to increasing issues with resistant bacteria. Such use is strongly restricted in organic husbandry, which instead aims to provide good animal welfare and enough space in order to promote good animal health. This report finds evidence that supports calls for a resolution from the European Parliament [351] calling for a reduction in antibiotics use in livestock and a promotion of extensive and organic rearing systems, as one measure of action against the public health threat of increasing antibiotics resistance.

The scopes of two recent reports, from Norway (2014) [361] and Denmark (2015) [286], in part overlap with the present report. Broadly, the reviewed results and conclusions presented in those reports are in line with this report. For several topics, important new evidence has been published in recent years. Consequently, in some cases stronger conclusions can be drawn today. Furthermore, the present report includes epidemiological studies of pesticide effects in the evidence base reviewed.

10. Policy options

This chapter assesses different policy options, discussed in light of the present literature review (Figure 3). Each option has its own advantages and disadvantages. The policy options presented here take account of existing EU policies and relevant proposals that are currently being considered within EU institutions (the European Commission and the European Parliament). Within the present framework, five policy options emerge. They are presented and discussed in the following sections.

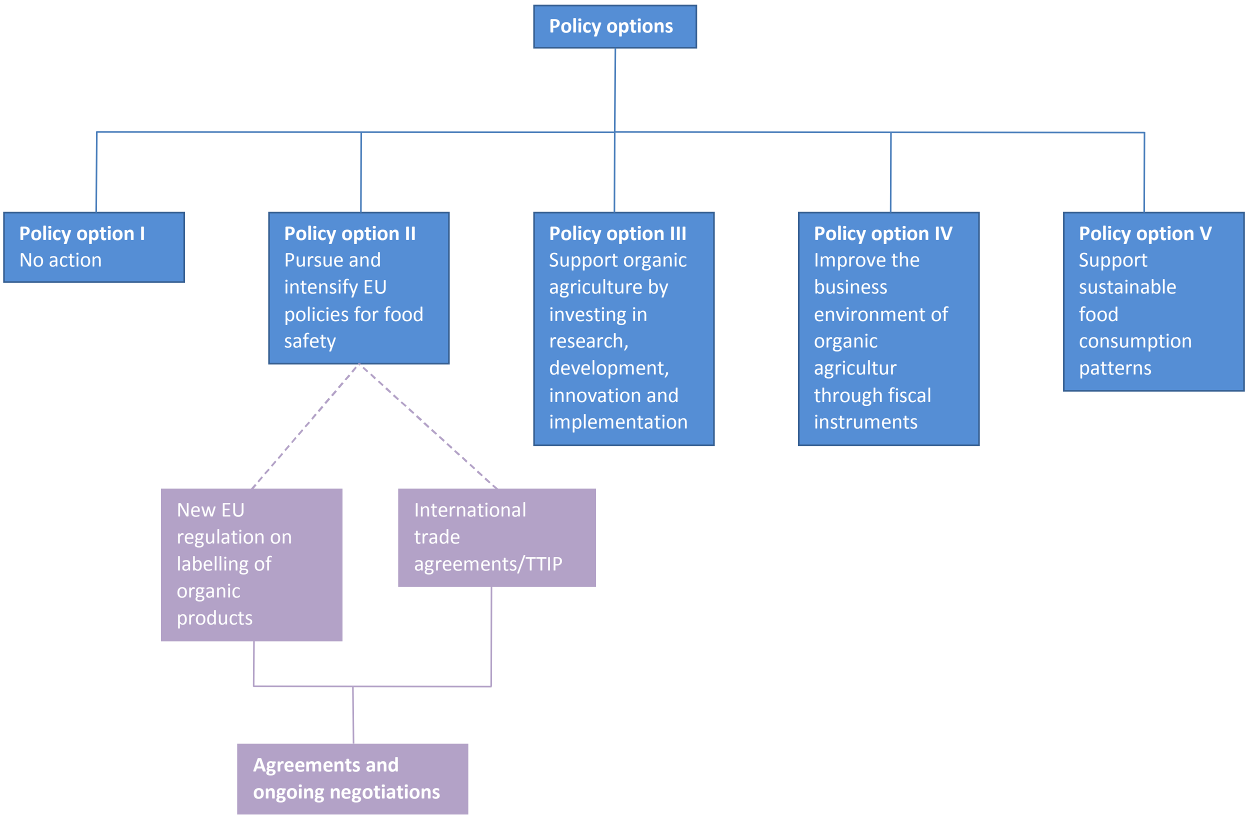

Figure 3. The five policy options and two ongoing negotiations and international agreements discussed in this chapter

10.1.1. Policy option 1: No action

Despite the stated political aim, there are no signs that the use of pesticides in the EU is decreasing. In addition, antibiotic resistance presents a growing problem for public health, although a slight decrease in antibiotic use in animal production has been noted in recent years. Furthermore, cadmium in agricultural soils from the use of mineral fertilisers continues to present a public health issue. Organic agriculture and organic food might contribute to alleviating these burdens to public health.

If no action is taken, an opportunity to address some important public health issues would be missed.

Citizens' health is a core EU priority [362]. Specifically with respect to cadmium in soils and antibiotic resistance, "no action" might be unsustainable because it may jeopardise the ability of future generations to meet their own needs due to long-term effects that may be difficult to reverse [363]. In addition, the adverse effects of certain insecticides on children's brain development may lead to an irreversible deterioration in citizens' health.

10.1.2. Policy option 2: Pursue and intensify EU policies for food safety

This report relates to EU policies and regulations for food safety primarily in three respects: the cadmium content in crops, the sustainable (= reduced) use of pesticides, and the development of antibiotic-resistant bacteria.

The European Commission has recently proposed the introduction of limits for the cadmium content of fertilisers, which may be progressively lowered over the next twelve years [245]. Such a reduction in the cadmium influx into soils is desirable from a human health perspective. Cadmium-containing phosphorus fertiliser is an important source of cadmium influx to EU soils. The flux of phosphorus from conventional to organic agriculture *via* farmyard manure and digestate has not been quantified, but a decreased cadmium influx to conventional agriculture *via* mineral fertiliser will eventually also decrease the cadmium influx to organic agriculture *via* farmyard manure and digestate. According to the limited data available, the cadmium concentration per kg phosphorus is generally lower in the phosphorus fertilisers that dominate in organic agriculture (mainly farmyard manure) compared to mineral fertilisers. Fertilisation strategies developed and used in organic agriculture, and limits for the cadmium content in mineral fertilisers, constitute potential strategies for decreasing the cadmium concentration in conventionally-produced crops.

With regard to pesticides, EU directive 2009/128 on the sustainable use of pesticides [114] is aimed at "reducing the risks and impacts of pesticide use on human health and the environment and promoting the use of integrated pest management and of alternative approaches or techniques such as non-chemical alternatives to pesticides". The parallel to organic agriculture is obvious as organic agriculture is closer to complying with the aims of this directive than contemporary conventional agriculture. This EU directive generally advocates the use of alternative approaches to pesticides where such alternatives exist. This directive is not concerned with the development of such alternatives, although in organic agriculture most pesticides are banned, irrespective of the existence of alternative approaches. This situation is a strong driving force for the development of non-pesticidal approaches to plant protection. As a result, the aims of the EU directive on the sustainable use of pesticides are more easily attainable with an organic agriculture that develops and optimises alternative approaches to plant protection. Such development would be advantageous, especially for population groups at risk, in particular pregnant women and children. Depending on the occurrence of pesticide residues in conventional foods, EU member states may develop advisories that recommend organic varieties of those fruits and vegetables that are likely to contribute the most to elevated pesticide exposures, while maintaining a high overall fruit and vegetable intake.

Regarding antibiotic resistance in bacteria, the European Parliament has expressed the opinion that the prophylactic use of antibiotics should cease [350, 351]. Specifically, the European Parliament has recommended the encouragement of "organic or extensive models of livestock rearing". Accordingly, there is a strong synergy between pursuing policies for the reduced prophylactic use of antibiotics and support for organic animal production.

In summary, EU food safety policies with respect to cadmium, pesticides and antibiotic-resistant bacteria are aimed at protecting the health of European citizens. With regard to pesticide residues, antibiotic-resistant bacteria and probably cadmium concentration in crops, organic products compare favourably to conventional products. There are some synergies and interactions between EU food safety policies and organic agriculture on these three issues. Within organic agriculture, crop and livestock management strategies are developed that may eventually be adopted by the entire agricultural system, thereby supporting EU policies for food safety. Political support for organic agriculture may to some extent also be looked upon as political support for EU food safety policies.

10.1.3. Policy option 3: Support organic agriculture by investing in research, development, innovation and implementation

Some plant diseases and pests cannot be satisfactorily managed using contemporary organic approaches and there is a need for new plant protection methods in organic agriculture. The development of novel approaches to plant protection based on ecology is research intensive. Many plant varieties have been bred for high-input conventional agriculture, but are used in organic agriculture as well; increased plant-breeding activities for varieties that are well adapted to plant protection management in organic agriculture are highly important. For animal production, varieties that are bred for less rapid growth and that remain productive, yet resistant and robust, are needed. Furthermore, there are bottlenecks in the implementation of best practices in organic plant production; specifically, some approaches to plant protection are rather knowledge intensive.

Investments in the further development of organic agriculture may improve its capabilities to serve as a provider of high-quality low-input food. This specifically relates to varieties and management systems with a low reliance on pesticides (plants) and antibiotics (animals), which in the long term may be adapted by the entire agricultural sector. Such investments can be made in research and innovation programmes as well as in agricultural consultancy services.

It is difficult to predict the economic benefits in relation to the costs of such investments. The benefits may stretch beyond the organic agricultural sector, as knowledge and solutions developed under such investments may be adopted by conventional farmers, thus supporting EU policies on sustainability, including a bioeconomy comprising plant nutrient cycling. Investments in the development of organic agriculture may therefore contribute to the development of solutions for sustainable agriculture.

10.1.4. Policy option 4: Improve the business environment of organic agriculture through fiscal instruments

It is difficult to estimate the costs to society of human health effects due to the exposure to cadmium and pesticide residues in food. It is also hard to quantify the contribution of intensive animal production to the development of antibiotic-resistant bacteria. These costs are negative production externalities that are not generally included in the pricing of pesticides, fertilisers or antibiotic drugs. Such costs can motivate the use of fiscal instruments in favour of practices that help avoid these costs. Taxes or fees can be imposed on practices that result in costs to society or the use of alternatives can be subsidised.

In Sweden, costs to society due to dietary exposure to cadmium have been estimated to be approximately € 50 per capita per year, calculated as the health care costs of bone fractures plus costs for lower quality of life and shorter life as a consequence of these fractures. Costs associated with other effects of cadmium exposure, such as renal disease or certain cancers, were not included in these calculations [364]. In contrast, a Danish study estimated that the calculated costs of disability-adjusted life years related to kidney disease and osteoporosis due to cadmium exposure were much lower [365], however this estimate did not include healthcare costs.

With regard to pesticides, the costs of health effects calculated from animal studies used in the EFSA risk assessment of active substances are expected to be very low, because if effects on human health are expected, a pesticide will not be approved. For example, annual health costs due to pesticide exposure in the EU have been estimated at € 0.15 per capita per year based on such data. However, there was very high uncertainty (between € 0.0004 and € 64) [366]. In contrast, costs due to the exposure to organophosphate insecticides have been estimated at € 260 per capita per year in the EU, based on dose-effect relationships found in epidemiological studies that are disregarded in the EFSA risk assessment.

Healthcare costs and productivity losses in the EU due to antibiotics resistance have been estimated at € 3 per capita per year for 2007 [367]. Antibiotics resistance causes approximately 25,000 deaths annually in the EU. In the USA, for 2008, healthcare costs and lost productivity are instead estimated to be € 150 per capita per year [368]. It is not possible to quantify what proportion of these costs is attributable to the use of antibiotics in animal production. However, more antibiotics are consumed by animals than by humans, both in the EU and globally, and low-dose prophylactic treatment, which carries a high risk of development of resistance, is commonly used in animals but not in humans. It is very difficult to predict future costs, but with the increasing prevalence of antibiotic-resistant bacteria, these costs are expected to increase substantially.

Fiscal instruments that aim to internalise such external costs into production costs are likely to serve public health and improve the competitiveness of organic agriculture due to its low use of pesticides and antibiotics. Such instruments could either be directed towards organic agriculture or towards the practices to be avoided or preferred, or in combination. In many cases, it may be meaningful to develop agronomic practices as part of a system rather than as isolated practices. Supporting organic agriculture as a system, and developing the legal framework for organic agriculture, takes such a system perspective into account. Supporting organic agriculture could maintain and increase its capacity to serve as a laboratory or test bed for environmentally-sustainable and healthy agricultural practices.

10.1.5. Policy option 5: Support sustainable food consumption patterns

Current average European food patterns are characterised by high meat consumption and low consumption of whole grains, fruit and vegetables compared to healthy and environmentally-sustainable levels. The promotion of healthy and sustainable food consumption is in line with central EU policies on public health and sustainability. It is notoriously difficult to influence individual food choices through the provision of information. Public catering (*e.g.* meals in schools, hospitals and retirement homes) represents a more direct route and may be a suitable focus for political action.

Within the EU-funded project "innovative Public Organic food Procurement for Youth" (iPOPY), strategies for and effects of the public procurement of organic food have been investigated with a focus on schools. One finding is that organic food may be used as an instrumental part of a strategy to promote healthy and environmentally-sustainable food habits in schools, with the involvement of pupils and staff [369, 370]. The final report for this project discusses policy options and recommendations for implementation [370].

As discussed in the present report, it is known that the consumption patterns of organic food consumers tend to be healthier compared to the general population. Likewise, due to the higher costs of organic food, public kitchens that serve a high proportion of organic food tend to serve food with a comparatively high content of plant proteins and vegetables, which is desirable from the perspectives of human health and environmental sustainability. EU institutions set the rules for public procurement in the EU and may thereby support sustainable food consumption patterns.

11. Ongoing negotiations and international agreements

11.1. New EU regulation on the labelling of organic products

Currently, a new EU regulation on the labelling of organic products is being negotiated. Of relevance to this report, a more rigorous policy regarding residues of pesticides in organic products is under discussion. Specifically, if residues of pesticides that are not authorised in organic agriculture are found in their products, it is proposed that organic producers may not market their products as organic for a period of up to two months while the source of contamination is being investigated. The source of contamination could be, for example, fraudulent use or labelling, spray drift or volatilisation from neighbouring fields, water contamination, contamination in the supply chain, mistakes in the supply chain *etc.*

From a human health perspective, risk assessments of acute and chronic exposure demonstrate that risks due to pesticide exposure are far lower for organic food than for conventional food, indicating that pesticide residues on organic food are currently a very small problem. Powerful action on pesticide residues in organic food, according to this suggestion, may impose a high economic risk on individual producers due to factors that are beyond their control. It appears more effective and proportionate to direct sanctions against (proven) fraudulent use and labelling and to regulate the use of pesticides that are known for their high potential of spray drift or volatility and long-distance contamination of fields and crops (*e.g.* pendimethalin and prosulfocarb [371]) or ground/surface water contamination, as well as to promote the use of non-chemical plant protection in conventional agriculture, than to take an overly restrictive perspective on residues in organic products. The latter may in effect constitute a barrier for the continued expansion of organic agriculture by introducing incalculable economic risks to individual producers.

11.2. TTIP and international trade

EU regulations set the rules for organic production in the EU. For goods imported into the EU, generally the standards in the country of origin are accepted as being equivalent. With the increasing international trade of agricultural goods, food produced according to foreign standards will increasingly be imported into the EU. Many countries follow the standards of the Codex Alimentarius for organic production [372]. Although these are quite similar to EU standards, there are some important differences. The relevance of such differences for human health will be illustrated here by organic products traded with the US. The EU and the US are currently negotiating the TTIP trade agreement, which is regarded as setting the trend for further international agreements in future.

Since 2012, US and EU standards for organic agriculture have been mutually accepted as equivalent in most situations [373]. While the trade volume of organic products between the US and EU is currently quite small, this may change if TTIP comes into force. Of relevance is primarily a different approach to the approval of pesticides for organic agriculture. In the EU, pesticides in organic agriculture are a small defined subgroup of substances already approved for conventional agriculture; such pesticides have therefore undergone toxicity testing and risk assessment according to the same principles as other pesticides. In the US, all “natural” substances are generally allowed as pesticides in organic agriculture unless specifically prohibited, and there is no general requirement for comprehensive toxicity testing of such pesticides. The situation is similar in many other countries that follow the rules of the Codex Alimentarius. This “naturalness” approach was abandoned by the EU in its first regulation on organic production in 1991 [374], and as such this would represent a setback for EU consumer protection. While there is no authoritative list of “natural” active substances in the US, products that are marketed for use as pesticides need to be registered, and a non-exhaustive evaluation of such registers [375-379] reveals that most of the pesticides of botanical origin for sale in the USA are either approved in the EU as well (*e.g.* pyrethrins) or are food constituents (*e.g.* capsaicin). Exceptions are kinetin from algae, extract from *Quillaja saponaria*, *Sabadilla* alkaloids, extract of *Chenopodium ambrosioides* and Douglas fir bark. Botanical pesticides tend to be rather unstable. This may reduce the risk of residues being present in foods, but it has not been systematically documented.

Basic toxicity testing has been performed for these compounds, but no comprehensive risk assessment comparable to EFSA evaluations is available. The EU could consider the option of taking responsibility for some form of consumer risk assessment of pesticide substances that have not been evaluated or approved in the EU, although they are used in other countries. This applies to pesticides used in both conventional and organic agriculture. This would increase consumer protection in the EU.

Another initiative that the EU could take is a systematic listing of pesticides that are actually used in organic cash crops in exporting countries, and an analysis of their residues in imported foods in order to document whether an exposure of European consumers is actually taking place.

Among the synthetic pesticides approved in US organic agriculture [380], boric acid can be highlighted. However, the US Environmental Protection Agency does not expect dietary uptake of boron from pesticidal applications to contribute significantly to the total dietary boron uptake [381].

With regards to antibiotic use, US organic standards are stricter than EU standards. Generally, no animal that has received any antibiotic treatment may be labelled organic in the USA. It is possible, but not documented scientifically, that this implies an even lower risk of contamination with antibiotic-resistant bacteria in US organic meat products compared to EU organic meat products.

In summary, it can be expected that with an increased import of organic foods from the US, products that are produced with practices not permitted in the EU will increasingly become available. Specifically, a wider range of compounds, including some “natural” compounds that have not been comprehensively evaluated for their safety, is approved for use as pesticides in the US as compared to the EU. It is unclear if such uses may lead to residues on imported foods. There is little specific reason for concern for human health, but there is some uncertainty associated with this development.

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This study reviews existing scientific evidence regarding the impact of organic food on human health from an EU perspective, with a focus on public health.

The development of environmentally sustainable and healthy food systems is an international priority. The study examines how organic food and organic agriculture can contribute to this in relation to public health.

Human and animal studies directly addressing the health effects of organic food are reviewed. Furthermore, evidence linking principles and rules of organic production to human health effects is discussed.

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