Journal of the Science of Food and Agriculture *J Sci Food Agric* **81**:924–931 (online: 2001)
DOI: 10.1002/jsfa.903

Featured Article

Organic agriculture: does it enhance or reduce the nutritional value of plant foods?

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Abstract: The possible differences between organic and conventional plant products are examined from the view of possible effects on human health. It is concluded that nutritionally important differences relating to contents of minerals, vitamins, proteins and carbohydrates are not likely, primarily since none of these are deficient in typical First World diets, nor are present levels of pesticide residues in conventional products a cause for concern. However, there is reason to believe that contents of many defence-related secondary metabolites in the diet are lower than optimal for human health, even for those where too high levels are known to be harmful. High biological activity resulting in adverse effects on growth of animals and children may be directly linked with promotion of longevity. There is ample, but circumstantial, evidence that, on average, organic vegetables and fruits most likely contain more of these compounds than conventional ones, allowing for the possibility that organic plant foods may in fact benefit human health more than corresponding conventional ones. The authors define testable scientific hypotheses which should be further investigated to provide more definitive answers to the question.

Keywords: secondary metabolites; human health; farming systems; plant defence

INTRODUCTION

Proponents of organic agriculture often claim that organically produced plant foods promote health of humans more than products from conventional production systems. Others claim the opposite, and many doubt that there is any difference. The most common argument used by the proponents is that when plants are grown with artificial nutrients and pesticides, they are supposed to lose their natural defence mechanisms. This is thought to result in reduced disease resistance and 'diluted' contents of minerals, vitamins and defence-related secondary metabolites, of which the last are indiscriminately considered beneficial for human health, using arguments such as their similarities to medicines. Opponents use almost the same argument to arrive at the opposite conclusion: that owing to inadequate nutrition of the plants and lack of protection against diseases, organic products are supposed to contain less of of proteins, sugars and vitamins and have increased levels of defence-related secondary metabolites, which are in this case considered harmful owing to their similarities to pesticides and other poisons.

Surveys of organic and conventional products tend not to solve the question, one of several reasons being confounding with differences among cultivars, which tend to be greater than those found between the two cultivation systems. However, both sides of the debate agree that only very few relevant unbiased high-quality studies have been conducted at all, and that sufficient data to resolve the major questions are still lacking. To define and, in the longer run, solve the dispute, at least two questions must thus be addressed.

1 Do organic plant products contain more or less of certain nutrients, minerals, vitamins and defence compounds than conventional ones?
2 To what extent are nutrients, minerals, vitamins and plant defence compounds beneficial or harmful to human health?

Regarding the first question, several studies have compared aspects of quality of organically and conventionally grown plant-derived foods. However, as concluded in a recent review, only small and inconsistent differences were found.[1] Only for nitrate and vitamin C were systematic tendencies apparent, with respectively lower and higher levels in organic material. On the other hand, in most studies, only macronutrients, vitamins or minerals were analysed, not the secondary metabolites involved in plant defence,

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Contract/grant sponsor: Danish Research Council; contract/grant number: 9901240
Contract/grant sponsor: DARCOF (Danish Research Centre for Organic Farming)
(*Received 13 November 2000; accepted 5 April 2001*)

which are those constituents which both 'parties' expect to differ most between the two systems. In the present paper, studies from other disciplines are assembled to provide an overview of the most likely situation, supplemented with preliminary studies of secondary metabolites in organic and conventional products.

The second question is not specifically related to organic products, but summarises nutrition science for plant foods in general, and an overall consensus regarding this subject does not exist. However, also here some indications can be assembled, and where knowledge is lacking, testable hypotheses can be defined.

EFFECTS OF GROWTH CONDITIONS ON PLANT CONSTITUENTS

Minerals, water, light, etc

A number of growth conditions are known to have specific effects on nutritionally relevant plant constituents. For proteins, soluble carbohydrates and vitamins, results are available from vegetables and other plant foods to understand how the contents are influenced by availability of plant nutrients, primarily nitrogen, phosphorus and potassium. Generally, protein content increases with nitrogen uptake[2] and sugar content rises when phosphorus levels are low relative to other elements.[3] Potassium levels do not seem to affect the composition of plant material systematically. Accumulation of vitamin C, ascorbic acid, is increased whenever the plant is subjected to oxidative stress, which may be caused by different conditions such as full sunlight, drought, low nitrogen availability[4] (Fig 1) or herbicides.[5] β-Carotene (vitamin A precursor) is associated with chloroplasts, primarily as an antioxidant and energy transporter, and thus tends to decrease under conditions where their proliferation is limited, eg owing to lack of nitrogen.[6] Where carotenoids occur as colourants, eg in carrots and pumpkins, the levels are generally highest in the treatments also optimal for growth[2,4] (Fig 1).

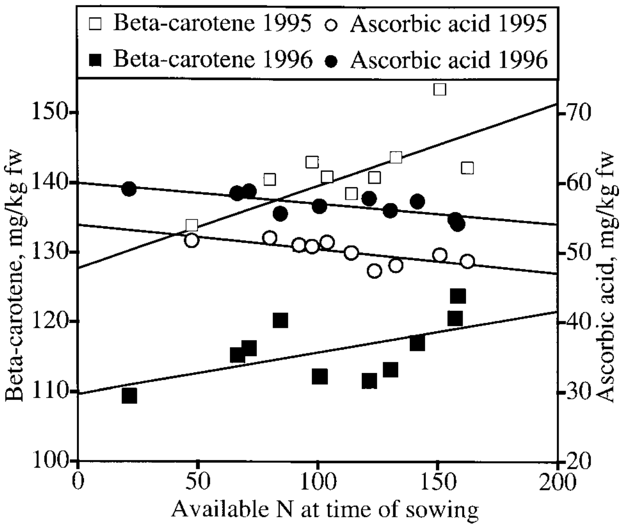

Figure 1. Relationship between soil content of inorganic nitrate, measured at time of sowing, and contents of ascorbic acid and β-carotene in carrots at harvest. Effects of year and N availability are significant at the 0.05 level or better. Redrawn from Ref 4.

However, when it comes to secondary metabolites, data on food plants become scarce. Here the general trends must be inferred primarily from investigations in the scientific discipline ecology, where extensive efforts have been made to understand the interactions between plants and the environment in nature. However, the few investigations of cultivated plants do support these general tendencies.

The first major theory in this field was the 'C/N balance theory',[7,8] which in its simplest form states that when nitrogen (N) is readily available, plants will primarily make compounds with high N content, eg proteins for growth and N-containing secondary metabolites such as alkaloids. When N availability is limiting for growth, metabolism changes more towards carbon (C)-containing compounds: starch, cellulose and non-N-containing secondary metabolites such as phenolics and terpenoids. The C/N balance theory can explain most, but not all, observed differences in plant composition due to natural and experimental differences in growth conditions. Thus it was developed into the more complex 'growth/differentiation balance theory'.[9,10] This theory states that a plant in any given situation will assess the resources available to it and optimise its investment in processes directed towards growth or differentiation, respectively. Here the term differentiation comprises increased formation of defence compounds as well as accelerated maturation and seed development. In this scheme the C/N balance is a special and typical case of the growth/differentiation balance theory, since low nitrogen availability is the most common growth-limiting condition in natural ecosystems.

A meta-analysis of leaves of many different species of wild woody plants showed consistent, characteristic effects on several groups of plant constituents.[11] N fertilisation resulted in higher contents of N-containing compounds, including free amino acids, and also increased terpene contents in most of the 20 studies where this was measured. In contrast, contents of starch, total carbohydrates, phenylpropanoids and total carbon-based secondary compounds decreased, while CO_2 enrichment or increased light had the opposite effects to N on most types of compounds. Note that, in these data, defence compounds are confounded with sunscreen pigments such as some flavonoids, which are not or less inhibited by N fertilisation,[12] so the effects on the defence substances are probably even greater. Corresponding data for cultivated plants are scarce, but those examined fit the same picture.[12–14] Note that this is also the case for the above-mentioned known effects of fertilisation on crop constituents.

As regards the less abundant minerals (trace elements), type and origin of the soil, factors that normally cannot be manipulated by the individual grower, have been shown to influence plant contents of selenium[15] and a few other elements. In contrast, no overall differences were observed between different cultivation systems on the same type of soil.[1] When small differences have been found, they could be explained as results of differences in inputs to the system, eg impurities in fertilisers used,[16] rather than differences in the ability of plants to accumulate the elements from the soil moisture.

Micro-organisms and pesticides

Compared with the effects of the physical and mineral environment on plants, the effects of micro-organisms and pesticides on plant constituents are much more difficult to predict. Many plants, when affected by a pathogen or certain chemicals, react by producing high levels of phytoalexins, very biologically active compounds that are not present or are present only at much lower levels in the undisturbed plant.[17] In some interactions between plant and disease micro-organisms this occurs as a hypersensitive response, where some plant cells themselves are poisoned in order to prevent spreading of the disease.[18] However, if plants are continually exposed to pathogens, they either defeat the pathogens or die, so no crop is obtained from them. Thus the very high levels of phytoalexins reported in phytopathological investigations have only rarely been observed in plant foods, which were otherwise considered fit for human consumption. With the exception of cucurbitacins in squash fruit and old cucumber cultivars,[19,20] phytoalexins seem to be rare in foods, although, to the best of our knowledge, no systematic surveys have been carried out on the occurrence of any phytoalexin in plant foods. However, since these compounds generally impart a distinctly bitter, very unpleasant taste to foods, as exemplified by bitter cucumbers, this would likely have been noticed more often if it were a common phenomenon. It can be argued that the presence of otherwise harmless micro-organisms may affect plant composition by somehow inducing defence reactions in the plants, but data seem not to be available regarding this hypothesis.

One case where the presence or absence of pathogens is known to systematically affect composition is that of potatoes, where the tubers must be harvested at an earlier stage of maturation when no fungicides are used to protect against late blight. Tuber composition changes during maturation, so the use of fungicides will result in more mature tubers with increased starch contents and lowered protein levels. However, since specific starch contents of potatoes are required in order to obtain products suited for the various uses of this crop, it is both possible and likely that early maturing and genetically starch-rich cultivars are or will be used to counterbalance this effect.

Regarding the use of synthetic pesticides, very little is known about effects on the composition of plant foods. A few studies indicate that the use of herbicides may induce accumulation of ascorbic acid by imparting oxidative stress on the crop plants, and of β-carotene owing to overshoot of homeostasis after partial inhibition of its synthesis,[5] but the magnitudes of these effects under normal field conditions are not known. Some fungicides, strobilurins, change the developmental rhythm of plant cells,[21] but again the consequences for product composition are not known. For both fungicides and insecticides, such studies are made difficult by the problem of distinguishing between effects of the pesticides themselves and effects of the increased incidence of pathogens in the control treatments. As an illustration of this problem, in one study of the effect of a herbicide, where weeds were not removed from the treatments receiving reduced doses, the effect on ascorbic acid content was completely reversed, since the presence of weeds exerted more stress on the crop plants than the herbicide did.[22] On the other hand, a reduction of ascorbic acid content in the herbicide-treated crop agrees well with the survey results showing marginally higher levels in organic vegetables.[1] In addition, most pesticides are mixed with detergents and other adjuvants, which are intended to make the epidermis more permeable to the pesticide, and thus must be suspected to induce various types of stress responses. However, when a new compound is put in use, only its effects on yield and visible damage to plants are measured, so effects on plant composition are at present not much more than hypothetical.

Of course, the use of pesticides also implies a risk of accumulation of residues in the product, which may in theory lead to harmful effects if harmful concentrations are obtained. This is a major concern of the authorities regulating the use of pesticides. Owing to this, the regulations on pesticide use are regularly adjusted according to safety evaluations of old and new compounds, and no evidence is available to indicate that residues resulting from the present, legal use of certified pesticides in Europe would pose a health risk to consumers.

In summary, no systematic effects of pathogens and pesticides on plant composition are known. The scattered knowledge available indicates that while effects may be present, they are most likely small, and the effects occurring in different cultivation systems may to some extent balance each other out by imposing different types of stress, which may affect plants in similar ways.

EFFECTS OF PLANT CONSTITUENTS ON HUMAN HEALTH

Types of plant constituents often mentioned as affecting human health are the following: vitamins, minerals, proteins, carbohydrates and plant secondary metabolites. Regarding beneficial and harmful effects of the first four of these, general consensus is similar: minimum levels of each must be present in the diet, contents greatly in excess of the minimum requirements do not provide any benefit, and the contents found naturally in vegetables and fruits are practically never so large as to become actually harmful. A slightly more controversial statement is that the content of each of these four types of constituents in plant-derived foods has no effect on human health, within the range of variation that is likely to occur in a normal varied diet typical of a developed country, with recommended supplements of vitamins and minerals. To put this in other words, no human or animal studies have shown effects on health of using plant foods with relatively high or low contents of any of the four types of nutrient, unless the other parts of the diet were distinctly deficient in one of these nutrients. To be directly provocative: when evaluating the relative nutritional value of different plant foods for use in developed countries, neither vitamins, minerals, proteins nor carbohydrates are obviously important targets, since if deficiencies do occur, they can be alleviated much easier from other sources.

For secondary metabolites the situation is very different. None of them are known to be absolutely necessary for a long and healthy life (per definition: in the past, as soon as a specific physiological role was shown for a secondary metabolite, it was redefined as a vitamin). Many commonly occurring secondary metabolites are known to be harmful if tested in high concentrations, and a few, such as linamarin from cassava and solanin from potato, are even harmful in regularly occurring concentrations in food plants. If the concepts for toxicity usually applied to pesticides and other synthetic chemicals were used for plant secondary metabolites, many of them would not pass a safety evaluation.[23,24] This is the evidence which leads some people to conclude that the intake of these compounds should generally be kept as low as possible.

On the other hand, many plant products containing high concentrations of potentially toxic compounds are obviously harmless to humans, since many people have been using them for many years with no apparent harmful effects. Examples of this are coffee, pepper (both black and chilli), parsley, radish, mustard and many others. Owing to this, special rules apply when plant products are being evaluated for human consumption, using concepts such as ‘long and established use’ to determine if a product is safe to use.[25] Thus, although in most cases it has not actually been experimentally investigated, it is generally accepted that, at normal levels of consumption, plant secondary compounds are not as harmful as would be expected from their LD_{50} values.

Even though the absence of these compounds does not by itself cause disease, there are many examples where one or the other compound or plant material can be used to prevent or treat diseases. In fact, it is well established that the greater the daily intake of vegetables and fruit, the smaller is the risk of the major deadly diseases in Western society, including cancer,[26] cardiovascular disease[27] and diabetes.[28] Vegetables and fruits are not major sources of vitamins, minerals, proteins or carbohydrates in the average diet. In contrast, plant secondary metabolites are unique to these types of foods, and these compounds thus comprise the most likely candidates for this general health-promoting effect. This also implies that the above-mentioned epidemiological evidence firmly contradicts the concern that plant secondary metabolites in general should pose a health hazard owing to their potential toxicity.

A few secondary metabolites have been studied for their effects on prevention or alleviation of disease,[29,30] but more than 50 000 different compounds are known from plants, and probably 5000–10 000 of these also occur in plant foods. Thus, within the foreseeable future, it is not of highest priority to obtain extensive characterisation of the effects and mechanisms of action of each and every compound. Instead it is necessary to use methods that can evaluate health effects of groups or mixtures of relevant compounds, which is also the way in which they actually occur in food. In this way it will be possible to obtain an overall understanding of the effects of plant foods on health, at a reasonable cost and a level of detail sufficient for improvements to be suggested and tested. Several such methods are under development (http://biomarkw.csl.gov.uk/) but not yet in general use.

In general, it can be safely assumed that our innate regulation of appetite and food preference is designed to cope with the conditions of pre-industrial and pre-agricultural society. The primary concern at that time was to obtain sufficient nutritional resources in terms of protein and energy, and a small surplus for withstanding times of need.[31] Thus an important observation in this respect is that a similarly positive effect as shown by vegetables and fruit, on the same types of diseases, is found when food intake is restricted without changing its composition. In many cases an optimum is found of about 60% of the food eaten when supply is unlimited.[32,33]

This indicates that, in situations of abundance, all animals tested, and most likely also humans, tend to eat more food than what is optimal from a health point of view if this situation persists. If this is the case, defence-related plant secondary metabolites, which retard growth and food utilisation, should promote health as a direct consequence of their toxicity (in fact, toxicity is often measured as retardation of growth of young animals[34]). Since many plant secondary metabolites have already been shown to act as antinutrients, making the protein or other essential components less available to us,[34,35] the seemingly contradictory combination of harmful and beneficial effects makes sense if viewed from the angle of mimicking caloric restriction.

Of course, this also means that the situation is most likely very different for human populations where food intake is limited by economic constraints (comprising most of the world’s population), since only ‘prosperity diseases’ are considered in the present review.

Taken together, this indicates that optimal concentrations probably exist for very many plant secondary metabolites, that in many cases one compound can substitute for another, and that for the majority of compounds this optimum is higher than the present daily intake in an average First World diet.

GROWTH CONDITIONS USED IN ORGANIC AND CONVENTIONAL AGRICULTURE

The rules used to define organic agriculture limit the use of synthetic pesticides and fertilisers to almost nothing.[36] The idea is to utilise instead the ecological mechanisms operating in nature. Plant nutrients are supplied through crop rotation and manure from farm animals in appropriate numbers. Plants are protected by the use of resistant varieties and a number of management tools, to avoid, rather than combat, problems with weeds, pests and diseases. This was of course the generally used technology before the invention of artificial fertilisers and pesticides. In the traditional agriculture of the pre-industrial society, yield was generally limited by the low availability of plant nutrients, just like in most of nature, and the natural defence mechanisms of the plants were fully operative.

In Western society, for many years the people who insisted on the use of organic agriculture were generally small minorities, often connected to particular beliefs or religions. However, with the increased emphasis in society on pollution and other negative effects of technology, society began limiting the use of the most dangerous pesticides. One of the methods was promotion of organic agriculture as a means to protect nature against pollution. During the 1990s, consumer demand for organic products has evolved, and increasing numbers of farmers are now changing to organic agriculture as it becomes possible to make a living by doing this.[37]

As a consequence of the recognition of organic agriculture as an instrument of environmental policy, several initiatives have been taken to improve the organic cultivation system, both on a national and a European scale. Like 100 years ago, the major problems are nutrient supply and protection against weeds, pests and diseases, and owing to the resurrected research activity, organic agriculture is becoming increasingly efficient, in some cases displaying yields close to average conventional agriculture.[38] This is achieved through new scientific developments enabling the efficient use of crop rotation and other methods to avoid nutrient losses due to leaching, combined with disease-resistant crops and new methods to enhance the competitive ability of crops towards weeds. As it happens, some types of organic agriculture have no problems to obtain the necessary levels of plant nutrients. For example, many dairy farms use clover/grass pastures as an important part of the feed supply for the cows. Such pastures accumulate in the order of $120\,\mathrm{kg\ N\,ha^{-1}\,yr^{-1}}$,[39] so when vegetables are grown in the first year after a 2 or 3 year pasture, the supply (and leaching to ground water!) of nutrients is often higher than what is recommended in conventional agriculture. Another factor in this respect is the fact that the soils with the highest natural contents of plant nutrients, eg former wetlands, are the places were economically viable organic agriculture is easiest to establish, so those soil types are probably over-represented, in particular for production of organic vegetables.

For the sake of protecting the environment against pollution, improved nutrient recycling is clearly a positive development. However, when nutrient availability increases in organic fields, it means that the conditions of the individual plant become more similar to those of conventional plants than if they were grown under nutrient-limited conditions. Altogether, organic vegetables and fruits must be expected to represent a wide range of growth conditions in terms of nutrient supply, with substantial proportions having either lower or higher nutrient availability than the average conventional field.

In contrast to organic agriculture, conventional vegetable producers obtain roughly the same nutrient supply across a variety of soil types and farming systems, since fertilisation is adjusted to the level which gives the highest yield of good-quality products. Also, since both vegetables and livestock are relatively work-intensive, they are rarely combined on the same farm. Thus, although over-fertilisation is probably a common occurrence on conventional animal farms, this has little impact on the growth conditions of vegetables and fruits.

For those crops where protection against pests and diseases is usually not a problem, such as carrots, one would thus expect variable compositions to occur among organic products. For crops with large losses due to diseases and insects, such as many fruit crops, the products must be grown using resistant cultivars and under restricted nutrient conditions[13] (when not considering production in areas where a copper-containing pesticide is still allowed owing to a temporary exemption to the EU rules). However, as long as the cost of supplying plant nutrients is generally higher for organic farmers than for conventional ones, it is safe to assume that normal market mechanisms will keep the average nutrient supply to the plants lower in organic than in conventional agriculture.

EFFECTS OF CULTIVATION SYSTEM ON NUTRITIONAL VALUE

Experiments at the Danish Institute of Agricultural Sciences have shown that it is possible to grow organic vegetables and fruits with different levels of plant nutrient supply. When the quality of the products was assessed in terms of vitamins, protein, nitrate, etc, they turned out to cover the same range as would have been expected for similar conventional crops.[4] The crops were carefully managed to prevent pests and diseases, but when those did occur, infestations were generally greater in treatments with high nutrient supply, as would be expected from ecological considerations.[13] Analyses of secondary metabolites in tissues of organic plants showed the expected significant effects of soil fertility on contents of the measured metabolites,[14] implying potential differences in effects on health among the products.

As mentioned above, only small or inconsistent differences have been found between organic and conventional products in contents of minerals and vitamins. However, the contents of protein, and in particular of nitrate, were consistently lowest in organic products, which confirms that they, on average, would have been grown with lower nutrient supply than the conventional ones. Studies of plant disease severity in conventional and organic systems also consistently show that overall disease incidence is not much higher in organic than in conventional farming, even when the same cultivars are used[40] (although cultivars known to be very susceptible were not included in these comparisons). This implies that the organically grown plants must somehow have more intrinsic resistance than the conventional ones, since they can cope so relatively well without the protection of pesticides.

Differences in nutrient availability will result in different contents of vitamins (Fig 1), but some vitamins will increase while others decrease, so this will not affect overall nutritional quality much.

Another factor distinguishing the cultivation systems is the use of disease-resistant cultivars. These are used in both conventional and organic agriculture, but they are more important and their use more widespread in the organic system. The few studies of resistant and susceptible cultivars which have addressed this question tend to find higher levels of defence compounds in the resistant ones.[41] However, the majority of studies of plant resistance only concern other defence mechanisms or the regulatory genes which initiate the defence reactions. Thus, while no absolute figures can be provided, it is a reasonable assumption that increased use of resistant cultivars in organic agriculture will cause higher contents of defence-related secondary metabolites in organic products. There is no reason to expect systematic differences in vitamin contents between resistant and susceptible cultivars.

It is often stated that it is difficult or impossible to compare levels of secondary metabolites between organic and conventional products, since it has repeatedly been shown that the differences between cultivars are greater than those between plants of the same cultivar grown under different conditions.[42] However, even if genotype differences cause a large variation within each system, a smaller but systematic effect of the growth conditions can still significantly affect the average levels, but the magnitude of the difference is very difficult to predict. As an example, in a preliminary study of wine, resveratrol content was on average 26% higher in organic than in conventional wines in paired comparisons of the same grape variety (with a range of −10 to +50%), while the variety averages differed between 0.1 and 28 ppm.[43] Taking together the many scattered results which can be considered relevant in this respect, we will dare to estimate levels of plant defence-related secondary metabolites in organic vegetables to be 10–50% higher than in conventional ones. The differences are probably smaller in fruits, but should be expected to increase (together with the price!) as the use of copper salts is abolished in organic cultivation.

On the one hand, if the developments of organic agriculture and conventional agriculture continue the present trends, where the costs of supplying organic plant nutrients decrease and restrictions on the use of fertilisers and pesticides in conventional agriculture increase, this difference will diminish and the two systems may become almost identical from a product composition point of view.

On the other hand, if the nutritional value of plant secondary metabolites can be better established and understood, minimum contents of these compounds may become part of the requirements for organic products. If this happens, differences in health-promoting effects between the cultivation systems may stabilise or increase, in parallel with the price difference.

CONCLUSION

If the defence-related secondary metabolites are the most important determinant of nutritional value of fruits and vegetables in the diet of the developed countries, then vegetable and fruit products grown in organic agriculture would be expected to be more health-promoting than conventional ones. Whether this difference is marginal or highly significant cannot be assessed with the present knowledge.

None of the other known or suspected differences between products from the two systems are sufficiently consistent and dietarily important to be expected to cause a difference in nutritional value.

RECOMMENDATIONS FOR FUTURE RESEARCH

Available model systems should be able to provide answers to the following questions.

1. Do plant defence compounds which retard growth at physiologically relevant levels also prolong life for experimental animals with ample food supply?
2. If so, are differences in levels of defence compounds found in relevant foods large enough to result in differences in longevity in relevant animal models?
3. Can markers for longevity based on end-points other than occurrence of specific diseases be developed?
4. If so, can they relate the results of animal studies to humans?
5. How do pesticides affect plant constituents?

The results will provide the necessary and sufficient justifications for different lines of research, including the inclusion of nutritionally relevant plant defence compounds as quality characteristics of plant products and studies of the probably many different specific mechanisms of action of health-promoting plant metabolites.

ACKNOWLEDGEMENTS

The contribution to this review by Kirsten Brandt was supported by grant 9901240 from the Danish Research Council to the project 'Health promoting compounds in vegetables' and that of Jens Peter Mølgaard by DARCOF (Danish Research Centre for Organic Farming) to the project 'Review of organic food and human health'.

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