Reviews

Does Organic Production Enhance Phytochemical Content of Fruit and Vegetables? Current Knowledge and Prospects for Research

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Summary. Demand for organically grown produce is increasing, largely due to concerns of consumers about health and nutrition. Previous studies have not shown a consistent difference of essential nutrients, such as vitamins and minerals, between organic food crops and the conventional counterparts. However, to date, little consideration has been given to phytochemicals, secondary plant metabolites with potential health-promoting properties. We first discuss factors that can influence the levels of phytochemicals in crops, and then we critically review the results of published studies that have compared the effects of organic and conventional production systems on phytochemical contents of fruit and vegetables. The evidence overall seems in favor of enhancement of phytochemical content in organically grown produce, but there has been little systematic study of the factors that may contribute to increased phytochemical content in organic crops. It remains to be seen whether consistent differences will be found, and the extent to which biotic and abiotic stresses, and other factors such as soil biology, contribute to those differences. Problems associated with most studies tend to weaken the validity of comparisons. Given the limitations of most published studies, needs for future research are discussed.

Driven by increasing consumer demand, organic farming has become one of the fastest-growing segments of U.S. agriculture, with sales of organic foods rising more than 20% annually since 1990 (Dimitri and Greene, 2002). Increasing demand for organics is a top consumer trend (Sloan, 2003) and reflects consumer perceptions of organic foods as more environmentally friendly (Goldman and Clancy, 1991; Wandel and Bugge, 1997), safer (Jolly et al., 1989), and more nutritious and health-promoting than conventional foods (Magnusson et al., 2003; Makatouni, 2002). Is organic food really healthier than its conventional counterpart? Answers to this question are now being sought against the backdrop of epidemic diet-related chronic diseases in the U.S. and most Western countries (Cordain et al., 2005; Mokdad et al., 2000); significant efforts, such as the "5-A-Day" program, to promote vegetable and fruit consumption and reduce health problems (Heimendinger et al., 1996); and reports of declining nutritional value of fruit and vegetables (Davis et al., 2004; Meyer, 1997).

Compared with conventional production systems, which typically rely heavily on off-farm inputs, including synthetic fertilizers and pesticides, organic farming is supposed to be more environmentally friendly. Organic farming emphasizes sustainable management practices, relying on techniques such as crop rotation, cover cropping, nutrient recycling, and integrated pest management (ATTRA National Sustainable Agricultural Information Service, 2004; Lotter, 2003). In the U.S., organic farming is governed by federal law (U.S. Congress, 2005), which established the National Organic Program (NOP) and uniform organic standards that prohibit the use of synthetic pesticides and fertilizers, sewage sludge, genetically modified organisms, and ionizing radiation (NOP, 2006). Information about the nutritional quality and health benefits of organic food crops would be of great interest to both consumers and producers.

Numerous studies on the nutritional quality of organic produce have been conducted, but have produced inconsistent results. Types of comparative studies include grocery store surveys, farm surveys, and comparisons of fertilizers and other cultural practices conducted on farms and in on-station replicated trials. Worthington (2001) compiled results from 41 published comparative studies, conducted a statistical analysis, and concluded that, by and large, organic produce was significantly higher in vitamin C, iron, magnesium, and phosphorus content, and lower in nitrate content. Magkos et al. (2003) concluded that vitamin C tended to be higher in organic leafy vegetables and potatoes (*Solanum tuberosum*), and protein seemed to be at a lower concentration but of higher quality in some organic vegetables. Furthermore, they discussed methodological problems associated with the majority of the comparative studies, because many factors might confound organic vs. conventional nutrient comparisons, including cultivar, microclimate environment, and postharvest practices.

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Bourn and Prescott (2002) reviewed approximately 50 comparative studies of the nutritional value of organically and conventionally grown foods, and concluded that lower nitrate level in organically grown crops was probably the only consistent result, possibly due to the relatively lower availability of nitrogen in organic farming systems. These authors also noted the lack of well-controlled studies and the lack of information about the impact of organic growing systems on phytochemicals such as flavonoids and phenolic acids. A review by Williams (2002) arrived at similar conclusions. She recommended controlled studies of phytochemical contents in plant foods, noting that flavonoids, phytoestrogens, and glucosinolates may differ in organic and conventionally grown vegetables. A further comprehensive review by the U.K. Soil Association (Heaton, 2002) also identified a need for additional studies of phytochemicals in organic crops and their roles in human health. Brandt and Mølgaard (2001) estimated that organic vegetables may contain 10% to 50% higher defense-related secondary metabolites than conventionally grown vegetables.

Phytochemicals are bioactive compounds ubiquitous in the plant kingdom. Apart from essential nutrients in foods, like water, proteins, fats, carbohydrates, vitamins, and minerals (Mozian, 2000; Titchenal and Dobbs, 2004), phytochemicals are mainly plant secondary metabolites. From an ecological point of view, their occurrence and distribution in plants is considered to be the result of natural adaptation and selection via complex, coevolutionary processes (Wink, 2003). According to Harborne (1999), secondary plant metabolites can be divided into four classes: phenolic compounds (e.g., flavonoids and phenolic acids), terpenoids (e.g., carotenoids and limonoids), alkaloids (e.g., indoles), and sulfur-containing compounds (e.g., glucosinolates). Phenolics constitute the largest group of phytochemicals, with several thousand identified in higher plants and several hundred found in edible plants (Manach et al., 2004). Recent reviews on phytochemical profiles in fruit and vegetables and protective roles of phytochemicals in human health include Dillard and German (2000), Heber (2004), and Meskin et al. (2004).

The objective of the present review is to examine evidence for enhancement of phytochemical content in fruit and vegetables through organic production practices. This question is addressed within the context of the overall body of knowledge of horticultural influences on phytochemical content of fruit and vegetables. Factors that may contribute to enhanced phytochemical content under organic production systems are critically assessed and needs for future research further identified.

Factors that influence phytochemical levels in fruit and vegetables

The amounts and types of phytochemicals in a plant are determined by a number of factors, including genotype, ontogeny, and environment. Manach et al. (2004) reviewed food phenolics and their bioavailability and briefly discussed factors contributing to variability of polyphenol levels, including genetics, maturity, environment, postharvest storage, and processing. Boyer and Liu (2004) reviewed factors influencing phytochemicals in apple (*Malus ×domestica*) and Dumas et al. (2003) similarly reviewed tomato (*Lycopersicon esculentum*). We briefly review some of the major factors known to influence phytochemical content in order to understand observed differences between organically and conventionally produced crops.

Genotype. Occurrence of phytochemicals differs among species. Of the 10 most consumed vegetables in the U.S., broccoli (*Brassica oleracea* Italica group) contains the highest amount of total phenolics, and cucumber (*Cucumis sativus*) the lowest (Chu et al., 2002). Marked differences in phytochemical content due to cultivar are common. For example, Howard et al. (2002) reported that disease-resistant breeding lines of spinach (*Spinacia oleracea*) had higher phenolic contents than commercial cultivars.

Plant tissue, fruit size, stage of development, and ripening. Phenolics usually accumulate in outer parts of plant or fruit tissues. For example, outer leaves of head lettuce (*Lactuca sativa*) have higher flavonoid concentrations than inner leaves (Hohl et al., 2001). Pear (*Pyrus communis*) peel is higher than flesh in total phenolics (Sanchez et al., 2003), and skin of tomato higher in flavonoids (Le Gall et al., 2003). Fruit size may also play a role. Small blueberries (*Vaccinium* spp.) have higher phenolic contents than large berries (Howard et al., 2003), but beta-carotene level in muskmelon (*Cucumis melo*) increases as fruit size increases within a certain range (Lester and Eischen, 1996). As reviewed by Dumas et al. (2003), lycopene content in tomato increases sharply during ripening. Typically, phenolic acid concentrations drop during fruit ripening, while the opposite occurs for flavonoid anthocyanins (Manach et al., 2004). Flavonoid content increases during inflorescence development in broccoli, in contrast to glucosinolates, which reach highest levels during the early or middle stages depending on the sulfur fertilization level (Vallejo et al., 2003a). Undoubtedly, intrinsic variability of phytochemicals is the primary factor to be considered in any production system attempting to enhance phytochemical levels in food crops.

Diseases and pests. Biotic stresses caused by diseases and pests can be a major constraint in many crop production systems. Plants manufacture and accumulate an array of defense-related phytochemicals under herbivore and pathogen attack (Dixon and Paiva, 1995; Hahlbrock and Scheel, 1989; Herms and Mattson, 1992).

Soil conditions. Few attempts have been made to link soil conditions to phytochemical content in crops. Lester and Eischen (1996) reported that muskmelon grown on fine sandy loam soils had less beta-carotene than those produced on silty clay loam soil. Oliveira et al. (2003) demonstrated that carotenoid levels in grapes (*Vitis vinifera*) were more affected by soil characteristics than irrigation. Irrigation did not affect carotenoid level in grapes produced on higher-water-retention capacity soil, but there was a 60% decline in carotenoids in irrigated grapes grown on a lower-water-retention soil compared to non-irrigated grapes. Wang et al. (2002) reported that levels of flavonols, anthocyanins, and phenolic acids in strawberries (*Fragaria* spp.) were higher using raised beds with plastic mulch than with using matted rows without mulch.

Fertilization. Phenolic compounds may accumulate due to a deficiency in nitrogen, phosphate, and iron (Dixon and Paiva, 1995; McClure, 1975). While increasing nitrogen application seems to decrease the level of phenolic compounds (Bourn and Prescott 2002), carotenoid content in fruit and vegetables tends to increase with higher nitrogen fertilization (Mozafar, 1993). The review of Dumas et al. (2003) reported that potassium deficiency may result in a decrease of lycopene level in tomato. A recent greenhouse study on red pepper (*Capsicum annuum*) fruit showed that lycopene and beta-carotene levels were raised by adding more calcium or nitrate to the root medium, but that total phenolic content was not affected (Flores et al., 2004). Leonardi et al. (2000) indicated that moderate salt stress increased the carotenoid concentration of cherry tomato (*L. esculentum* var. *cerasiforme*). Total glucosinolates in broccoli inflorescences did not seem to differ between poor and rich sulfur fertilization when sulfur deficiency in soil was not observed (Vallejo et al., 2003b).

Irrigation. Drought is likely to contribute to accumulation of phenolics. Tovar et al. (2002) demonstrated that as irrigation levels increased, L-phenylalanine ammonia-lyase activity and phenolic concentrations in olive fruit decreased. According to Esteban et al. (2001), irrigation tended to reduce the concentrations of total polyphenols and total tannins in the skin of grape berries. However, effects of irrigation on total anthocyanin concentration were inconsistent over 2 years. Furthermore, concentrations of monoglucosides of five main anthocyanins at harvest were higher under irrigation. The relationship between water availability and content of lycopene and other carotenoids in tomato was complex (Dumas et al., 2003). Deficit irrigation (0.75 ET) did not affect lycopene content in ripe and overripe watermelons (*Citrullus lanatus*) (Bang et al., 2004; Leskovar et al., 2004). Evers et al. (1997) reported that irrigation might cause reduction in alpha- and beta-carotene contents in celery (*Apium graveolens*).

Pesticide application. Plant secondary metabolism can be affected by pesticides, which may either increase or decease concentrations of phenolic compounds in plants, depending on the mechanism of action of the pesticide (Daniel et al., 1999; Lydon and Duke, 1989).

Season, location, and climatic conditions. Climatic conditions can profoundly influence phytochemical contents in plants. Overwintered spinach harvested in the spring showed higher concentrations of total phenolics than spinach planted and harvested in the fall, possibly due to stress associated with temperature, light intensity, and disease pressure during the winter season (Howard et al., 2002). Researchers in Spain found that late-season (spring) production of broccoli tended to enhance the total glucosinolate and total flavonoid contents in the inflorescence in comparison with early-season (winter) production (Vallejo et al., 2003b, 2003c). Owing to different environmental conditions represented by different locations and years, phytochemical level often varies with location and year, and therefore results in inconsistent data from various studies. Long-term studies at a wide range of locations are probably preferred for phytochemical investigation.

Goldman et al. (1999) recommended that model crops be employed to study important agricultural factors that influence the phytonutrient content in plant foods and the accumulation and distribution patterns of different phytonutrients. With the identification of multiple factors that influence phytochemical content, integrated strategies are expected to be utilized in farming systems to optimize production and quality. Using broccoli, cauliflower (*B. oleracea* Botrytis group), and radish (*Rapanus sativus*) as model crops, Schreiner (2005) proposed cultural practices to produce phytochemical-enriched vegetables by crop management strategies involving cultivar selection, fertilization, irrigation, seasonal control of temperature and irradiation, and scheduling of planting date and harvest time.

Examining evidence of improved phytochemical content in organically grown fruit and vegetables

The lack of consistent differences in vitamin and mineral content between organically and conventionally grown crops has led to an increased interest in the effects of these production systems on the accumulation of phytochemicals. To date, comparisons between organic and conventional farming systems have focused mostly on either the whole system or fertilizer applications. Although studies of whole farming systems are often recommended, due to various confounding factors it is difficult to attribute differences between whole systems to specific effects (Bourn and Prescott, 2002). It is not clear which variables in organic farming systems might have the greatest effect on the phytochemical content of crops. It has been postulated that the absence of pesticides, or the nutrient availability in the organic systems, induces or promotes production of phytochemicals in organically grown plants (Brandt and Mølgaard, 2001).

Phytochemical level in organically grown vegetables. Ren et al. (2001) reported that organically grown onion (*Allium cepa*), green pepper, and leafy greens showed 1.3 to 10.4 times higher quercetin concentration and possessed higher antioxidant and antimutagenic activities, compared with conventional crops from a nearby farm. Unfortunately, soil conditions, cultivars, and harvest stage were not reported and little information was provided about horticultural practices, thereby limiting the explanatory value of this report. In this study (Ren et al., 2001) chitosan was applied as a soil amendment prior to planting, and sprayed on crop leaf surfaces as an insect repellent. However, it was not reported whether the application of chitosan contributed to the increase of flavonoids in organic vegetables.

Caris-Veyrat et al. (2004) reported that, on a fresh weight basis, organic tomato contained higher lycopene, beta-carotene, rutin, and naringenin than conventional tomato; whereas on a dry weight basis, only beta-carotene and rutin were significantly higher in organic tomato. By both measures, chlorogenic acid was higher in conventionally grown tomatoes. When tomato purees were analyzed, production method did not affect the carotenoid content, but polyphenols were increased by organic cultivation. Unfortunately, the experimental design used for production of organic and conventional tomato did not appear to include adequate replication and randomization to make statistically valid conclusions.

Ferreres et al. (2005) and Sousa et al. (2005) reported that organic tronchuda cabbage (*B. oleracea* Tronchuda group) tended to have higher total phenolic content in leaves than did conventional. The authors speculated that input of chemical fertilizers and/

or pesticides in conventional farming systems might interfere with the biosynthesis of phenolic compounds in plants. However, lacking replication in the experimental design, their observations supporting organically grown cabbage were not substantiated by adequate statistical analysis.

Young et al. (2005) found no differences between organic and conventional lettuce, collards (*B. oleracea* Acephala group), and pac choi (*B. rapa* Chinensis group) for most flavonoids and phenolic acids evaluated, but did find significantly higher total phenolics in organic pac choi. In contrast to previously mentioned studies, our experimental design included sufficient replication of experimental plots to allow us to make statistically valid comparisons. However, it was not possible to definitively attribute differences between organic and conventional pac choi with respect to flea beetle damage or to fertilizer regimes.

Phytochemical levels in organically grown fruit. According to Weibel et al. (2000), phenolic compounds (mainly flavanols) were 18.6% higher in organically produced apples compared to apples of the same cultivar from adjacent conventional farms. The authors indicated that the paired farms were "reasonably close together." However, soil conditions and cultivation practices were not described.

Carbonaro et al. (2002), seeking markers for quality of organic produce, reported higher polyphenol contents and polyphenol oxidase activities in organic peaches (*Prunus persica*) and pears than in conventional fruit from the same orchard. They also reported similar levels of oxidation products in organic and conventional samples. The merit of this study lies in careful control of cultivar, tree age, fruit maturity, and soil type. Nonetheless, inconsistencies occurred with respect to concentrations of ascorbic acid, citric acid, and tocopherols in organic vs. conventional samples; thus, convincing evidence to support the authors' contention of enhanced antioxidant defense system as a result of organic production was missing.

Asami et al. (2003) reported higher phenolics in organically and sustainably produced marionberry (*Rubus ursinus*), strawberry, and corn (*Zea mays*), with a sustainable agricultural system resulting in the highest total phenolic content. Problems with this study were critically reviewed by Felsot and Rosen (2004). Due to unclear differentiation of sustainable production from conventional production, it seemed inappropriate to contrast these two systems. Without the description of soil types in the case of marionberry, and with different soil types involved in the case of corn, it is not valid to attribute significant differences to different agricultural practices.

In a comparative study on plum (*Prunus domestica*), Lombardi-Boccia et al. (2004) investigated conventional cultivation on tilled soil and organic farming on tilled soil, clover (*Trifolium subterraneum*) -covered soil, and natural meadow-covered soil. While organic producers might use cover crops more frequently than conventional growers, it is perhaps only valid to make comparisons between organic and conventional fruit trees receiving similar tillage practices. Conventional plums on tilled soil contained higher total phenolic content than organic ones. Inconsistent results were observed when specific phenolic compounds were further analyzed. Caffeic acid, ferulic acid, chlorogenic acid, trans-p-coumaric acid, myrecitin, and kaempferol increased under organic production, while protocatecuic acid, neo-chlorogenic acid, and quercetin decreased. The comparison of organic plums grown under different soil management systems showed that trifolium mulch was associated with the highest level of phenolic acids, while natural meadow mulch was correlated with enhanced contents of ascorbic acid, tocopherols, and beta-carotene, indicating the potential to affect phytochemical content with management practices.

Malusà et al. (2004) compared the influence of conventional and three types of organic fertilization (animal manure, a commercial inoculant of "mycorrhiza and plant growth promoting bacteria," and a combination of both) on grape yield and quality. Yields were reduced by organic treatments, but flavonoid and anthocyanin contents in grape skins were higher. The authors related low nitrogen availability in the organic vineyard to the increased level of phenolics in the grape skin. However, polyphenol content differed among organic treatments, with significantly higher contents in treatments receiving inoculant treatments. Although this study was controlled adequately for cultivar and soil type, it did not provide information about previous organic vs. conventional cultural practices, nor whether there were differences in pest/disease management between organic and conventional production.

Effects of organic production on phenolics have also been reported to be cultivar dependent. Häkkinen and Törrönen (2000) reported that, of three strawberry cultivars tested by sampling from organic and conventional farms, increased phenolic compounds only occurred in one cultivar under organic conditions, possibly due to pathogen attack. Although cultivars and harvest stage were identified in their study, no information on soils, climates, and management practices was given for the various farms.

Another study showed that levels of total phenolics and anthocyanins were significantly higher in organically grown red oranges (*Citrus sinensis*) than in those grown using a system of integrated farming practices that included components of conventional and organic systems (Tarozzi et al., 2006). Higher antioxidant activity of organic oranges was demonstrated using two cell culture models. Unfortunately, conclusions of this study represent little more than an observation since both organic and non-organic samples were purchased from a retail store, and no cultivation information was provided. Statistical analysis of samples from different lots is not comparable to that of truly replicated samples from soundly designed field experiments.

Phytochemical levels in processed products from organic fruit and vegetables. In addition to fresh produce, processed products from organic fruit and vegetables have also been investigated. Packaged soups made from organic vegetables contained nearly six times as much salicylic acid as non-organic soups (Baxter et al., 2001). In a comparison of ketchup samples from different commercial sources, organic ketchups had higher total carotenoid and lycopene contents than the non-organic brands (Ishida and Chapman, 2004). Such retail market studies would be more valuable if they provided an accurate reflection of the quality of organic or conventional food purchased on average by consumers. However, with no information about genotype, environmental conditions, and production methods used to produce the organic and conventional products, hypotheses to explain these observed differences could not be formulated. Tinttunen and Lehtonen (2001) found higher levels of *trans*-resveratrol in organic wines in a comparison of nine organic red wine and six normal red wine samples of French origin. A study in Turkey reported the variability of individual phenolic compounds and total phenol levels in organic and conventional wines from six grape cultivars, and indicated that conventionally produced wines tended to have a higher total phenolic content (Yldrm et al., 2004).

Considering the continuing high interest in phytochemicals and a lack of systematic research to determine if organic farming systems can be a practical way of producing functional food crops, much research remains to be done. Nevertheless, in a broader sense, the influence of diverse production systems on phytochemical composition of food crops is likely to become a promising research area for ensuring and improving the nutritive quality of foods.

Limitation of current studies on phytochemicals in organic food crops and future work

Since genetic and environmental factors have distinct effects on phytochemicals, these factors should be carefully considered in organic production systems. Unfortunately, these factors are generally not well addressed in most comparisons between organic and conventional production (Bourn and Prescott, 2002). Within the framework of "organics," crop genotype and organic management practices, as well as season and location, deserve systematic study. There are many organic production conditions, and they can significantly vary both within and among farms and regions. Without an understanding of the key components of organic farming in comparison with conventional production, it will be difficult to control the specific elements in organic systems correlated with improved phytochemical contents. Well-designed experiments should aim to disaggregate and define the important factors that may contribute to phytochemical differences between organic and conventional fruit and vegetables.

Systematic research needed on production factors under organic systems. A common explanation for reported differences in phytochemicals between organic and conventional produce is that organic systems are more "stressful" than conventional systems due to the limited and restricted use of pesticides in organic systems, thus allowing for greater incidence of biotic stresses (Asami et al., 2003; Carbonaro et al., 2002; Manach et al., 2004; Tarozzi et al., 2006). Clearly, additional factors, such as quality and quantity of nutrients available to plants, may also be responsible for differences in phytochemical content both between organic and conventional production systems and within organic and conventional systems. For example, under organic production, Nørbaek et al. (2003) reported that concentrations of flavonoids and phenolic acid in leaves of barley were reduced by increasing fertilization rates of farmyard manure or cattle slurry.

Lundegardh and Martensson (2003) postulated that organically produced plant foods might be expected to be higher in health-promoting phytochemicals than conventional foods because of differences between production systems in incidence of diseases and pests, microbiological activity of soils, and availability of soluble nutrients to growing plants. Results of comparisons of the influence of organic and synthetic fertilizers on insect population and plant resistance are rather inconclusive, although a number of studies have demonstrated the suppressive effects of organic fertilizers on insect pests in various crops (Culliney and Pimentel, 1986; Morales et al., 2001; Prakash et al., 2002; Yardim and Edwards, 2003). Influence of organic fertilizer has varied with year and insect species (Yardim and Edwards, 2003), but organic fertilizers may have potential to reduce the susceptibility of crops to pest attack in organically managed systems (Phelan et al., 1995; Yardim and Edwards, 2003). If this is so, links between possible increased production of phytochemicals in crops and reduced pest incidence, as well as soil nutrient availability and plant uptake under organic conditions, need to be addressed.

Based on a 21-year study, Mäder et al. (2002) demonstrated that, compared with conventional production, organic farming led to greater soil biological activity and stability, higher calcium and magnesium in soil, and lower soluble phosphorus and potassium in soil, but higher activities of dehydrogenase, protease, and phosphatase, indicating phosphorus availability through microbial transformation. Poudel et al. (2002) showed that the pools of potentially mineralizable nitrogen were much greater in organic than conventional systems, but that nitrogen mineralization rates in the conventional systems were higher. To date, little work has been conducted to explore the connections between these specific features and phytochemical production under organic conditions as compared to conventional systems. Considering the interest in utilizing soil inoculants such as compost tea (Quarles, 2001; Scheuerell and Mahaffee, 2002) and effective microorganisms (Daly and Stewart, 1999) in organic production, the indirect influence of soil biology on phytochemical production also warrants further study. In ongoing work, replicated organic and conventional plots in open fields and high tunnels are being used to study the effects of soil biology, fertility, and biotic stress effects on phenolic and antioxidant contents, primarily in leafy green vegetable crops (Zhao et al., 2004, 2005).

Postharvest changes in phytochemicals also need more investigation. Tarozzi et al. (2004) reported that, in general, fresh organic and conventionally produced apples did not differ in health-promoting phytochemicals, but cold storage significantly affected antioxidant properties of apples regardless of the production method.

Our review of the literature revealed multiple reports on phytochemicals in organic and conventional crops that were weak on experimental design and sampling of the crops being produced for comparison of phytochemicals. This is an area where horticulturists can bring important disciplinary expertise to multidisciplinary research efforts.

Exploring molecular mechanisms. Few studies have examined the molecular mechanisms of phytochemical synthesis in organically produced crops. Kumar et al. (2004) described differences in crop performance and in gene expression of tomato crops grown in a hairy vetch mulch-based system, or in conventional production using polyethylene mulch. The decomposition of organic mulch up-regulated specific genes (e.g., nitrogen- and cytokinin-responsive genes and some defense genes) in tomato and led to higher levels of certain proteins and secondary metabolites. Plant secondary metabolism is thought to be regulated systematically by signal transduction pathways that are triggered by various stress factors (Sudha and Ravishankar, 2002). Understanding the mechanisms of phytochemical synthesis and degradation should help us identify and manipulate the contributing factors in production systems.

Many organic management practices are not restricted to organic farming; if their roles in enhancing phytochemical levels can be clearly identified, conventional farming systems may also receive benefits in terms of producing phytochemical-enriched food crops.

Testing organic food for health benefits. As we try to enhance phytochemical content of foods through farming systems, further information will be needed on the health-promoting effects of plant secondary metabolites. Simply boosting levels of one or two phytochemicals in foods may not be essential for benefits. Eventually, phytochemical-enriched organic foods will need to be tested on animals and humans for their bioavailability and health-promoting effects. In a human intervention study, organically produced diets that had higher contents of quercetin and keampferol resulted in higher urinary excretion of quercetin and kaempferol than conventionally produced diets, but the proportion of flavonoid excretion to the intake, as well as most biomarkers of antioxidative defense, did not differ between the two diets (Grinder-Pedersen et al., 2003). In another study comparing consumption of organic vs. conventional wines, no significant difference was found in terms of low density lipoprotein oxidation in human blood samples (Akcay et al., 2004).

Concluding remarks

To assess thoroughly the potential for and benefits of phytochemical improvement in organic systems will require interdisciplinary collaboration involving horticulturists and others, including food scientists, nutritionists, entomologists, plant pathologists, and biochemists. On the basis of limited literature, it is difficult to draw any definitive conclusions, although it seems that organic farming might have some potential for producing phytochemical-enriched fruit and vegetables. Whether consistent differences will be found, and the extent to which biotic and abiotic stresses, and other factors, such as soil biology, contribute to those differences remains to be determined. Very likely, consumer demand for organically grown produce will continue to increase. Both consumers and producers will be well served by a clearer understanding of the benefits that might be expected from consumption of organically grown foods and of the production techniques that may be used to enhance crop nutritional value.

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