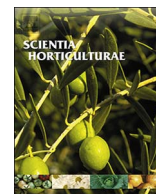




Contents lists available at ScienceDirect

Scientia Horticulturae

journal homepage: www.elsevier.com/locate/scihorti

Watermelon and melon fruit quality: The genotypic and agro-environmental factors implicated

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ARTICLE INFO

Keywords:

Aroma volatiles
Bioactive compounds
Citrullus lanatus
Climacteric
Cucumis melo
Ripening
Sugars
Texture

ABSTRACT

Watermelon [*Citrullus lanatus* (Thunb.) Matsum. & Nakai] and melon (*Cucumis melo* L.) are popular annual fruit crops of the gourd family *Cucurbitaceae*, drawing from discrete botanical backgrounds. For both these dessert fruits, quality is what mainly influences consumer behavior and formulates recurring purchasing habits and brand loyalty within reasonable cost. The current review examines the configuration of sensorial quality attributes during development and ripening, as compounded by highly coordinated growth and differentiation processes of various fruit tissues associated with differential expression of stage-specific genes, which affect flavor, aroma, color and texture. The genotypic effect on fruit quality is examined, which in the case of sweet melon is ramified into varietal groups demonstrating differential ripening physiology of climacteric or non-climacteric nature with important implications for key sensorial characteristics, especially aroma and texture. Current advances on the role of key agronomic factors influential on quality are discussed, such as grafting and rootstock-scion interaction, controlled water and thermal stress, targeted plant nutrition applications, and the genotype \times environment \times management interaction. Several cardinal issues warranting further research were identified: the ripening-dependent accumulation and metabolism of carotenoids and the link between carotenoid profiles and volatile fractions, particularly the role of apocarotenoids as substrates in the synthesis of aroma volatile molecules; the coexistence of ethylene-dependent and ethylene-independent regulation of ripening processes in melons; physiological incompatibility in melon graft combinations and its implications for fruit quality; rootstock mediation of watermelon volatile fraction; the role of osmoregulatory molecules as L-citrulline in cell expansion and turgor affecting mesocarp firmness; stage-specific carbohydrate partitioning and metabolism in developing fruit and its potential manipulation through thermal treatments; robust model building on transplanting dates, resilient to genotype \times environment interaction. Understanding the concerted effects of the genotypic, physiological and agro-environmental factors visited in the current review is instrumental in the efforts for improving quality and expanding market share for watermelon and melon fruit.

1. Introduction

Watermelon [*Citrullus lanatus* (Thunb.) Matsum. & Nakai] and melon (*Cucumis melo* L.) are major crops of the gourd family *Cucurbitaceae*, which do not interbreed and draw from distinct botanical origins (Paris et al., 2012; Paris, 2015). Watermelon has a narrower genetic base than melon (Nimmakayala et al., 2014; Sebastian et al., 2010), and it is native to the drier areas of south central Africa, near the Kalahari Desert (Namibia and Botswana), where bitter and sweet forms were found in the wild and consumed by humans and animals (Rubatzky, 2001; Wehner et al., 2001). One theory claims it was

derived from the perennial relative *Citrullus colocynthis*, found in the wild in archaeological sites; while another theory is that it was domesticated from wild forms of *Citrullus lanatus* found in central Africa. Watermelon has been cultivated in Africa for over 4000 years. Seeds and plants parts found in Egyptian tombs indicate that watermelons were widely cultivated in the Nile valley before 2000 BCE. From Africa, they were introduced to India at about 800 CE and China at 900 CE, and then extended to Southeast Asia, Japan, Europe and the Americas in the 1500's. Watermelon, is an annual plant with long angular trailing vines bearing lobed leaves, branched tendrils and separate solitary male and female flowers. The plant is typically monoecious with alternating

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<https://doi.org/10.1016/j.scienta.2018.01.032>

Received 20 June 2017; Received in revised form 12 January 2018; Accepted 15 January 2018

0304-4238/ © 2018 Published by Elsevier B.V.

staminate (male) flowers appearing first and pistillate (female) flowers later with ratios in favor of maleness (e.g. 7 staminate: 1 pistillate). Watermelon fruits are round, oval or elongated with a size typically ranging from 1.5 to 15 kg. The rind is light to dark green with stripes of various patterns. The flesh may range from white, green, yellow, orange to red, though consumers associate the internal quality with deep red, pink or intense yellow, in addition to sweetness and texture.

Melon center of origin is believed to be tropical to subtropical West Africa, with a secondary center encompassing a broad region that covers Iran, southern Russia, India and east China (Yamaguchi, 1983). According to Pitrat et al. (2000) melons are classified in seven groups, of which four are sweet melons: *cantalupensis* (cantaloupe in Europe), *reticulatus* (netted muskmelon in the U.S.), *inodorus* (casaba, honeydew, Piel de sapo, yellow canary types), and *makuwa*; and three are non-sweet or high-acid melons: *flexuosus* (snake melon), *dudaim* (pomegranate melon) and *conomon*. Melon has also long trailing vines bearing shallow-lobed, oval, or kidney-shaped leaves. The typical flowering habit of melon is andromonoecious (hermaphrodite and staminate flowers), although other forms are also present (Rudich, 1990). The fruit size and shape is highly variable among types and cultivars with the external skin color being white, green, and yellow-toned, and skin texture smooth, sutured or netted. The flesh (mesocarp) color is typically green or orange, but pink and white are also found.

Watermelon fruit is non-climacteric, its quality profile develops rather slowly during ripening, its physiological maturation terminates at harvest, and it does not develop highly conspicuous indices of harvest maturity (Kyriacou et al., 2016). Drawing on a wider genetic base, melon has a more complex configuration of quality owing to the diverse ripening patterns and associated aroma profiles of its botanical varieties. Varieties of the *reticulatus* group exhibit ripening-related abscission, whereas both the *cantalupensis* and *reticulatus* varieties are characterized by steep climacteric ripening pattern, intense aroma, melting texture, brief shelf-life and post-harvest ripening, provided they are picked physiologically mature (Pech et al., 2008; Allwood et al., 2014). Varieties of the *inodorus* group are non-aromatic, they do not abscise from the plant, they are slow-ripening and non-climacteric, but generally have a longer shelf-life than the odorous varieties.

Watermelon and melon are undoubtedly among the most popular annual culinary fruit crops worldwide, as evidenced by their cultivated acreage and production. Watermelon accounts for 4.7% of acreage and 7.8% of world vegetable production, including root crops (Food and Agriculture Organization of the United Nations, <http://faostat.fao.org>); whereas melon accounts for 1.7% and 2.2% respectively. Watermelon is the second annual fruit crop in acreage and production after tomato (Supplementary Table 1), while both watermelon and melon production are heavily concentrated in Asia, where 84.0% and 73.6% of world production is concentrated, respectively (Supplementary Table 2). Most production takes place in open field, usually protected under low tunnels until flowering initiation, covered either with polyethylene plastic for the early crop or with insect-proof net against viral vectors for the late crop. Trellised production under high tunnels is more commonly practiced for melon than watermelon.

As with most horticultural products, the concept of quality for watermelon and melon fruit is shaped by the interests of the various stakeholders implicated in the agroindustry chain, but conventionally it is defined as the complex of properties that ultimately captures the expectations of the retail customer and commands repetitive buying behavior (Kader, 2008). The perception of quality draws on intrinsic traits of horticultural commodities, dictated by genotypic, cultural and eco-physiological factors, and on extrinsic traits formulated by the socio-economic and marketing environ (Kyriacou and Rouphael, 2018). The regulatory context for fruit and vegetable quality comprises crop-specific class standards that are based on limited key visual and organoleptic criteria (Commission Implementing Regulation (EU) No543/2011). These criteria essentially define acceptability thresholds and mainly provide practical, effective and mostly non-destructive means to

facilitate standardization. They do not, however, address more complex compositional aspects relating to sensorial quality, or to the nutritional and bioactive value of food, which consumers are increasingly aware of (Kyriacou and Rouphael, 2018). Consumer studies have indeed highlighted that quality is more important to consumers than price when the latter varies within the anticipated range (Harker et al., 2003). Provided that the cost of purchase is not prohibitive, quality is what mainly influences consumer behavior and formulates recurring purchasing habits and brand loyalty.

Trends in the last decade, which dictate breeding and cultivar selection, and inadvertently influence watermelon quality, are the increasing demand for personal or mini fruit (< 3 kg) and midi (3–7 kg) watermelon cultivars and for seedless triploid cultivars (Freeman and Olson, 2007). Demand is also rising for cultivars suitable for the fresh-cut industry. Watermelons and melons command 13.4% and 7.8%, respectively, of the US fresh-cut fruit market (Cook, 2015). Moreover, the rapid expansion of vegetable grafting as a tool for addressing mostly soil-borne biotLeic but also abiotic threats to crop establishment and production has found sweeping application in watermelon and to a lesser extent in melon production (Leskovar et al., 2016; Louws et al., 2010; Rouphael et al., 2010; Savvas et al., 2010; Schwarz et al., 2010), with important implications for fruit quality (Kyriacou et al., 2017). The present review attempts to summarize and provide critical insights on current advances in watermelon and melon production that impact fresh fruit quality. It describes the constitution of sensorial and bioactive quality of these fruits and its configuration during fruit development and ripening, physiological factors modulating quality, genotypic and rootstock-mediated effects on quality, as well as the main agro-environmental factors at play.

2. Quality with respect to genotypic variability and ripening behavior

2.1. Configuration of watermelon fruit quality

2.1.1. Developmental quality

The watermelon fruit is a firm-walled pseudo-berry, or pepo, developed from an inferior ovary comprising three parietal carpels, each consisting of two locules bearing variable numbers of ovules (Simpson, 2010), which in triploid seedless cultivars remain underdeveloped and the seeds are abortive (Ramakrishna and Amritphale, 2005). Quality in watermelon is determined during development and ripening through highly coordinated processes involving differential expression of stage-specific genes during growth and differentiation of various fruit tissues, which in turn affect sweetness, flavor, aroma, color, texture, and firmness (Wechter et al., 2008; Grassi et al., 2013). Fruit development is divided into a very brief period of ovary enlargement (fruit setting) following successful fertilization, succeeded by a period of mitotic growth terminated when the ovary assumes a diameter of about 35 mm, and finally a period of cell enlargement ending when the fruit assumes full size, ranging from 30 to 40 days after fruit setting depending on cultivar earliness (Fig. 1; Fukuoka et al., 2009; Soteriou et al., 2017). While earliness is strongly a varietal characteristic, the time to commercial maturity is also influenced by the environment and cultural factors affecting crop load or sink competition by vigorous rootstocks (Sakata et al., 2007; Soteriou et al., 2014). The period from fruit setting to optimal harvest maturity varies with cultivar earliness, generally ranging from 30 to 45 days, and constitutes a reliable but cultivar-specific harvest maturity index (Soteriou et al., 2014). Other practical, non-destructive indices often used include browning and drying of tendrils nearest the fruit, loss of surface gloss, yellowing of the ground-spot and a dull instead of metallic sound produced when the fruit is thumped with the knuckles (Maynard, 2001; Sun et al., 2010; Vinson et al., 2010). The configuration of key sensorial quality characteristics commences before the cell enlargement phase is terminated but continues even after final fruit size is attained (Soteriou et al., 2014).

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