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"Physiological quality" of organically grown vegetables

Francesco Orsini [a], Albino Maggio [b], Youssef Rouphael [b], Stefania De Pascale [b,*]

[a] Department of Agricultural Sciences, University of Bologna, Viale Fanin 44, 40127 Bologna, Italy
[b] Department of Agricultural Sciences, University of Naples Federico II, via Università 100, 80055 Portici, Naples, Italy

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ABSTRACT

Organic production is gaining an increasing share of the vegetable market since it is promoted and perceived by consumers as healthier and safer for the environment. Despite the general acceptance of these benefits, the alleged higher nutritional value of organic compared to conventional products has not been well defined in terms of physiological processes. The lower yield observed under organic farming is likely caused by genetic determinants of specific varieties used in this system and/or an exposure to biotic and abiotic stresses that may affect organic crops. In response to these stresses, plants physiologically accumulate organic molecules that in addition to have a protective function for the plants may also have potential health benefits (antioxidants). In this general frame, this review discusses the concept of *physiological quality*, defined as the commercial (*e.g.*, sugar content, fruit firmness, % dry matter) and nutritional characteristics (*e.g.*, concentration of vitamins, antioxidants, minerals and other valuable health-related molecules) of the harvested product determined by physiological responses to a specific cultivation process/regime. Main biotic and abiotic stresses occurring in vegetable crop systems, with an emphasis on key differences between organic *vs.* conventional farming, are described. Functional links between accumulation of nutritionally valuable molecules, organic farming, environmental and cultural stresses are then discussed. Finally, how plant breeding may contribute to improve organic crops is briefly addressed. We overall highlight that organic farming may have *intrinsic* values associated to the peculiarities of the cultivation process *per se* that so far have not been sufficiently considered and exploited.

1. Introduction

For vegetable crops, it is generally accepted that growth under organic cultivation is lower as compared to those grown conventionally (Worthington, 2001; van Bueren et al., 2011). Yield reduction under organic regime has been recently addressed in a meta-analysis in which 1000 observations from 115 studies were considered (Ponisio et al., 2015). Based on this study, organic yield was 20% lower than conventional ones, although this gap was around 10% when organic cultivation protocols were associated with optimal crop rotations. Lower yield under organic regime has also been documented by Seufert et al. (2012), who pointed out that differences with conventional cultivation are highly contextual. System specificity and site features may lead to 5% yield decrease for low-input rain-fed legumes and perennials, while 13% reduction was observed when crop rotation was considered only for organic farming and 34% reduction when similar agronomic practices were used in both systems (possibly because the use of synthetic pesticides and fertilizers may have led to higher yield under conventional farming). Dorais and Alsanius (2015) reported that an averaged 11% yield reduction was observed in organic horticultural farming, mainly due to scarcity of genotypes adapted for this system as well as stress-associated effects, which may impact organic crops more than conventional crops (*e.g.*, pest outbreak and/or nutritional imbalances). A reduced growth is generally associated with sub-optimal environmental conditions such as disease infestation (Nachimuthu et al., 2012), nutrient limitation (de Ponti et al., 2012), water deficit (van Bueren et al., 2011) or other constraints which may ultimately expose plants to various levels of stress and affect organic and conventional systems in a different way. Considering that organic crops may overall produce 5 to 50% less than conventional crops (Del Amor, 2007; Berner et al., 2008; Benbrook, 2009; Quirós et al., 2014), it is possible that these crops experience some level of stress that could be responsible for the observed reduced yield. It is also conceivable that ecotypes/cultivars that are used in organic farming are genetically more resilient and tolerant to environmental constraints, a trait that comes along with a reduced growth and constitutive accumulation of stress protective molecules (Maggio, 2002). In response to both biotic and

* Corresponding author. Fax: +39 081 7755129.
E-mail addresses: f.orsini@unibo.it (F. Orsini), almaggio@unina.it (A. Maggio), youssef.rouphael@unina.it (Y. Rouphael), depascal@unina.it (S. De Pascale).

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abiotic stresses, plants activate a series of counteracting measures, including molecular and physiological mechanisms that consent short- and long-term adaptation to a sub-optimal environment (Atkinson and Urwin, 2012). Among these measures, the accumulation of specific organic molecules and secondary metabolites with multiple functions has a critical role in ensuring plant growth and development under unfavourable conditions. These molecules include, for instance, ascorbate (Suzuki et al., 2013), tocopherols (Benbrook, 2009), proline (Maggio et al., 2008; Sperdouli and Moustakas, 2012), polyamines (Hussain et al., 2011), carotenoids (Barański et al., 2014) and glucosinolates (Barbieri et al., 2008). All these compounds are thought to contribute to intra- and intercellular signaling (Suzuki et al., 2014), cellular water homeostasis (Bandyopadhyay et al., 2012) and ROS scavenging (Sharma et al., 2012). Plants that are defective in either constitutive or stress-induced accumulation of one or more of these molecules are likely to be hypersensitive to environmental stresses (Munné-Bosch and Alegre, 2002; Díaz et al., 2010; Atkinson and Urwin, 2012; Caverzan et al., 2014). More interestingly, these molecules are also important to human health (Hunter and Burritt, 2012; Erba et al., 2013; Ribas-Agustí et al., 2013) and therefore they indirectly attribute an *extra value* (compared to non-stressed plants) to basic nutritional properties of fruit and vegetable (Lairon et al., 2010). Several *in vitro*, pre-clinical and clinical investigations have revealed an inverse relationship between high consumption of vegetables and the lower incidence of chronic diseases such as cancer, ischemic stroke and cardiovascular diseases (Garcia-Alonso et al., 2004; Slavin and Lloyd, 2012). In particular, polyamines are involved in cell growth and proliferation and may have an important role in the diet of young but also older people, since the level of polyamines decreases with aging (Hunter and Burritt, 2012). Similarly, glucosinolates and their breakdown products (isothiocyanates) have anticancer activity (Razis and Noor, 2013). Tannins, tocopherols and carotenoids are known to have protective effects against degenerative diseases (Garcia-Alonso et al., 2004; Erba et al., 2013; Ribas-Agustí et al., 2013). Based on all the above, if organically grown vegetables can be considered in some respect *constitutively stressed plants* and/or *plants which are pre-adapted to some level of stress* (Maggio et al., 2013; van Bueren et al., 2011; Seufert et al., 2012), they could also be considered as *constitutive accumulators of valuable nutritional molecules*. However, the intrinsic value of this functional link has been supported by scattered physiological and biochemical evidence and largely underestimated with respect to agronomic and commercial implications. This knowledge gap has been cause of missed opportunities. For example, local germplasm with pronounced adaptability traits to low-input environments could be re-considered in function of its ability to accumulate these molecules (Barbieri et al., 2008; van Bueren et al., 2011; Lester and Saftner, 2011) and eventually be recovered, improved and *branded* as organic product with *multiple values.* These values may include suitability to low input agriculture (environmentally friendly), ability to introduce biodiversity (environmentally functional), ability to provide highly nutritional properties and even intrinsic nutraceutical activity (beneficial for health). The purpose of this review is to shed some light on the functional and pre-determinate links between cultivation practices and environmental conditions and the physiology of organically grown plants with the overall objective of defining those agronomic and genetic determinants that may associate organic farming to a stable and predictable higher nutritional value. In this context we introduce the concept of *physiological quality* defined as the commercial (*e.g.*, sugar content, fruit firmness, % dry matter) and nutritional characteristics (*e.g.*, concentration of vitamins, antioxidants, minerals and other valuable health-related molecules) of the harvested product determined by physiological responses to a specific cultivation process/regime. The physiological quality, therefore, is not defined by genetic and environmental determinants *per se* but by the cultivation process that, in a given environment, may constitutively and consistently enhance the expression of quality components through the activation of physiological responses.

To further explore these concepts, we began to analyse how environmental stresses may affect product yield and quality. Regardless of the cultivation system, crops generally experience and adapt to various levels of stress during their growth cycle (Jenks and Hasegawa, 2008; De Pascale et al., 2012; Mickelbart et al., 2015). A number of studies suggest that lower yield and improved nutritional parameters of organic crops are associated with greater stress exposure during crop growth (van Bueren et al., 2011; Seufert et al., 2012). Low yield, however, can also be a *side effect* associated with the recovery of less productive traditional genotypes with natural resistance to various diseases and valuable organoleptic properties, which may suit organic productions (Ponisio et al., 2015). Therefore, the questions to answer are: *are organic crops constitutively pre-adapted to environmental stresses? Are they more stressed than conventional ones and, if so, what is making them more stressed? Is the specific low growth-stress-organic association conducive to a constitutive accumulation of valuables molecules?*

2. Abiotic factors

Most critical abiotic stresses for vegetable crops include drought, flooding, salinity, adverse soil pH, nutrient toxicity and/or deficiency and heavy metal contaminations, but also temperature stress and suboptimal light and/or CO_2 levels (Suzuki et al., 2014). Drought, salinity and temperature stress are expected to further increase on a global scale because of climate change (Royal Society, 2009; Parida and George, 2015). In principle, each of these stresses and their combinations affect plant growth both under conventional and organic farming systems, although with different magnitude. For example, plastic mulching (generally associated with conventional agriculture, although currently frequent in North America for field vegetable crops grown organic) may preserve more soil moisture than straw mulching (Tu et al., 2006). To avoid pest outbreak, organic farmers have to be more rigid in controlling humidity around the canopy, limiting overhead irrigation (van Bueren et al., 2011; Ponisio et al., 2015). Consequently, under organic regime, plants may experience tissue water content fluctuations and eventually short- or long-term water stress. Under organic farming no synthetic fertilizers are allowed, instead emphasis is placed on the use of dry and liquid organic fertilizers such as fish meal or powder, pelleted chicken manure, seabird and bat guano, feather, alfalfa, soybean, bone, blood, and meat meal (Gaskell and Smith, 2007; Tuomisto et al., 2012). Organic fertilizers are less concentrated nutrient sources than conventional fertilizers (Seufert et al., 2012). Moreover, some of them are characterized by low mineralisation rates leading to lower nutrients bioavailability, in particular of nitrogen in coincidence with nutrient-demanding phenological stages (Zhao et al., 2009; Lester and Saftner, 2011). For phosphorus, studies on whole farm P budgets highlighted annual P deficits in organic production systems possibly caused by over-exploitation of P reserves built up under previous conventional management (Nelson and Janke, 2007). As a result, organically grown vegetables may respond to temporarily nutrient deficiency/availability (Mondelaers et al., 2009) by activating their defence system and, enhancing the levels of antioxidants (Vallverdú-Queralt et al., 2012). Several studies on the nutritional quality of the produce have reported that organically nitrophilic vegetables (leafy, root and tuber vegetables) have approximately three times less nitrate in comparison to conventional crops possibly due to lower availability of nitrogen in organic farming systems under critical phenological stages (Worthington, 2001; Bourn and