Potassium nutrition on tomato (*Solanum lycopersicon* L.) has an impact on production, postharvest behavior, and fruit sensory profile

Doctoral Dissertation

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List of Relevant Abbreviations

ANOVA	Analyses of Variances
AS	Ambient Conditions
B	Boron
BER	Blossom End Rot
Ca	Calcium
CI	Chilling Injuries
cm	Centimeter
CO_2	Carbon dioxide
DM	Dry Matter
DWD	German Weather Service
FA	Fatty Acids
Fe	Iron
FS	Applied Fertilization Solutions
IR	Daily Irrigation
K	Potassium
L	Liter
LFM	Loss of Fresh Matter
LW	Leached Water
Mg	Magnesium
Mn	Manganese
N	Nitrogen
Na	Sodium
P	Phosphorus
PA	Polyamines
PCA	Principle Components Analysis
PR	Precipitation
PUT	Putrescine
R+AS	Refrigerated + Ambient Conditions
S	Sulfate
SPD	Spermidine
SPN	Spermine
TA	Titratable Acidity
TSS	Total Soluble Solids
WC	Water Consumption
WUE_p	Agronomic Water-use Efficiency
Zn	Zinc

1. General introduction

In the last twenty years, demand for various diets and food resources is gradually increasing due to the accelerated growth of world population (Garnett et al. 2013). Recently, people have been paid more attention to their daily diet and health. Thus, the importance of an adequate amount of fruits and vegetables in the daily diet to mitigate the risks of chronic diseases has been demonstrated (Liu 2013; Slavin and Lloyd 2012). Tomato fruits are one of the most important vegetables in the daily diet in developing countries (FAOSTAT 2020), due to their high contents of vitamins, minerals, sugars, and antioxidants (Gharezi et al. 2012). Recently, the world production of tomato recorded 181 million tons in 2019, where the leading countries are China, India, USA, Turkey, and Egypt (FAOSTAT 2020). Likewise, the consumption of tomato products is gradually increasing worldwide, ranking the second place after potato, with about 56 g per capita daily (FAOSTAT 2020).

Botanical Traits and Cultivation Requirements of Tomato

Tomato (*Solanum lycopersicon* L.) is an vegetable of the *Solanaceae* family and originally cultivated in the sub-tropical regions (Paran and van der Knaap 2007). It is an annual plant and commonly grown in both open field and in controlled conditions e.g. greenhouses (van Dam et al. 2005). The plants can reach a height of over two meters and the stem ranges between erect and prostrate. There are various types of leaf shapes, which altered between the genotypes. The flowers are bisexual self-fertile, but the pollen is only released by vibration (da Silva et al. 2008).

Growth of tomato requires a relatively cool and dry climate to achieve high yield and good fruit quality. The optimum temperature ranges between 19 °C and 30 °C as below 10 °C and above 38 °C the plants are damaged (Roberts et al. 2002). Fruit set and color development require temperatures between 20 °C to 24 °C. Daylight between 12 – 18 hours is optimal for fruit set and the color development of leaves and fruits. The annual precipitation between 60 – 150 cm is optimum for tomato to achieve well growth (Nicola et al. 2009; Saadi et al. 2015). Water stress and long dry periods can cause dropping the buds and flowers off. However, heavy rain and air humidity are not favorable for tomato plants due to increasing the incidence of fungus infection (da Silva et al. 2008). The preferred soil type is well drained sandy loam soil, with a pH range of 5.5 and 6.8, minimum depth of 15 cm to 20 cm and adequate nutrient sources (van Dam et al. 2005).

Potassium and Boron Nutrition of Plants

The most demanded nutrient by tomato plants is potassium (K), and thus K concentrations in plant tissues and fruits are the highest among other nutrients (Almeida et al. 2015). Plants take up K only in its ionic form K^+ and remains in the plant as K^+ as it does not involve in the structure of biomolecules. This makes it highly mobile in the plant system (Marschner 2012). A profound function of K is to load the photosynthesis assimilates into the phloem and transport them from source to sink organs (Koch et al. 2019). In tomato, the major sink organs are the fruits and higher accumulation of the photosynthesis products leads to high yields. Moreover, K stimulates the formation of large numbers of flowers and early mature fruits (Varis and George 1985), which finally increases the fruits yield. Transport of assimilates, namely sugars, into tomato fruits results in increasing the total soluble solids (TSS) content (Tavallali et al. 2017), hence increasing the sweetness flavor as that was stated by many researches (e.g. Amjad et al. 2014; Javaria et al. 2012). The concentration of K in the cytosol contributes to the maintenance of the pH in an optimal range for enzyme activation (Marschner 2012). Ripening of tomato fruits depends mainly on enzyme functions to reach the full maturity by decreasing starch content and increasing total reducing and non-reducing sugars (Singh et al. 2000). Furthermore, a high concentration of K catalyzes the production of organic acids to balance the cation-anion ratio (Etienne et al. 2013), which increases the acidity flavor. Deficient K plants display necrotic spots on the margins of the leaves while the fruits have disorders in coloring and the shape (Figure 1). That decreases the quality of tomato fruits for two reasons: first, impairment of the photosynthesis due to a lack of leaf chlorophyll (Ozores-Hampton et al. 2012) and second, the color formation of the fruits is not uniform (Zhang et al. 2015). Another essential role of K is adjusting stomatal conductance which is important to minimize water loss by evapotranspiration in tomato, hence it has the potential to a better water use (Kanai et al. 2011). Moreover, K has been reported to have a significant role in mitigating the effects of biotic and abiotic stresses such as cold and drought stress (Cakmak 2005; Wang et al. 2013).

Figure 1. Leaves and fruits of Primavera. A and C leaf and fruits of sufficient K supply. B and D leaf and fruits of deficient K supply (Photos: Daoud, 26.07. 2016).

Among micronutrients, born (B) is an essential nutrient for the plants, because it has significant functions in cell wall synthesis, carbohydrate metabolism, sugar transport and phenol metabolism (Broadley et al. 2012). Moreover, it is involved in sugar transport by producing sugar-borate complex, hence enhances the sugar content with high B dose (Woods 1994). B has also an enhanced effect on the yield, K uptake and shelf life of tomato fruits (Davis et al. 2003). Nonetheless, under B deficiency, the permeability of membranes increased which led to higher loss of phenolics, amino acids and sucrose (Cakmak et al. 1995).

However, growers try to fertilize beyond the needs of the plant to avoid the risk of yield reduction due to under-fertilization (Hartz et al. 2005). Therefore, better knowledge of the optimal nutrition requirements can reduce the excessive application of these nutrients, which results in saving costs and resources. Many studies reported no further increment on total yield with excessive K supply (e.g. Liu et al. 2011; Ozores-Hampton et al. 2012).

Marketable Yield and External Quality Attributes

Tomato is a multipurpose vegetable and can be consumed as fresh, cooked, and processed into various products e.g. ketchup and juice (Gharezi et al. 2012). With these versatile potentials, the production of tomato alters according to the final purpose of consumption. Regarding the fresh consumption, the production should consider external characteristics such as color and firmness, as well as odor intensity and ultimately favorable flavor (Oltman et al. 2014). The previous breeding programs of tomato production have focused on increasing yield and diseases resistance as the main goals (Bai and Lindhout 2007). Several studies focused on increasing tomato yield either by breeding (Gur and Zamir 2004), or by specific cultivation managements (Hogendoorn et al. 2006; Krieger et al. 2010) as well as by optimizing plant nutrition (Heeb et al. 2006; Mazed et al. 2015). However, these goals have been changed in the last decades in order to meet the consumer’s demands for a better taste and aroma of fresh tomato fruits (Bai and Lindhout 2007). In this context, the term “marketable yield” was introduced in tomato production and it refer to the fruits that have a better visual appearance from the consumer’s point of view (Kleinhenz et al. 2003). The European Commission regulated specific standards for the marketing of ten products including tomatoes, whereby the fruits must meet these standards to be classified as marketable fruits (EU 2018). The standards considered the consumers’ preferences of tomato fruits such as the color, freshness, and shape.

With respect to the fruits’ color, several studies attempted to improve the skin color intensity of tomatoes (e.g. Chapagain and Wiesman 2004; Kabelka et al. 2004). The color of tomato fruit surface is the first external quality attribute evaluated by consumers (Pathare et al. 2013). The color of full ripe fruits varies greatly depending on the genotype. While the most common color of tomato fruits is red, other genotyps show green, yellow, and even black color (Klein et al. 2005). Red color of ripening tomato is largely due to the presence of lycopene and the degradation of the chlorophyll from the fruit tissues (Tadesse et al. 2015). In non-red tomato genotypes, other pigments such as ß-carotene and lutein (Hart and Scott 1995) and flavonoids (Ballester et al. 2010) are involved in color formation.

Generally, the formation of the fruits' color during the ripening stages is highly influenced by several factors e.g. temperature, sunlight, biotic and abiotic stress, and soil nutrients availability (Kays 1999).

During the ripening of tomato fruits, the changes in surface color are associated with degradation of the fruits' texture and as a result the fruits become more mellowed (Kader et al. 1978). The softening in the fruits texture is related to cell wall modifications (Sozzi et al. 1998). The fruits firmness is often used to estimate organoleptic quality and it is strongly associated with fruit ripening after maturity and during storage (Lesage and Destain 1996).

Nutritional Composition of the Fruits

Fruit flavor can have an important nutritional effects, as a most preferred flavor stimulates a higher intake (Mathieu et al. 2009). Tomato fruits contain important nutrients such as antioxidants and minerals and beside sugars, acids, and volatile compounds are the main contributors to tomato flavor (Beckles 2012). Total soluble solids (TSS) indicate the quantity of dissolved solids in a solution (Beckles 2012; Thakur et al. 1996). Many studies documented a high correlation of TSS value with tomato sugars content (e.g. Kader 2008; Malundo et al. 1995). The TSS in tomato fruits consists of 65% sugars (sucrose and hexoses), 13 % acids (citrate and malate) and other minor compounds e.g. minerals, phenols, amino acids (Balibrea et al. 2006; Kader 2008). The values of TSS differ according to fruits size: large beefsteak tomatoes (3 % to 5 %) contain less TSS than cocktail tomatoes (9 % to 15 %) (Gautier et al. 2010; Luengwilai et al. 2010). Fruit TSS content is also influenced by the pre-harvest environment such as temperature, water availability, soil mineral content, and sunlight radiation (Dorais et al. 2008). Similarly, postharvest practices have a high impact on TSS content e.g. storage conditions, timing of harvest, and handling techniques (Kader 1986).

The content of titratable acids (TA) defines the acidity taste and include malic and citric acids as main acids in tomatoes (Beckles 2012). Content of TA is important for the taste of tomato as the consumers desire fruits that have sweet and sour taste, juicy, flavorful, and typical tomato odor (Oltman et al. 2014; Piombino et al. 2013). It has been stated, that a minimum TSS of 5% with a minimum TA of 0.4%

is the preferable ratio to produce a good tasting tomato (Kader 1986; Kader et al. 1977). The TA proportion varies with the fruit ripening stage, which is higher in unripe fruits than in full ripe ones. Moreover, TA content is highly influenced by the growth conditions e.g. temperature, sunlight, and soil mineral composition (Bertin et al. 2001). Tomato fruits are rich of minerals: 100 g of fresh edible portion contains around 0.5 mg of Fe, 244 mg of K, and 13 mg of Ca (Erba et al. 2013; Nonnecke 1989). Accordingly, including tomato in the daily diet can support the recommended daily intake of minerals.

The tomato flavor is a complex combination of non-volatile and volatile compounds. Beyond the adequate TSS and TA, a fruit should also contain a sufficient amount of volatile components (Mathieu et al. 2009). Over 400 volatile compounds have been detected in tomato, however, only about 15 – 20 were found to have an impact on human perception (Baldwin et al. 2008). Most of the volatile compounds are derived from some essential compounds; such as amino acids, carotenoids, fatty acids, and others in tomato (Klee 2010), which could act as sensory cues for nutritional and health value (Goff and Klee 2006). The majority of commercial produced tomatoes have generally green, earthy, and musty aroma, while the typical, as good defined aroma is characterized as fruity and floral (Baldwin et al. 2008). Since the volatile compounds derived from some secondary compounds, the changes in these components due to environmental conditions could possibly influence the volatile composition in tomato fruit (Rambla et al. 2014).

Postharvest Handling and Storage

Postharvest handling and storage of tomato has a remarkable effect on quality of tomato. Generally, most of the qualitative losses in tomato fruits happen between harvest and consumption stages (Kader 2005). Postharvest practices goals are to maintain the quality and diminish losses of tomato fruits between production and consumption (Kader 2003). Presently, tomato is produced in different regions over the world where suitable growth conditions or developed cultivation systems such as hydroponic cultures exist. Therefore, transporting tomatoes from the production to non-production locations is necessary to balance the distribution of tomato products (Valenciano and Mesa 2004). Tomato is a perishable vegetable due to its relatively high moisture content (90 – 95%), which results in a short shelf life of the fruits (Arah et al. 2016). Storage temperature has a major influence on tomato shelf life. In short-term storage (up to a week), ripe fruits can be stored in ambient conditions with suitable ventilation, while in long-term storage the ripe fruits can be stored at temperatures of about 10 – 15 °C (Žnidarčič and Požrl 2006). Nevertheless, tomatoes are sensitive to low temperature (below 10°C) storage, whereby the fruits can rapidly develop chilling injury (CI) symptoms (Raison and Lyons 1986). Household refrigerated storage is a very common practice to store tomato fruits by consumers, however, CI symptoms occur alongside with decrease in fruits quality under typical refrigerator temperature (4 to 8 °C) (de León-Sánchez et al. 2009). Overall, tomato fruit quality in the postharvest period cannot be enhanced but only be maintained (Tigist et al. 2013). In this context, some techniques can be applied to reduce the incidence of CI in stored tomato fruits and diminish the loss of fruit quality; such as optimized plant nutrition in pre-harvest cultivation (Cantliffe 1993). For instance, an application of K fertilization can enhances the performance of tomato fruits during the postharvest period (Tavallali et al. 2017).

Sensory Evaluation of Tomato Fruits

Consumers prefer tomatoes that are red, firm, and medium to small in size, they should be as well flavorful, juicy, sweet, and of sour taste (Oltman et al. 2014; Piombino et al. 2013). They complain about the tomato flavor, which has among others rapidly increased the number of research with the objective to enhance tomato flavor (Causse et al. 2002). Consequently, the sensory evaluation became more important to characterize fresh consumed fruits and vegetables (Meiselman 2013). In fresh tomato consumption, a set of external, like color and firmness and internal like taste and aroma determine fruits' quality (Causse et al. 2002). In this context, sensory evaluation is an suitable method to describe all of these different attributes and to identify consumer favorites (Heeb et al., 2006). Recently, the most common methods in estimating tomato flavor include both sensory evaluation by a trained panel and instrumental analyses (Kanski et al., 2020a).

Objectives of the Thesis

Since the focus on improving tomato quality started, many studies were performed to contribute to this goal. One possibility is to optimize the plant nutrition and to test the effect of different nutrients on tomato quality (Roosta and Hamidpour 2011). Potassium was one of the most studied nutrients beside N and P in relation to tomato quality. A positive effect of K on tomato fruits quality has been demonstrated by many studies (e.g. Amjad et al. 2014; Besford and Maw 1975; Chapagain and Wiesman 2004; Lester et al. 2010). Based on the present knowledge, three novel aspects regarding the effect of K nutrition on tomato were studied as follows:

1- The impact of K on yield, agronomic water-use efficiency (WUE) and fruit quality was evaluated with different K supply from deficient to excessive. The effect of excessive K on WUE and fruits quality in tomato has been so far not studied. Hence, the following objectives of this study were:
   1a). Evaluate WUE, yield, and fruits quality attributes under different levels of K fertilization.
   1b). Examine the effect of excessive K on the mineral composition in the fruits and understand the relationship between WUE and fruit quality under K fertilization.

2- Several techniques have been applied to maintain tomato fruits quality in postharvest stage. One of these techniques is optimized plant nutrition in pre-harvest stage. Therefore, an application of various K and B fertilization on tomato was done, and the fruits behavior afterward in postharvest stage was evaluated to illustrate the following objectives:
   2a). Evaluate the effect of K and B fertilization on the quality of fruits stored in ambient storage (20 °C) and refrigerated + ambient storage (4 + 20 °C).
   2b). Understand the role of K and B fertilization enhancing the cold tolerance of stored fruits in refrigerated conditions + ambient storage.

3- The influence of K supply on sensory attributes of tomato fruits was evaluated. Moreover, the relationship between sensory traits and instrumental determined data under K fertilization is still not well studied, thus the central objectives of this work are:

3a). Investigate the effect of K on sensory characters and instrumental determined traits.

3b). Explore the correlation between instrumental determined traits and sensory evaluation of tomato fruits under K fertilization.

2. Different potassium fertilization levels influence water-use efficiency, yield, and fruit quality attributes of cocktail tomato—A comparative study of deficient-to-excessive supply

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Abstract

Tomato is the foremost vegetable in the world in terms of production and consumption and has considerable nutritional benefits in addition to its economic importance. High yield, water-use-efficiency (WUE), and desirable fruit quality are strongly influenced by potassium (K). So far, the effect of excessive supply of K on those parameters has not been studied in cocktail cultivars. Thus, and for a comprehensive view, we evaluated the effect of six different K fertilization regimes; from deficient K1, moderate K2, optimal K3 and K4, to excessive K5 and K6 on two cocktail tomato cultivars. With increasing K supply, the fruit's content of K, Magnesium (Mg), and Iron (Fe) increased while that of Calcium (Ca), Sodium (Na), and Zink (Zn) decreased. WUE, marketable yield, and total soluble solids (TSS) increased until K4, color and dry matter (DM) until K3, while Titratable acid (TA) reached its highest value at K5 in cultivar (cv.) Primavera. In cv. Yellow Submarine, marketable yield, color, TSS, and TA were the highest at K4, while WUE and DM increased following the highest K supply at K6. Optimal K application—3.66 – 4.00 g plant^{-1}—enhanced WUE, marketable yield, and fruit quality attributes such as color attributes a* and b*, TSS, TA, DM of cocktail tomatoes, whereas excessive K fertilization increased the surplus of K and the studied attributes remained unaffected. The results of this study, therefore, indicate that K fertilization should be implemented at the lowest possible efficient concentrations.

Keywords: *Solanum lycopersicom L*; potassium; water-use efficiency; yield; quality traits; minerals

Introduction

Being one of the most consumed vegetables worldwide, tomatoes have been recommended alongside other foodstuffs as a balanced healthy diet (FAOSTAT, 2018). What makes it favored is not only its versatility as being consumed fresh or processed (Adegbola et al., 2019), but also its richness of beneficial phytochemicals such as phenols (Dumas et al., 2003). To oppose the negative effects of biotic and abiotic stresses, the plants endeavor to increase the antioxidants production e.g. carotenoids and phenols (Akula & Ravishankar, 2011), in which K involves actively in catalyzing production-related stresses such as drought (M. Wang et al., 2013). In order to supply the world's growing population with tomatoes stable and rising yields of the fruits are required. This in turn needs an adaptive supply system for nutrients and water. The availability of fresh water is decreasing in the world alongside recent detrimental climate changes and global warming (FAOSTAT, 2018). This makes it crucial to practice comprehensive water management, especially in the agricultural sector. Improving the WUE of crop plants is a necessary approach to tackling the present challenges of climate changes (Pinstrup-Andersen et al., 1999). Several studies have investigated the WUE of crop plants (e.g. Juarez-Maldonado et al., 2014; Medrano et al., 2015). A high WUE can be achieved by adopting management practices such as optimized plant nutrition (Blum, 2009). In this context, previous studies have demonstrated that K has a positive effect on WUE enhancement in crop plants (e.g. Jákli et al., 2018; Kanai et al., 2011). Due to its essential role in adjusting stomatal conductance, K can minimize water loss by transpiration. Increasing concentration of K in guard cells leads to increased turgor thereby opening the stomata, but with the exclusion of K from guard cells stomatal closure occurs (Jákli et al., 2018). Additionally, the flow of K into the guard cells in dark reactions opens the stomata; this stimulates the uptake of CO_2 into the leaf resulting in higher carbon assimilation, hence higher yield (Engels et al., 2012). As a complex attribute, yield is influenced, among others, by environment conditions, cultivation system, and nutritional fertilization. One of the essential functions of K is loading the assimilates into the phloem and transporting them from source to sink organs, as has been confirmed in potato plants by Koch et al. (2019). In this regard, K has a remarkable effect on the yield as was stated on wheat (Maurya et al., 2014), strawberry (Ebrahimi et al., 2012), and cocktail tomato (Amjad et al., 2014). In this matter, growers instinctively use fertilizers in surplus of plant demands rather than bear the risk of low yield owing to under-fertilization (Hartz et al., 2005). However, it was pointed out that excessive K supply led to a decrease in the yield hence to low economic returns due to increased input costs (Römheld & Kirkby, 2010).

The current study is a continuation of a project initiated by Sonntag et al. (2019). They studied the effect of K on cocktail tomato yield and fruit quality traits, and they found a positive amelioration in the yield formation with increasing K until optimal supply. Also, a positive effect of increasing K supply on fruit color (Hartz et al., 2005) and fruit content of TSS, TA, and DM (Sonntag et al., 2019; Tavallali et al., 2017) was found.

Here, two questions could be raised: 1) Is there an effect of K application on WUE in cocktail tomato cultivars? 2) Will a further supply above optimal K increase the fruit yield and influence the fruit's quality?

Taking a more holistic view, knowledge of the effect of excessive K on WUE and the attributes of fruit quality in tomato is limited and needs further investigation. No studies with emphasis on the excessive supply of K on WUE and fruit quality in tomato have been published to date. Very few studies, however, demonstrated the effect of only excessive K on tomato yield (e.g. Hartz et al., 2005; Liu et al., 2011). Thus, we performed an outdoor-pot trial with two cocktail tomato cultivars—Primavera and Yellow Submarine—under different levels of K fertilization, ranging from deficiency to excessive, to evaluate the WUE, yield, and fruit quality traits. Since the minerals are known to have either antagonistic or synergistic effects on each other (Hawkesford et al., 2012; Koch et al., 2019), we also examined the effect of different K levels on the mineral accumulation in tomato fruit.

Material and Method

Experimental Setup

In 2017, an outdoor experiment was carried out with two cocktail tomato cultivars (Figure A1), Primavera and Yellow Submarine (Kiepenkerl, Everswinkel, Germany). These cultivars showed a good response to K fertilization as previously found (Sonntag et al., 2019).

The seeds were sown on 5 April into seedling starter trays with capacities of 0.1 L. After three weeks, they were transplanted to nursery pots each with a diameter of 11 cm and a capacity of 1 L in the greenhouse. Greenhouse conditions comprised 16 hours of daylight with a mean temperature of 22˚C during the day and 18˚C at night. The soil in the starter trays and nursery pots was a pure peat ("A 400", Stender, Schermbeck, Germany). The final transplantation to an outdoor location took place seven weeks after sowing, on 30 May. The seedlings were planted into Mitscherlich vessels each with a diameter of 20 cm and a capacity of 6.2 L filled with peat as soil (Gartentorf, Naturana, Vechta, Germany). The peat was treated in advance with lime ($CaCO_3$) to adjust the pH between 5 and 5.5 and mixed with phosphorus ($Ca(H_2PO_4)_2$) in a solid form. The plants were pruned weekly to maintain one major stem and arranged in a randomized block design with six replicates per cultivar and K level. The weekly harvest took place from 13 July to 25 September.

Application of Fertilization

Based on the fertilization setup in the previous project (Sonntag et al., 2019), six levels of K in the form of liquid K_2SO_4, were applied weekly during the growing season. The K treatments consisted of the following—low K1: 0.5 g plant^{-1}; moderate K2: 2.0 g plant^{-1}; optimal K3: 3.66 g plant^{-1} and K4: 4.0 g plant^{-1}; excessive K5: 4.5 g plant^{-1} and K6: 5 g plant^{-1}. Nitrogen (N) was applied weekly alongside K and the other macro- and micronutrients were applied at the final transplantation, and two more times during the season (Table A1).

Fruit Minerals

Fruits were analyzed for their minerals content according to the method of Koch et al. (2019). An amount of 100 mg fine powder of lyophilized fruits was put in Teflon tubes and then digested in the microwave (Ethos terminal 660, Milestone, Sorisole, Italy) for minerals estimation.

Agronomic Water-Use Efficiency

Agronomic WUE was calculated at the aboveground biomass level (Jákli et al., 2018). To estimate WUE, aboveground plant compartments, biomass (stems + leaves) and fruit yield as well as water consumption (WC) were summed up for each plant. The WC of each plant was calculated as follows:

$$\text{WC (per L)} = (\text{IR} + \text{FS} + \text{PR}) - \text{LW}$$

Then the following equation, according to Jákli et al. (2018), was applied:

$$\text{WUE [g FM L}^{-1}\text{]} = \frac{Biomass + fruit\ yield}{WC}$$

FM: fresh matter, IR: daily irrigation; FS: applied fertilization solutions; PR: precipitation during the growing season; LW: leached water.

Irrigation was carried out daily with the same amount of distilled water for all the plants. The application of fertilization was calculated at the end of the season and applied weekly in a liquid form. Precipitation was estimated by distributing 15 rain gauges (1 L per m^2; Lux GmbH, Wermelskirchen, Germany) between and beneath the plants (Figure S2). Through this distribution, differences in precipitation in areas beneath plant cover and in exposed areas could be evaluated. This data was also compared with data from the German Weather Service (DWD – *Deutscher Wetterdienst*). Apparently, the precipitation data showed no significant differences between places, beneath plant cover and in exposed areas; or between DWD data and our data (Table A2). The plants were placed on transport wagons for Mitscherlich vessels. The plates beneath collected the leached water from the plants for weekly estimations.

In order to reduce evaporation from the soil to the lowest level, the soil was covered with a layer of equal amounts of quartz sand. It was assumed that the evaporation was alike for all plants; therefore, evaporation from the soil could be neglected and was excluded from the calculation of WC.

Estimation of Yield

Fruits were weighted for each plant on a weekly basis, starting from the first harvest date (July 13) until the end of growing season (September 25), to estimate the yield. The fruits were sorted into two types—marketable yield and unmarketable yield (Figure A3). According to the EU Law, (2011) of marketing standards for fresh tomatoes, the fruits must be intact, clean, free of any visible matter, fresh, and free from damage or any abnormal external existence. Based on these standards, the fruits were immediately categorized into marketable and unmarketable groups during the harvest (Figure A3).

Attributes of Fruit Quality

Color, DM, TSS, TA, and total phenols were estimated at the fully ripe stage of fruits (Table A3). Fruit color was determined by Chroma Meter (CR-400, Konica Minolta Optics, Japan). The two equatorial sides of each fruit were measured, and the readings reported in the L*, a*, b* system. Subsequently the fruits were mixed for two minutes in a food blender (MQ 5000 Soup, Braun, Neu-Isenburg, Germany) to achieve a homogenized puree. Thereafter, DM, TSS, and TA were determined according to Sonntag et al. (2019).

Total phenols were extracted from 0.25 g of freeze-dried sample (EPSILON 2–40, Christ, Epsilon 2–40, Osterode, Germany) by adding 5 ml of 80 % ethanol in a falcon tube, according to the method of Keutgen and Pawelzik (2007).

Statistical Analysis

Statistical analyses were performed using SPSS software, version 22 (IBM Corporation, New York, United States). Data were normally distributed, according to Shapiro-Wilk test ($p<0.05$), and the variance was homogenized according to the Welch test. Differences between K treatments were determined by performing one-way ANOVA at $p<0.05$, followed by Tukey's post-hoc test for each parameter within the cultivar. The correlation analyses were performed using the Pearson model in SPSS.

Results

Fruit Mineral Contents

The highest application of K resulted in the highest content of K which significantly varied from K deficient plants at K1 as they recorded the lowest K content (Table 1). However, rising application of K above K2 did not result in any significant increase in the K content of the fruits.

Being independent of K treatment, the content of Mg did not significantly alter in Primavera fruits, whereas in Yellow Submarine fruit it showed a significant increase with rising levels of K from low to moderate (K1: 7.25 mg 100 g^{-1} DM to K2: 8.81 mg 100 g^{-1} DM). Though, the rising supply of K above K2 in the case of Yellow Submarine did not show any significant increase in the Mg content. Low K treatment resulted in the maximum content of Ca in Primavera (K1:6.19 mg 100 g^{-1} DM) and Yellow Submarine (K1: 5.15 mg 100 g^{-1} DM). The Ca content decreased with increasing supply of K (Table 1). The reduction was significant with increasing K supply in Primavera but not in Yellow Submarine. Fruits with K1 treatment had the highest Na content in Yellow Submarine (2.01 mg 100 g^{-1} DM); in Primavera, it was 2.56 mg 100 g^{-1} DM. Generally, increasing K fertilization significantly reduced Na content in the fruits of both cultivars.

Of all other analyzed minerals, only Fe content increased with the rising levels of K supply in both cultivars (Table 1). The maximum content of Fe was recorded at K4 (6.24 µg 100 g^{-1} DM) in Yellow Submarine—a significant increase from the lowest content of 4.50 µg 100 g^{-1} DM at K1. On the other hand, the Zn content showed a reduction with rising K fertilization (Table 1). It decreased significantly in Yellow Submarine but not in Primavera

Table 1. Fruit mineral composition at different K fertilization levels. Values are means (n = 6) and the significance level 5 % was adopted for identifying significant K treatment effects according to Tukey's test. Lower case letters determine significant differences in Primavera. Capital letters identify significant differences in Yellow Submarine. Linear correlation with Pearson test between K and the other minerals. The asterisks ** refer to the correlation significance at 0.01 level.

		Macronutrients (mg 100 g^{-1} DM)					**Micronutrients (µg 100 g^{-1} DM)**				Na **(mg 100 g^{-1} DM)**
		K	Mg	Ca	P	S	Fe	B	Mn	Zn	
Primavera	K1	154.10^{b}	7.08^{a}	6.19^{a}	27.00^{a}	14.86^{a}	3.22^{a}	0.93^{a}	1.52^{a}	2.31^{a}	2.56^{a}
	K2	201.02^{a}	8.43^{a}	4.78^{ab}	28.58^{a}	15.26^{a}	4.58^{a}	1.02^{a}	1.48^{a}	1.90^{a}	0.83^{b}
	K3	208.72^{a}	7.69^{a}	4.79^{ab}	24.01^{a}	13.82^{a}	3.97^{a}	0.79^{a}	1.43^{a}	2.10^{a}	1.58^{ab}
	K4	219.28^{a}	7.45^{a}	4.55^{ab}	$24\text{-}39^{a}$	14.47^{a}	4.89^{a}	0.82^{a}	1.34^{a}	2.22^{a}	0.78^{b}
	K5	233.33^{a}	8.30^{a}	3.36^{b}	29.5^{a}	15.69^{a}	5.13^{a}	0.87^{a}	1.13^{a}	2.16^{a}	0.79^{b}
	K6	247.28^{a}	9.01^{a}	4.39^{b}	28.33^{a}	14.89^{a}	5.71^{a}	1.05^{a}	1.32^{a}	1.99^{a}	0.72^{b}
Yellow Submarine	K1	144.73^{B}	7.25^{B}	5.15^{A}	34.42^{A}	14.56^{A}	4.50^{B}	0.95^{A}	1.27^{A}	2.12^{A}	2.01^{A}
	K2	213.63^{A}	8.81^{A}	3.82^{A}	33.14^{A}	17.12^{A}	4.85^{AB}	0.94^{A}	1.18^{A}	2.21^{AB}	0.78^{B}
	K3	234.06^{A}	9.75^{A}	4.67^{A}	30.80^{A}	15.24^{A}	5.56^{A}	0.99^{A}	1.36^{A}	1.95^{B}	0.62^{B}
	K4	256.76^{A}	9.91^{A}	4.86^{A}	31.99^{A}	15.36^{A}	6.02^{A}	1.06^{A}	1.32^{A}	1.84^{B}	0.61^{B}
	K5	262.03^{A}	8.98^{A}	4.39^{A}	29.90^{A}	15.43^{A}	5.44^{A}	0.97^{A}	1.37^{A}	1.92^{B}	0.85^{B}
	K6	265.86^{A}	9.57^{A}	4.45^{A}	31.01^{A}	14.99^{A}	6.24^{A}	0.95^{A}	1.19^{A}	1.87^{B}	0.86^{B}
Linear correlation (***r***)			0.964**	0.597**	0.840**	0.871**	0.938**	0.887**	0.768**	0.776**	0.050

Agronomic Water-Use Efficiency

Agronomic WUE ameliorated with increased K supply. While, K-deficient plants recorded the lowest WUE; it was 39.38 and 21.11 g FM L^{-1} in Primavera and Yellow Submarine, respectively (Figure 2). WUE improved significantly by 52% with increasing K supply in Primavera; the highest WUE at K4 being 60 g FM L^{-1} followed by K3. In Yellow Submarine, the maximum WUE of K treatments was 35.35 g FM L^{-1} at K6; it was significantly higher (67%) than at K1. The cultivar effect was notable whereby the lowest K level in Primavera had higher WUE than achieved at the highest K regime in Yellow Submarine.

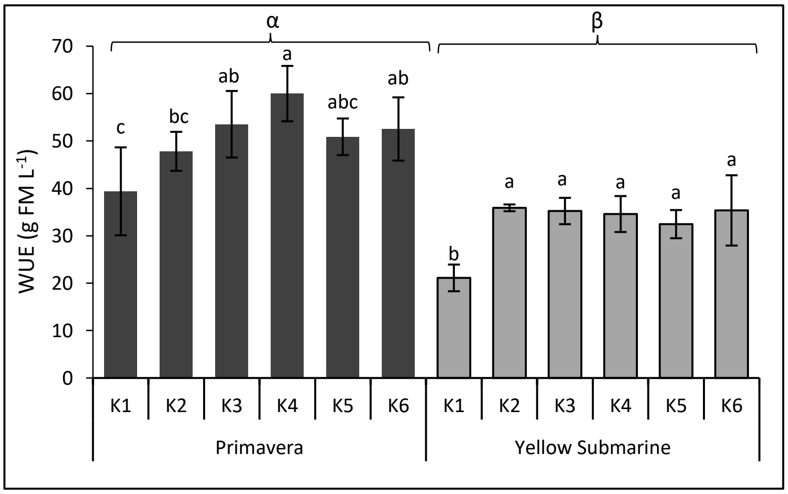

Figure 2. Agronomic water-use efficiency (WUE) influenced by different K fertilizations in the cultivars Primavera and Yellow Submarine. Values are means (n = 6) with standard deviation on each bar. The significance level 5 % was chosen for identifying significant K treatment effects according to Tukey's test. Lower case letters determine significant differences within the individual cultivar. Greek letters identify significant differences between cultivars.

Marketable and Unmarketable Yield

The highest marketable yield was recorded at K4 in both cultivars with Primavera at 1.11 kg $plant^{-1}$ and Yellow Submarine at 0.63 kg $plant^{-1}$ (Figure 3). Interestingly, the highest percentage shares of marketable yield in total yield were 73% at K1 in Primavera and 72% at K4 in Yellow Submarine. The maximum unmarketable yields scored 46% in Primavera and 34% in Yellow Submarine, both at K5. The maximum total yield was recorded at K4 in both cultivars—significantly in Primavera with 1.77 kg plant^{-1} and insignificantly in Yellow Submarine with 0.87 kg plant^{-1} (Figure 3).

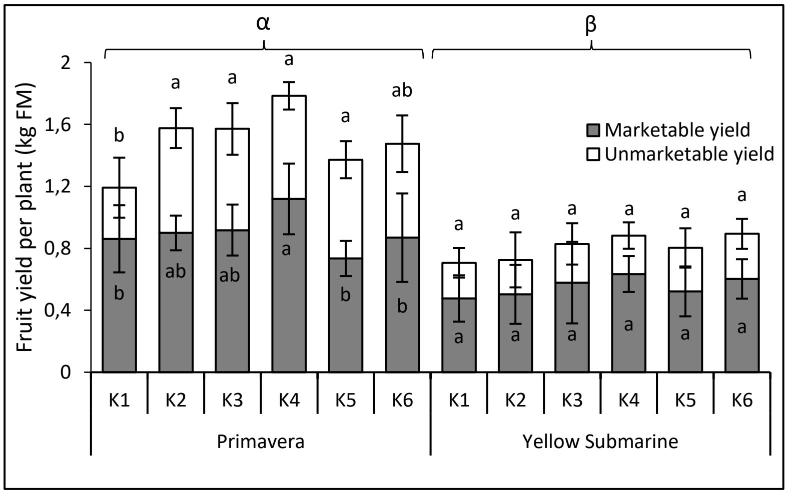

Figure 3. Marketable and unmarketable yield under different K fertilizations in the cultivars Primavera and Yellow Submarine. Values are means (n = 6) with standard deviation on each bar. The significance level 5 % was selected for identifying significant K treatment effects according to Tukey's test. Lower case letters determine significant differences within the individual cultivar. Greek letters identify significant differences between cultivars.

Fruit Quality Attributes

The maximum red color value of a* in Primavera was at K3 and it was 41% significantly higher than the lowest value of level K1 (Figure 4A). With regard to the Yellow Submarine fruit color, the highest yellow color value of b* was at K4 with a significant 23.5 % increase from the lowest of K1 (Figure 4B). Actually, K fertilization concentrations rising to excessive amounts did not result in any significant development of the color values in both cultivars.

The application of K increased the °Brix values significantly in Yellow Submarine but not in Primavera (Figure 5A). The fruits of Yellow Submarine had a significantly higher TSS content in relation to Primavera fruits. The lowest TSS value in Yellow Submarine at K1 (7.7 °Brix) was almost equal to the highest TSS value in Primavera at K6 (7.8 °Brix).

Similar to TSS, the DM content of Yellow Submarine increased with rising K application only from K1 to K2 significantly (Figure 5B), while the TA content in fruits displayed differences between K fertilization levels in both cultivars (Figure 5C). The increase in TA occurred with rising K levels and ranged from 0.35% to 0.69% with about 97% amelioration. TA increased significantly up to K3 in Primavera and up to K2 in Yellow Submarine. Further application of K did not significantly influence TA content. The fruits of Primavera had significantly less DM and TA content than Yellow Submarine fruits did.

By contrast, total phenolic compounds decreased in the fruits of K3 and K4 levels in Yellow Submarine and Primavera alternately (Figure 5D). This observation was not significant among K treatments in Yellow Submarine though. Nonetheless, the content of total phenolics at K4 in Primavera reduced significantly compared to K1 only (Figure 5D). Excessive supply at K5 and K6 surprisingly revealed an increase in total phenolic compounds, which was matching the effect of K-deficiency at level K1.

The correlation between WUE and all the abovementioned fruit quality attributes was negative and not significant; TSS (r = - 0.178), TA (r = - 0.126), DM (r = - 0.216), color (r = - 0.212), and total phenols (r = 0.065).

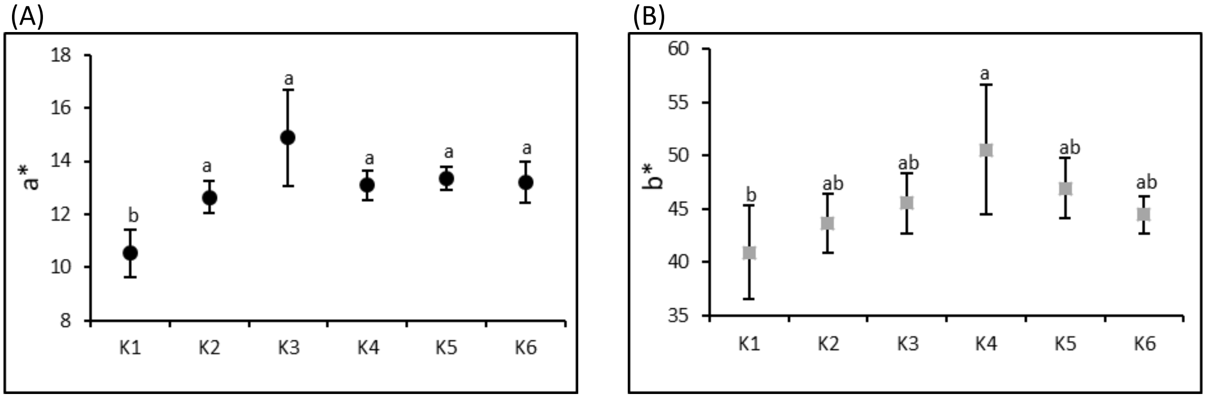

Figure 4. Fruits color values at different K levels. (A) Color index for fruits of Primavera and (B) Color index for fruits of Yellow Submarine. Values are means (n=6) with standard deviation on each marker. The significance level (5%) was determined for classifying significant effects of K treatment according to Tukey's test. Lower case letters determine significant differences within the individual cultivar.

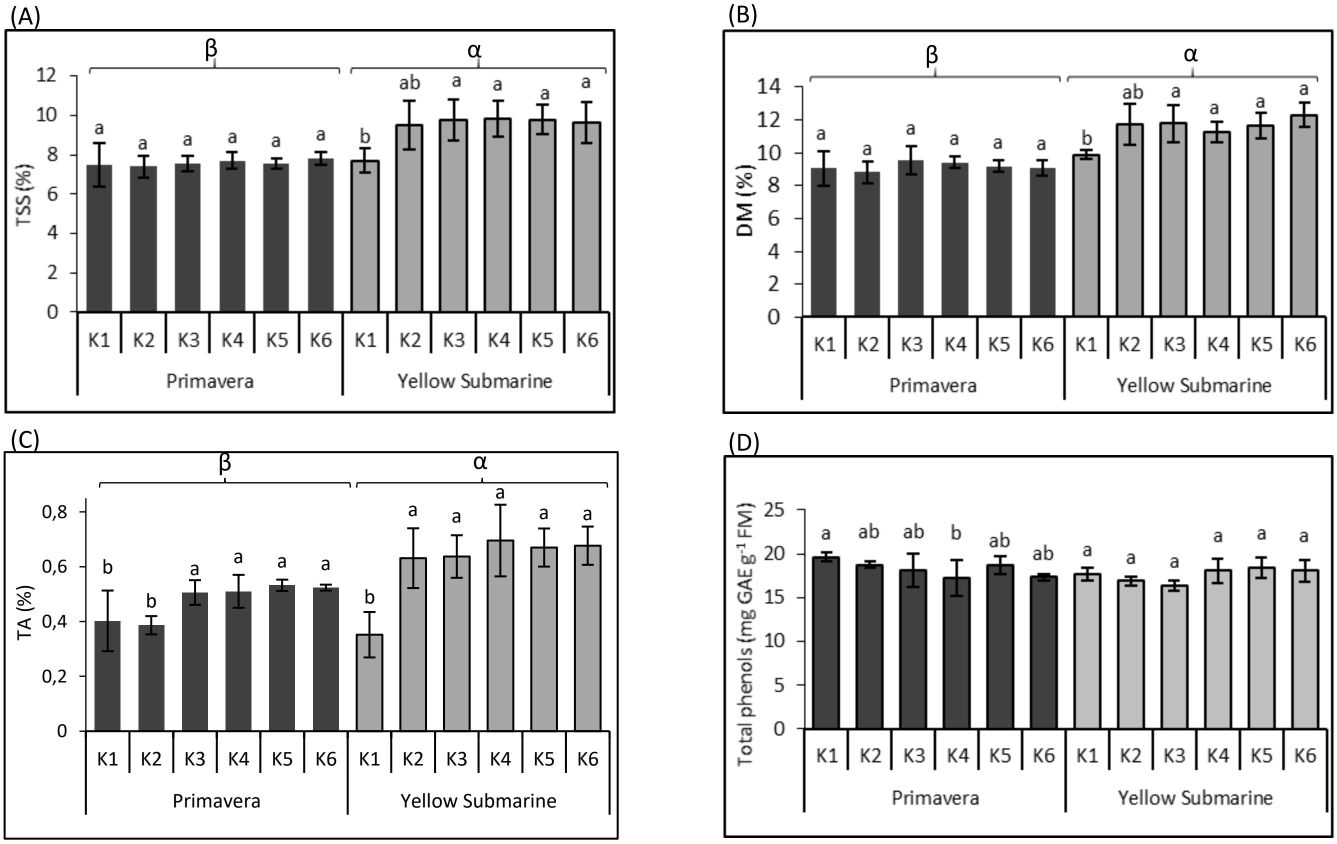

Figure 5. Fruit quality attributes. (A) TSS, (B) DM, (C) TA, and (D) Total phenols. Values are means (n=6) with standard deviation on each bar. The significance level (5%) was adopted for identifying significant effects of K treatment according to Tukey's test. Lower case letters determine significant differences within the individual cultivar. Greek letters identify significant differences between cultivars.

Discussion

Effect of K Supply on Fruit's Mineral Composition

In this study, K concentration in fruits increased with its rising supply by 44% in Primavera and 88% in Yellow Submarine. Generally, K concentrations in the cytosol are maintained at a specific range (100–200 mM) even under K deficiency but with further K fall, K contents in the cytosol decrease (Zörb et al., 2014). In this study, deficient application of K was constant throughout the growing season, hence K content in the fruits and biomass altered significantly between K1: deficient and K2: moderate. Further increase of K supply above K2 did not significantly influence K content in fruits though a positive increment was recorded. These findings are comparable to the study of Hartz et al. (2005) as they found no significant increase in K content in tomato fruits after excessive K supply. This is presumably due to the preservation of K in the cytosol (Zörb et al., 2014), which restricts the accumulation of K in the fruits at a specific range. This contradiction between increasing K supply and no significant increase in K content in fruits is supposedly due to the accumulation of K in the fruits reaching the maximum threshold at the optimal K supply, while excessive supply has no further effect. In contrast, the concentrations of K in the biomass (stem + leaves) increased significantly with rising K to the highest level in both cultivars (Figure A5).

As anticipated, the content of Na and Ca in fruits decreased with rising K supply. Higher plants have developed a selectivity strategy in the uptake of K as compared to Na and Ca (Zörb et al., 2014). K has antagonistic effects on the uptake of Ca at higher K concentrations (Fageria, 2001). In the present study this antagonism was not assumed, since the higher K contents resulted from a stronger K supply. However, the uptake of Ca and Na was not varied (Table A1). Rising K supply increased Mg content significantly in fruits of Yellow Submarine but not in Primavera. The uptake of Mg can be highly suppressed by other cations such as K (Senbayram et al., 2016). However, a contradiction was shown in the present results as Mg content in fruits increased with rising K supply. This happened presumably due to the higher application of K compared to Mg. In this matter, the plants developed specific K-transport systems to ensure sufficient K uptake and these transporters could not be exploited by any other nutrients (Horie et al., 2011). But the Mg transporters are not specific and can be utilized also by K (Senbayram et al., 2016). Consequently, the high application of K stimulated K transporters to carry K, and the Mg transporters were used to take up mostly Mg.

Micronutrients in the fruits had varying responses to rising K supply. The Fe content in fruits increased, Zn content decreased. Availability of Fe in the soil depends on the pH value; and the availability is very low in alkaline soils (Broadley et al., 2012). Application of K_2SO_4 can influence the root zone pH-stat rapidly (Chang & Roberts, 1992). Conceivably, here the increasing application of K has changed the value of pH to acidic value, thus enhancing the uptake of Fe by the plants (Neumann & Römheld, 2012). Interestingly, this could create a new approach to human nutrition especially in case of Fe deficiency (Johansson et al., 2014), as the fertilized tomato with sufficient K could contain higher concentrations of Fe. Conversely, Zn concentrations in tomato fruits decreased with rising application of K. K impairs the uptake of Zn from fertilization solutions by the plants (Hafeez et al., 2013).

Effect of K Supply on Agronomic Water-Use Efficiency

As a major parameter indicating plant performance under stress conditions, WUE is considered to be positively influenced by K fertilization (Malvi, 2011). In this study, K fertilization enhanced WUE by 52% in Primavera and by 67% in Yellow Submarine compared to K-deficient supply, namely K1. K plays a major role in osmoregulation by adjusting stomata movements that results in the reduction of evaporation (Grzebisz et al., 2013) which, consequently, decreases plant water consumption and ameliorates the final yield (S. Kanai et al., 2007). Here, WUE increased in Primavera with K fertilization until K4 followed by a decrease due to excessive application of K. This occurs possibly due to luxury K supply which, in some cases, causes K deficiency (Hawkesford et al., 2012) leading eventually to a decrease in plant growth (Figure A5). The other essential function of K can be attributed to the maintenance of osmotic potential in the rhizosphere that considers K as the most desired nutrient to sustain the osmotic concentrations (Malvi, 2011). That means, applying excessive K into the rhizosphere can increase its osmotic concentration compared to the ones in root cells, which reduces the water uptake leading to lower WUE. Although, the K concentration in the rhizosphere was not evaluated but the determination of K concentration in the leached water exposed a linear increase in it with rising K application (data not shown). However, such an observation with regard to WUE could not be made in the case of Yellow Submarine due to the continuous increment in the biomass weight with rising K fertilization (Figure A5). In this context, it has been shown that not only K has an impact on WUE, but many other factors, such as weather conditions, cultivation systems, and crop variety, have also been taken into account to influence WUE performance, e.g. in wheat plants (Abbate et al., 2004). Our studied tomato cultivars had different morphological characteristics (Figure A1) that might account for these alterations with regard to WUE. Primavera has tomato-typical leaves while Yellow Submarine leaves look like potato leaves, which are flatter and expose a larger area to sunlight, and hence greater evaporation can be witnessed vis-á-vis the typical tomato leaves.

Effect of K Supply on Marketable and Unmarketable Yield

The marketable fruit yield increased with rising K fertilization in both cultivars. This is presumably due to the function of K in translocating and accumulating the assimilates from sources to sinks, which increases the yield as was stated in the case of potato tuber yield (Koch et al., 2019). Under deficient K levels, the accumulation of soluble carbohydrates diminishes, which leads to inferior crop product (Malvi, 2011). This was confirmed in the present study as with the increase of K up to K4 the quality of the fruits improved; and it resulted in an increase in the marketable yield. However, further increasing of K application did not achieve any increase in the marketable yield, but a decrease. In this context, it was found that an excessive application of K decreased the yield of tomatoes because it ultimately increased the unmarketable yield (K. Liu et al., 2011; Ozores-Hampton et al., 2012). Supposedly, there was a luxury uptake of K with its excessive application without any improvement in the marketable yield but an increase of unmarketable yield. As per EU Law (2011), unmarketable fruits are not intact or have abnormal external defects. With excessive application of K, rates of Ca uptake decrease as an outcome of the antagonism between K and Ca (Malvi, 2011) (Table 1). This leads to Ca deficiency in tomato plants which, in turn, leads to blossom-end-rot (BER). The BER can be defined as a local deficiency of Ca in the bottom of tomato fruits (Adams & Ho, 1993). It starts with the softening of tissues to a dark green color that gradually turns brown and eventually black (Saure, 2001), hence the fruit lose their marketing value. This observation was highly perceived in both studied cultivars under excessive K regime. On the other hand, K provokes heavy blossoms and early maturity of fruits (Varis & George, 1985); accordingly, the size of the fruit could be smaller even under the required marketable limit and, therefore, classified as unmarketable yield. Due to the higher accumulation of K in the cytosol the osmotic potential increases (Zörb et al., 2014) thus causing skin tension and consequently fruits cracking (Lichter et al., 2002). Hence, the cracking in the skin of the fruits is highly anticipated with an excessive of K fertilization (Figure A3).

Effect of K Supply on Fruit Quality Attributes

Rising K supply improved fruit color of both studied cultivars. Being a major external attribute, the color of tomato fruit is considered to be positively influenced by K fertilization as demonstrated by previous studies (e.g. Brandt et al., 2006; Taber et al., 2008). The color red values (a*) of Primavera fruits varied significantly ranging between 10 and 14 (Figure 4A). Rodriguez-Amaya (2001) stated that K might catalyze some enzymes in the synthesis of carotenoids such as phytoene synthase, which produces phytoene, the first component in the carotenoids' pathway. Therefore, K can increase the synthesis of carotenoids which contribute to the color intensity of tomato fruits (Arias et al., 2000). The yellow color results from ß-carotene and lutein synthesis alongside decreasing content of lycopene (Hart & Scott, 1995). The color data of Yellow Submarine revealed a significant increase with rising K fertilization until optimal supply—K3. These results were different from the findings of Taber et al. (2008) in which no significant effect of K on ß-carotene content was found, but it indicated a significant positive correlation between ß-carotene content and color value b* (Arias et al., 2000). In our study, increasing the application of K to excessive levels did not reveal any significant color changes in both cultivars. This was probably due to the fact that the synthesis of the carotenoids reached the maximum level with optimal K supply while the additional accumulation of K in the cytosol exposed no further effect on the formation of carotenoids.

Besides the visual color evaluation of tomato fruits, consumers estimate the taste and especially the sweetness. In this research, TSS was taken as an expression of sweetness. Significant variations with K fertilization in Yellow Submarine were perceived; however, a further increase in K fertilization to an excessive level did not show any significant amelioration in TSS content. Sugars constitute about 65% of TSS in fresh tomato fruit (Adel A Kader, 2008). In their research, Kanai et al. (2007) described K as having a reinforcement role in carbon assimilation and photosynthesis translocation from leaves to fruit, which leads to higher concentrations of sugars in the cytosol. Accordingly, the enhancement of TSS with K supply can be projected to our results. Remarkably, the cultivar effect was observed for TSS content, with Yellow Submarine fruit having significantly higher TSS content than that of Primavera fruit. In this context, it has been mentioned that TSS content altered between different genotypes (Beckles, 2012).

Generally, a minimum TSS of 5 °Brix and a minimum TA of 0.4% are the desired combination for a good tasting of fresh tomato (Adel A Kader, 2008). TA content in this study ranged from 0.38% to 0.69% and increased positively with rising K fertilization. Etienne et al. (2013) proposed that higher K concentrations in the cytosol provoked the production of organic acids in order to balance the cation-anion ratio. Hence, our results can confirm these findings as TA increased with K supply. Nonetheless, additional supply of K above the optimal level did not enhance TA significantly. Once again, the cultivar effect was noted as TA content was significantly higher in Yellow Submarine than in Primavera fruit.

Dry matter (DM) content, a very important attribute of fruit quality increased with rising K supply in both cultivars. It ranged from 8.81% to 12.29%, which was higher than the findings of Molyneux et al. (2004) in six cocktail tomato cultivars (7–9%). Previous researches pointed out a significant increase in DM in salad and cocktail tomatoes with raising K application (e.g. Amjad et al., 2014; Javaria et al., 2012); consequently, we could confirm these outcomes in the current study. Nevertheless, further application of K to an excessive level did not reveal any significant changes in DM content in fruits. It was stated that

K ameliorated DM content in tomato fruit due to the increase in photosynthesis accumulation in the cytosol (Hawkesford et al., 2012). Notably, DM results match TSS results in this study, which was also proposed in a previous work (Beckles, 2012). Moreover, the cultivar effect on DM content was revealed as being similar to TSS and TA results; Yellow Submarine fruit had higher DM content than what Primavera showed.

In the previous project by Sonntag et al. (2019), an increment in TSS, DM, and TA with rising K fertilization was demonstrated, whereas the color values increased in Primavera only. We could confirm these findings for TA in both cultivars, for TSS and DM in Yellow Submarine, and for the color values in Primavera. While the color values of Yellow Submarine decreased significantly in the results of Sonntag et al. (2019), they increased in our research. Obviously, that was due to the alteration in the environment conditions, as both experiments were conducted in different years (see chapter M&M). In this context, it was pointed out that the carotenoids—hence the color of tomato fruits—TSS and DM were highly influenced by the cultivation conditions e.g. temperature, solar radiation (Beckles, 2012), and foliage surface (Brandt et al., 2006). Furthermore, the remarkable effect of the cultivar on TSS, TA, and DM response to K application was observed and in agreement with the outcomes obtained by Sonntag et al. (2019).

Total phenols are influenced by many factors and an important one is soil nutrient status (Caldwell et al., 2005). The plants typically strive to synthesize more secondary metabolites, e.g. phenols, to confer protection under abiotic stress conditions (Akula & Ravishankar, 2011). Normally, K catalyzes the production of phenols under stress conditions to assist the immune system in confronting the undesirable circumstances e.g. drought, cold, saltiness (M. Wang et al., 2013; Zörb et al., 2014). In our study, the plants were grown under the same conditions, with the exception of deficient and excessive K applications. Therefore, they did not attempt to produce more phenols under optimum K supply.

Nevertheless, total phenols production increased in both deficient and excessive K supply conditions. The reason behind this increment with excessive K could be justified by the findings of Hawkesford et al., (2012), where they pointed out that the luxury supply could behave likely as deficient conditions. When the plants were fed with excessive K, presumably, the high concentration of K in the plants (Table 1, Figure A5) provided the enzymes with an incorrect signal that led them to catalyze more phenols compounds.

Currently, there is no report on the relationship between WUE and quality of tomato fruits under K fertilization. WUE correlated negatively with fruit quality attributes though not significantly. The plant attempts to reduce water uptake as a water preservation strategy under sufficient K supply. It can be assumed that diminishing availability of water in the cells can negatively influence fruit quality as a reason of dilution effect. Notably, K has a positive effect on WUE, which can be achieved by adjusting stomatal conductance (Jákli et al., 2018). Moreover, K has a major role in translocating the assimilates (Kanai et al., 2007). In this context, it can be supposed that the plants tend to direct K rather into stomatal conductance and translocation activities in leaves and stems than into the metabolism of the fruits as sink organs.

Conclusion

This study aimed to demonstrate the effects of excessive K on WUE, yield components, fruit mineral contents and quality of tomatoes; and to clarify the relation between WUE and fruit quality attributes. The following conclusions are drawn: (i) Excessive K supply did not have a positive influence on WUE and marketable yield, whereby the enhancement of K reached a threshold at level K4. Further supply of K had no effect. (ii) Fruit color also ameliorated with the supply of K to a specific threshold (level K3 in Primavera and level K4 in Yellow Submarine), while TSS, DM, and TA showed enhancement with increasing K to the maximum level, though not significantly. (iii) In fruits, K, Mg, and Fe content increased gradually with K increasing to an excessive level, while Ca, Na, and Zn contents decreased due to the antagonism between K and these ions; and (iv) fruit quality attributes had poor and negative correlations with WUE as supposed.

In general, our findings, combined with those of Sonntag et al. (2019), demonstrate that optimal K supply (levels K3 and K4) significantly increase WUE, marketable yield, and fruit color. While excessive K supply does not predict a significant amelioration, it leads to a surplus of K fertilization resources with regard to the studied cultivars Primavera and Yellow Submarine. Consequently, our results show that optimal nutrient use for yield and quality formation as well as WUE is cultivar-specific. Using tomatoes as an example, the results also indicate that K supply above the optimum cannot be optimally used by the plants and should, therefore, be avoided for reasons of sustainable use of resources.

3. Effect of Potassium and Boron Fertilization on the Quality of Ripening Tomatoes (*Solanum lycopersicon* L.) at Different Storage Conditions

Abstract

Storing tomatoes either in a household fridge or during transportation is a common practice, especially in developed countries. However, this can result in deterioration of the fruit quality because the tomato is a perishable vegetable. Optimized plant nutrition in pre-harvest conditions can maintain the quality of the fruit's quality during storage. Potassium (K) is considered to have a positive influence on the quality of tomatoes during the period of postharvest handling. Boron (B) on the other hand is stated to have a positive effect on the shelf life of tomatoes.

In this study, the effects of various K and B levels on the quality of the stored fruits in two different storage conditions have been evaluated. Two levels of K—K1 and K2—combined with two levels of B—-B and +B—were applied to two cocktail tomato cultivars—Primavera and Yellow Submarine. The fruits in the breaker stage were stored either at ambient conditions (AC) or in refrigerated + ambient conditions (R+AC). At the end of the storage period, the K and B content, fruit color intensity, loss of fresh matter (LFM), chilling injuries (CI), and contents of dry matter (DM), total soluble solids (TSS), titratable acid (TA), polyamine (PA), and fatty acid (FA) were estimated. Application of K did not reveal a significant effect on the fruit color. Moreover, neither K nor B mitigated LFM, and CI incidence. The fruit contents of TSS, TA, and DM increased with rising supply of K at both storage conditions. Among the PA components, only putrescine (PUT), was significantly decreased with the increasing supply of K. More profound elucidation of the combined effect of K and B supply on tomato fruits postharvest behavior is a matter of further investigation in a cultivar-specific manner.

Keywords: tomato, potassium**,** boron, ambient storage, refrigerated storage, fruits chemical composition.

Introduction

Generally, most consumers store tomatoes in household fridges after purchase; however, this procedure might reduce the fruit quality. Several studies reported a decreasing quality in terms of soluble solids and acids of ripe tomato fruits during storage in household fridges (e.g. de León-Sánchez et al. 2009; Maul et al. 2000). Monitoring ripening and extending the shelf life of tomatoes are important aspects during the storage of the fruits under low temperatures (Constan-Aguilar et al. 2016), which is the most common method for tomatoes during transportation or storage e.g. in household fridge.

Optimized plant nutrition during plant growth could have a significant effect on the postharvest behavior of the fruits in the storage facilities (Cantliffe 1993). In this matter, potassium (K), being an essential macronutrient for the plant, is involved in many physiological and chemical processes, such as enzyme activation, photosynthesis assimilates translocation, and fruit development during the postharvest period (Constán-Aguilar et al. 2014; Hawkesford et al. 2012). Boron (B), on the other hand, is an important micronutrient for plants with significant roles in cell wall synthesis, carbohydrate metabolism, and sugar transport (Broadley et al. 2012).

As a climacteric and perishable vegetable, tomato has a short shelf life usually about 2–3 weeks due to its relatively high moisture content from 90–95% (Gharezi et al. 2012). The shelf life of stored tomatoes is affected by many factors such as the storage temperature, the maturity stage of the fruit, the cultivar background, and the fertilization supply during growth (Dorais et al. 2008). In this context, Lester et al. (2010) summarized a positive effect of K on extending the shelf life of many horticultural crops including tomatoes; Davis et al. (2003) concluded that B enhanced the shelf life of tomato fruits by reducing the occurrence of cracking point and concentric cracks.

In terms of maturity stage of fruits, it is more common to store tomato in full ripe stage. However, in other regions tomatoes are mainly harvested at breaker stage (Le Strange et al. 2000; Roberts et al. 2002). The breaker stage can be determined when a noticeable break in color, less than 10 %, of other green color is shown (Camelo et al. 2004). However, breaker fruits are more susceptible to produce chilling injuries (CI) symptoms under refrigerated conditions compared to the full ripe fruits (Gómez et al. 2009).

The storage temperature has a major influence on the shelf life of tomatoes. At short-term storage (up to a week), ripe fruits can be stored at ambient conditions with suitable ventilation; at long-term storage the ripe fruits can be stored at temperatures of about 10–15°C (Žnidarčič and Požrl 2006). Tomato fruits are susceptible to temperatures below 10°C, which is reflected in the expression of CI (Roberts et al. 2002). In household fridges, the common temperature is between 4–8°C, which is below the crucial temperature threshold of tomatoes to develop CI. In this context, a few recent studies have demonstrated the fertilization effect on diminishing CI symptoms, specifically the effect of K (e.g. Constán-Aguilar et al. 2014; Tavallali et al. 2017). This could be due to the role of K enhancing the resistance of plants against abiotic stress by mitigating the damage of the reactive oxygen species as suggested by Cakmak (2005). Wang et al. (2013)described that adequate K supply catalyzes the production of antioxidants such as polyamines (PA) under cold-stress conditions, which is important in mitigating CI occurrence (Sharma et al. 2017).

Good overall tomato flavor is stated as having high sweetness and a fruity flavor with low sourness and less green-tomato flavor (Tandon et al. 2003). However, consumers have not been satisfied with the flavor of tomatoes (Causse et al. 2010). Several studies demonstrated that K has a positive effect on the quality of tomatoes such as total soluble solids (TSS), titratable acids (TA) (Sonntag et al., 2019), and dry matter (DM) content (Tavallali et al., 2017). The combination of K and B fertilization on tomato decreased the incidence of the shoulder-check defect and increased fruit quality (Huang and Snapp 2009). However, the quality of the fruit quality at postharvest cannot be enhanced but only be maintained (Tigist et al. 2013).

Postharvest conditions influence the quality of tomatoes (e.g., color, TSS, TA, and DM) as has been reported in many studies (e.g. Beckles 2012; Kanai et al. 2007). Some studies have investigated the effect of K on the fruits under postharvest practice (e.g. Constán-Aguilar et al. 2014; Tavallali et al. 2017), as they stated a significant increase in fruits' K-content and bioactive compounds of the fruits with rising K application in cherry tomatoes. However, the role of K enhancing these attributes under refrigerated conditions is still not clear and the impact of a combined K and B fertilization on the performance of tomatoes under postharvest conditions has not yet been studied. Therefore, the objectives of this work are (i) to investigate the effect of K and B fertilization on the quality of tomatoes stored at ambient conditions (20°C) and at refrigerated + ambient conditions (4°C + 20°C) and (ii) to evaluate the effect of K and B on cold tolerance of the tomatoes stored at refrigerated + ambient conditions. We hypothesize that (1) the combination of K and B application will positively influence the quality of the fruit's, and (2) the cold tolerance of the fruits under refrigerated + ambient conditions will be increased with rising K and B fertilization levels.

Materials and Methods

Plant Material and Experimental Set-up

In summer of 2017, an outdoor pot experiment was conducted with two cocktail tomato cultivars Primavera and Yellow Submarine (Kiepenkerl, Everswinkel, Germany). The seeds were sown on April 5 in planting seeds trays with capacities of 0.1 L. Then, the seedlings were transplanted into 11-cm nursery pots after three weeks with capacities of 1 L in the greenhouse. The greenhouse conditions included 16 hours of daylight, 22˚C during the day and 18˚C at night. The soil in the trays and pots contained a mixed peat (A 400, Stender, Schermbeck, Germany). The final transplanting took place outdoor after 7 weeks of sowing on May 29th, when the seedlings were planted in 20-cm Mitscherlich vessels with capacities of 6.2 L filled with substrate peat as the soil (Gartentorf, Naturana, Vechta, Germany).

Two different concentrations of K in combination with two various levels of B were applied weekly during the growing season. The application of K was in the liquid form of weekly application of K_2SO_4, while the B supply was in the weekly application as liquid form of H_3BO_3 to the soil directly (Table 2). Nitrogen (N) was applied weekly in parallel with K as a mixture of (NH_4NO_3 + $Ca(NO_3)_2$ •$3H_2O$) for weekly treatments with

K2-B and K2+B and every second week for K1-B and K1+B. To balance the sulfate S for K1-B and K1+B, another N solution as $(NH_4)_2SO_4$ was applied every alternate week with the previous mixture (NH_4NO_3 + $Ca(NO_3)_2 \bullet 3H_2O$) (Annex, Table A4). The other macro and micronutrients were applied during final transplanting and one more time during the season at the eighth week after the final transplanting (Annex, Table A1). Irrigation was performed with distilled water whenever necessary and the plants were pruned weekly to maintain one major stem. The plants were arranged in four replicates with a randomized block design.

Table 2. K and B fertilization application on tomato plants during the growing season (May – September 2017).

	K_2SO_4 (g plant^{-1}), weekly	H_3BO_3 (g plant^{-1}), weekly
K1 -B	0.5 (K low)	0.018 (B low)
K1 +B	0.5 (K low)	0.063 (B high)
K2 -B	3.66 (K high)	0.018 (B low)
K2 +B	3.66 (K high)	0.063 (B high)

Fruits Sampling and Storing

From each treatment, 10 fruits in the breaker stage (Annex, figure A6) were sampled to be stored at two different conditions:

Storage at Ambient Conditions

The fruits were collected on August 3rd to be stored at 20°C with a relative humidity of 90% for 15 days. The fruit color, LFM, DM, K and B content, TSS, and TA were analyzed at the end of the storage period for the stored fruits (Table 3).

Storage at Refrigerated + Ambient Conditions

The fruits were sampled on August 9th and stored at 4°C with a relative humidity of 60% for three weeks. Afterwards, the fruits were transferred to a 20°C storage facility with a relative humidity of 90% for 7 days.

At the end of the experiment, fruit color, CI, LFM, DM, K and B content, TSS, TA, PA, and FA were estimated (Table 3).

Table 3. Overview of storage experiments and analysis during and after the storage period.

Storage experiment	Fruit maturity stage [(a)]	Temperature, duration	Analyses after storage
Ambient conditions (AC)	Breaker	20°C, 15d	Fruit color, LFM, DM, K and B contents, TSS, TA
1. Refrigerated + 2. ambient conditions (R+AC)	Breaker	1. 4°C, 21d + 2. 20°C, 7d	Fruit color, LFM, CI, DM, K and B contents, TSS, TA, PA, FA

[(a)]. In each experiment 10 fruits were stored and analyzed.

Determination of Skin Color Intensity

The color measurement was performed with a Chroma Meter (Konica Minolta; CR-400 Ver. 1.13; Tokyo; Japan) at two symmetrical locations around the equator of all the fruits of each sample. The evaluation of the color of Primavera was chosen to be expressed as a*/b* ratio and the color of Yellow Submarine as hue angle (°H). The unit a*/b* represents -0.5 = green and 0.8 = red, respectively. The unit °H is represented in the following degree measurements: 0°H = red, 90°H = yellow, and 180°H = green.

Loss of Fresh Matter and Occurrence of Chilling Injury

The LFM was determined on the stored fruits at both storage conditions. Thereafter, the CI symptoms were estimated on the stored fruits of R+AC only. It was done after transferring the fruits from refrigerated (4°C) to ambient storage (20°C). The calculation of CI was as a percentage of the infected fruits out of the total number of stored fruits per sample.

Quality traits and Mineral Composition of the Fruits

Determination of Dry Matter, Total Soluble Solids, and Titratable Acidity

The samples for the assay of DM, TSS, and TA were blended for two minutes with a kitchen blender (Braun; MR500; Kronenberg; Germany) to achieve a homogenized puree. Thereafter, about 10 g of the puree was dried according to the method of Naumann and Bassler (1976) for estimating the DM. The rest of the puree was centrifuged for 20 minutes at room temperature and 5000 g (Centrifuge 5804 R, Eppendorf, Hamburg, Germany). The supernatant was filtered (filter papers: MN 615 1\4 Ø 90 mm, Düren, Germany) and collected. To determine the TSS, three drops of the supernatant were added to the refractometer's prism assembly (Hand Refractometer, Krüss Optronic, Hamburg, Germany). The readings of the °Brix values were recorded to estimate the TSS content in the fruits. According to the method LMBG (1983), 3 ml of the same supernatant were added to 20 ml of distilled water to determine TA and were automatically titrated by the device (TitroLine 96, Schott, Mainz, Germany) until a stable pH value of 8.1 was reached. The acid content percentage was calculated with the following equation:

$$Acid\ \% = \frac{ml\ 0.1\ N\ NaOH\ x\ N\ x\ ml\ equivalent\ factorof\ predominant\ acid}{ml\ of\ the\ sample}\ X\ 100$$

The PA, putrescine (PUT), spermidine (SPD), and spermine (SPN) were extracted according to the method of Niether et al. (2017) by using 100 mg of freeze-dried material (EPSILON 2-40, Christ, Epsilon 2 – 40, Osterode, Germany). After extraction, the PA were estimated by High-Performance Liquid Chromatography (LC-2000 Series; Jasco; Pfungstadt; Germany).

Total FA extraction followed the experimental protocol of Thies (1971). The total FA composition was analyzed by gas chromatography GC-FID (Thermo Electron Corporation, Trace GC Ultra; Autosampler: A.L.S. 104). The samples were injected into the column (Permabond FFAP-0.25 µm, 25 m x 0.25 mm) with a volume of 0.2 µl. The column temperature was 205°C, the injector temperature was 250°C, and the detector temperature was 250°C. The carrier gas was hydrogen at a pressure of 100 kPa. The quantity of each FA was expressed as a relative percentage of the total FA content (Annex, Table A5). The displayed results have been provided as a ratio between the sums of unsaturated/saturated FA concentrations.

Determination of K and B Contents

To determine the K and B contents of the fruits, an amount of 100 mg of fine powder of lyophilized tomato fruits were put in Teflon tubes and then digested in a microwave (Ethos terminal 660, Milestone, Sorisole, Italy) for mineral extraction according to the method of Koch et al. (2018). Subsequently, the samples were analyzed using inductively coupled plasma-optical emission spectrometry (ICP-OES) method (Vista-RL ICP-OES, Varian, Palo Alto, USA).

Statistical Analyses

Statistical analyses were performed by the SPSS software (Version 22) (IBM Corporation, New York, United States). Data were normally distributed according to the Shapiro-Wilk test ($p<0.05$) and the variance was homogenized according to the Welch test. The differences between the K treatments were determined by performing one-way ANOVA at $p<0.05$, followed by Tukey's post-hoc test for each parameter within the cultivar.

Results

Effect of K and B Supply on the Quality of Fruit Stored under Ambient Conditions

K and B Contents, Fruits Color Intensity, Loss of Fresh Matter, and Dry Matter

The fruit content of K and B displayed a corresponding response to the fertilization application on the plants (Table 4). The highest values of K content were found at the highest K application treatments at K2-B and K2+B. The maximum fruit B content was at the highest level of B supply treatments at K1+B and K2+B.

In Primavera, the highest a*/b* value was at K2+B (1.32) and the lowest value at K1-B (1.01). No significant differences between the treatments were detected (Figure 6A). The maximum °H value in Yellow

Submarine fruits was recorded at K1-B (104.05) while the lowest value was recorded at K2+B (107.38) with no significant differences between the treatments (Figure 6B).

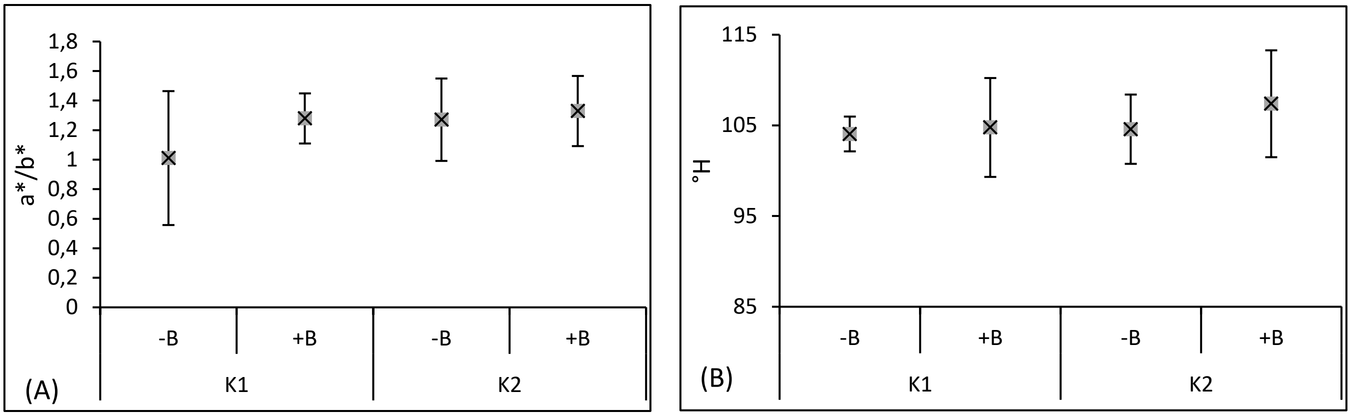

Figure 6. Fertilization effects on the fruits color intensity of two cultivars: (A) Primavera and (B) Yellow Submarine.

The results of LFM showed no effect of fertilization application (Figure 7A). Maximum loss occurred at the highest fertilization application level K2+B in both cultivars. Level K2-B showed the lowest LFM, though was not significant. The DM content elevated with the fertilization supply in both cultivars (Figure 7B). The DM content ranged from 7.29% (K1+B) to 10.58% (K2-B).

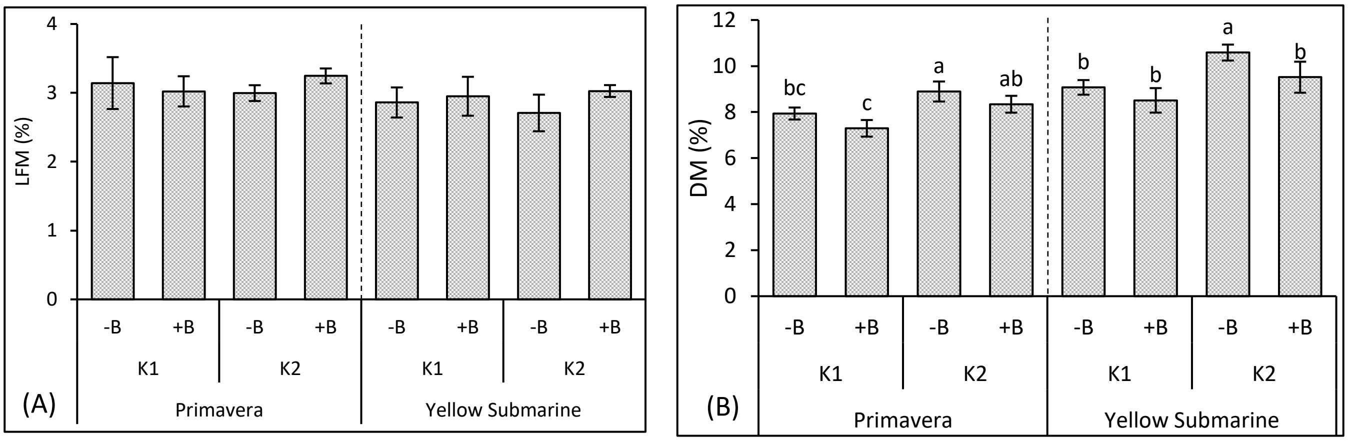

Figure 7. Fertilization effect on fruits quality attributes of two cultivars: Primavera and Yellow Submarine. (A) Loss of fresh matter. (B) Ddry matter content. The small letters refer to the significant variances at p = 0.05 between the mean values within the cultivar.

Total Soluble Solids and Titratable Acids

With respect to TSS content, there was a significant increment with the fertilization application in both cultivars (Figure 8A). Level K2-B revealed the maximum TSS content in both cultivars 8.55°brix in the Yellow Submarine fruit and 7.10 °brix in the Primavera fruit. The lowest TSS was at level K1+B in both cultivars with a significant difference from the other fertilization levels. The TA content enhanced with fertilization supply (Figure 8B). The maximum TA was reached at level K2-B (0.74%) while the lowest was at level K1-B (0.35%). A significant increase of TA was revealed at K2-B and K2+B in both cultivars.

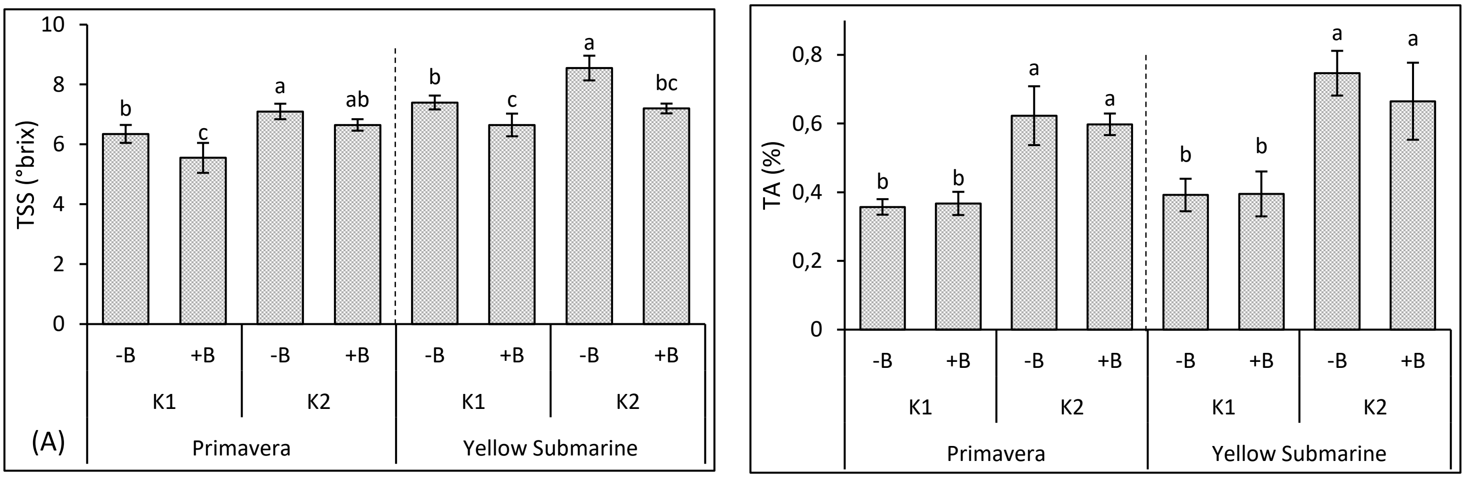

Figure 8. Fertilization effect on fruits quality attributes of two cultivars: Primavera and Yellow Submarine. (A) Content of total soluble solids and (B) Content of titratable acids. The small letters refer to the significant variances at p = 0.05 between the mean values within the cultivar.

The Effects of K and B Supply on the Quality of Fruit Stored under Refrigerated + Ambient Conditions

K and B Contents, Fruit Color Intensity, Chilling Injuries, Loss of Fresh Matter, and Dry Matter

K and B concentrations of the fruits altered significantly and exhibited compatible anticipated results with the level of fertilization (Table 4). The highest K application at K2-B and K2+B significantly increased K concentrations in the fruits of both cultivars. Likewise, maximum B content of the fruits was at the highest level of B supply treatments at K1+B and K2+B (Table 4).

Table 4. Concentrations of K and B in the fruits of two cultivars: Primavera and Yellow Submarine. The fertilization levels (Table 1). Mean values ± STD. The small letters refer to the significant differences at p = 0.05 between the fertilization treatments. AC = ambient conditions, and R + AC = refrigerated + ambient conditions (Table 3).

		K (mg DM g^{-1})		**B (µg DM g^{-1})**	
Fertilization levels		**AC**	**R + AC**	**AC**	**R + AC**
Primavera	**K1 -B**	14.91^{b} ± 1.04	17.30^{b} ± 2.59	14.56^{b} ± 5.17	19.12^{b} ± 5.51
	K1 +B	14.79^{b} ± 0.34	16.85^{b} ± 0.53	27.81^{a} ± 3.39	33.95^{a} ± 3.87
	K2 -B	26.64^{a} ± 2.01	30.40^{a} ± 1.44	12.41^{b} ± 1.18	16.10^{b} ± 1.43
	K2 +B	27.48^{a} ± 1.42	29.25^{a} ± 3.59	26.21^{a} ± 3.98	29.85^{a} ± 3.55
Yellow Submarine	**K1 -B**	16.52^{b} ± 0.96	18.74^{b} ± 0.95	11.42^{b} ± 1.53	15.30^{b} ± 0.98
	K1 +B	16.62^{b} ± 1.08	18.49^{b} ± 1.76	22.65^{a} ± 3.95	27.86^{a} ± 4.81
	K2 -B	28.90^{a} ± 1.70	33.66^{a} ± 2.91	12.10^{b} ± 1.21	16.10^{b} ± 1.53
	K2 +B	28.84^{a} ± 1.94	34.63^{a} ± 1.36	23.55^{a} ± 2.87	29.04^{a} ± 2.07

No significant differences among the treatments regarding color intensity were detected in Primavera fruits but the lowest a*/b* value was found at level K1-B (Figure 9A). The fruits of Yellow Submarine also did not significantly vary with the fertilization supply and the lowest °H value was reached at level K2-B (Figure 9B).

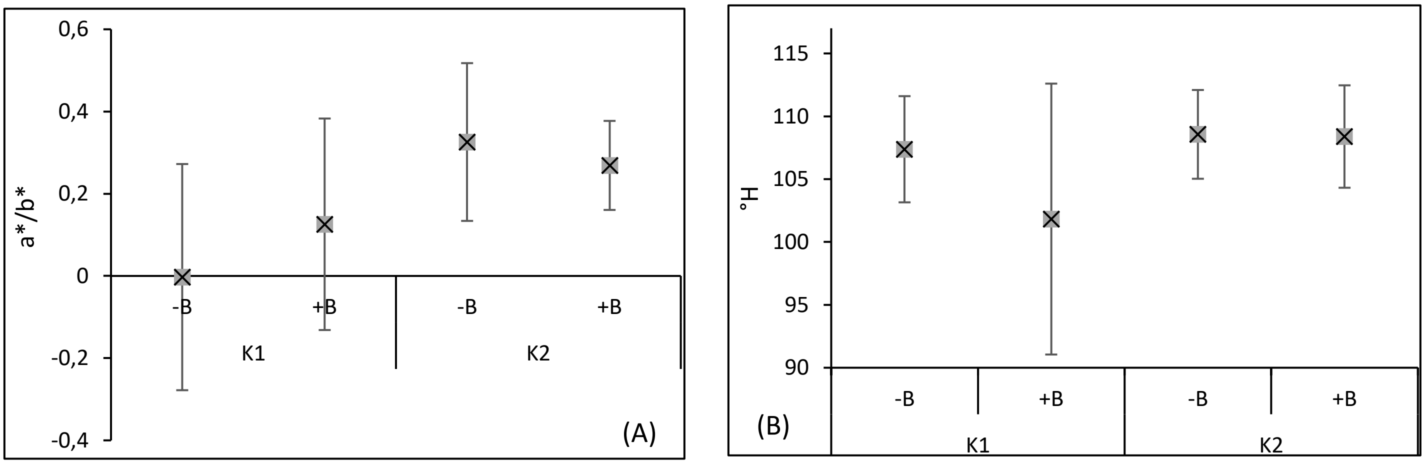

Figure 9. Fertilization effects on the fruits color intensity of two cultivars Primavera and Yellow Submarine. (A) Primavera (B) f Yellow Submarine.

The results of CI are expressed as the final evaluation at the end of the storage period (Figure 10). The fruits of both the cultivars did not vary significantly with the fertilization supply with respect to CI. The susceptibility to possess CI was higher in the Primavera fruits in comparison to the Yellow Submarine fruits. The lowest value was 12.5% at level K2-B in Yellow Submarine and the highest value was 57.5% at level K1+B in Primavera.

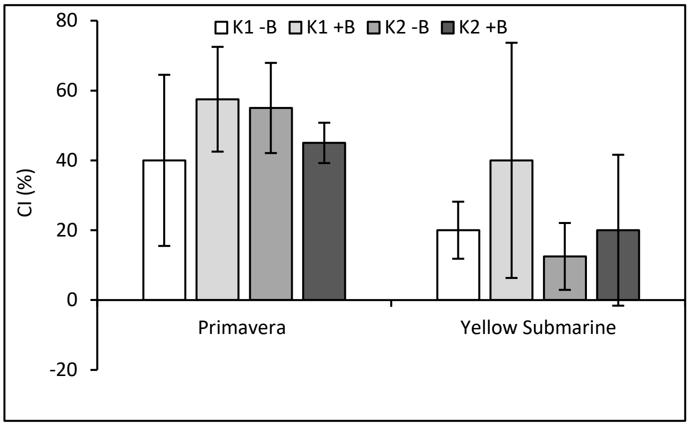

Figure 10. Chilling injury symptoms on the fruits of two cultivars: Primavera and Yellow Submarine stored in R+AS conditions.

There was no significant effect of the fertilization on the LFM of the studied cultivars (Figure 11A). The LFM ranged from 1.53% (K2-B) to 4.15% (K1+B). The DM content was increased with K application in both cultivars (Figure 6B). Maximum DM achieved at level K2-B (10.3%) in Yellow Submarine and (8.37%) in Primavera. Only in Yellow Submarine the level K2-B significantly increased compared to the other fertilization levels.

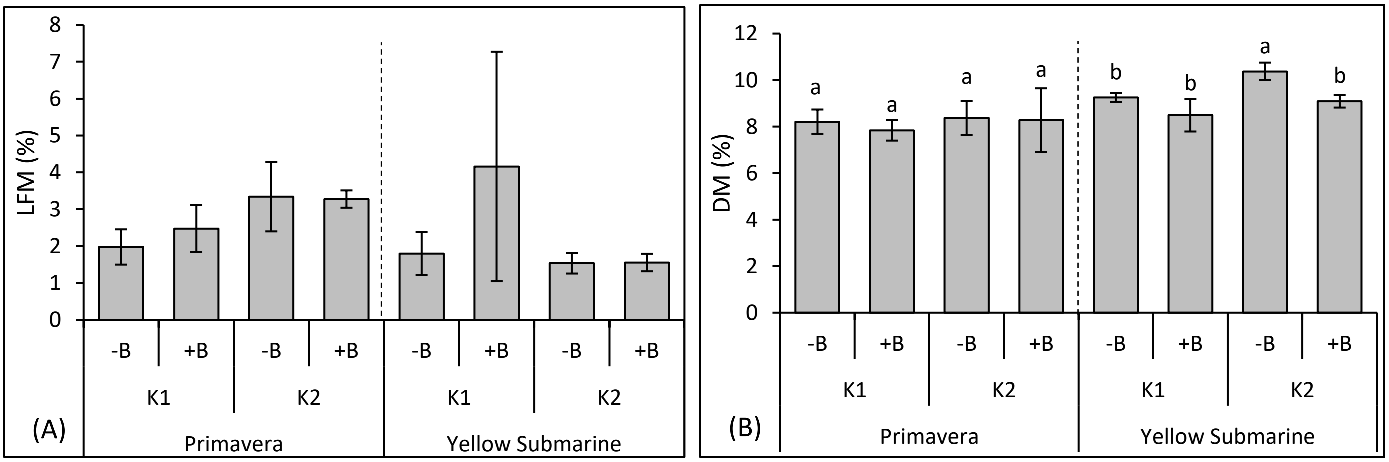

Figure 11. The effect of fertilization on the quality attributes of the tomato fruits of two cultivars: Primavera and Yellow Submarine. (A) Loss of fresh matter and (B) Dry matter content. The small letters refer to the significant variances at p = 0.05 between the mean values within the cultivar.

Total Soluble Solids, Titratable Acids, Polyamines, and Fatty Acids

The fertilization supply enhanced the fruit TSS content in both cultivars (Figure 12A). The highest TSS value was reached at level K2-B in both cultivars; 8.25°brix in the Yellow Submarine and 6.45°brix in the Primavera fruits. Level K2-B significantly increased TSS only in the Yellow Submarine fruits. An increase with the fertilization supply in both studied cultivars was recorded regarding the content of TA (Figure 12B). Maximum TA was at level K2-B (0.78%) in Yellow Submarine while the lowest TA was at level K1-B (0.36%) in Primavera. A significant increase of TA was revealed with high K levels K2-B and K2+B in both cultivars.

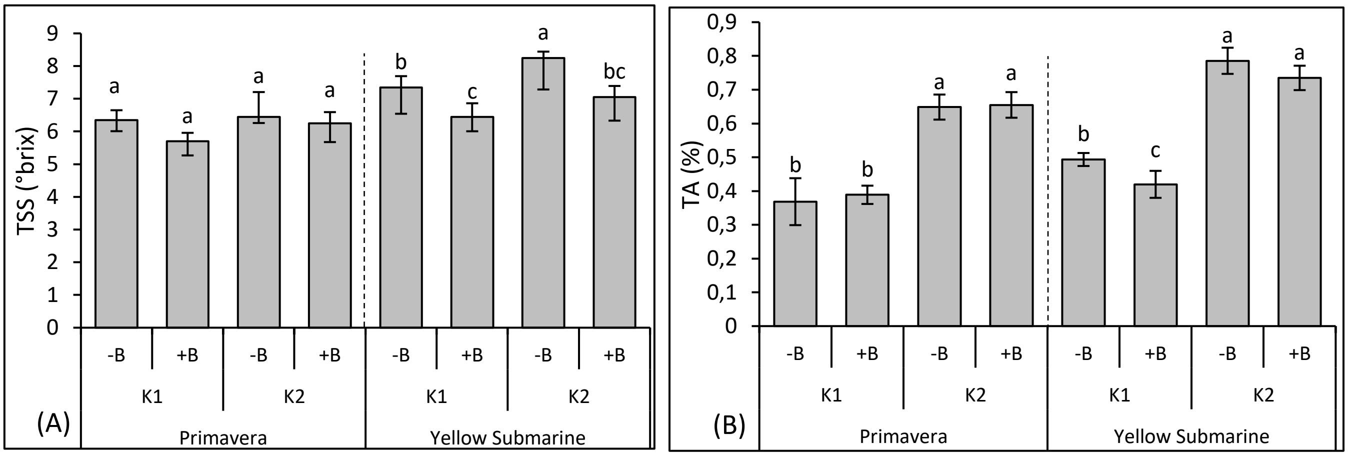

Figure 12. The fertilization effect on the quality attributes of the tomato fruits of two cultivars: Primavera and Yellow Submarine. (A) Content of total soluble solids and (B) Content of titratable acids. The small letters refer to the significant variances at p = 0.05 between the mean values within the cultivar.

Among the PA, only the content of PUT decreased significantly with the rising supply of K in both cultivars (Figure 13A). The maximum SPD was achieved at level K2+B in both cultivars, although this increment was not significant. The SPN ameliorated with the fertilization application, though it was slight and not significant.

The FA results are presented as the unsaturated (US)/ saturated (S) ratio between the sums of the US/S FA concentrations in the fruits (Figure 13B, Table A5). The fertilization supply had a significant influence on the US/S ratio in the Yellow Submarine fruits but not in Primavera fruit. Level K1+B significantly increased the US/S ratio from K1-B only in the Yellow Submarine fruit.

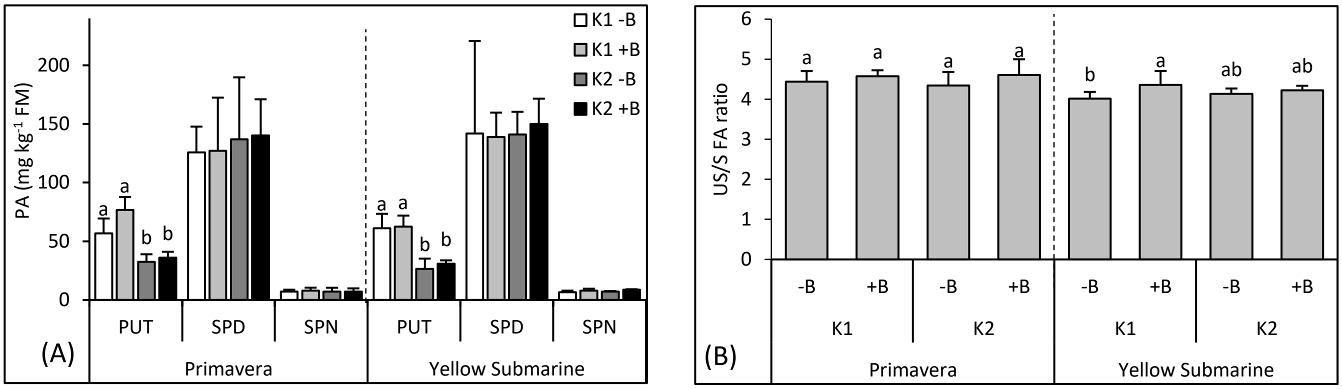

Figure 13. The fertilization effect on the quality attributes of tomato fruits of two cultivars: Primavera and Yellow Submarine stored in R+AS= refrigerated + ambient conditions. (A) Polyamines content and (B) the ratio unsaturated / saturated fatty acids content. The small letters refer to the significant variances at $p = 0.05$ between the mean values.

Discussion

Effect of Potassium and Boron Supply on Fruit Quality during Ambient Storage

Color Intensity of Fruits

In this study, the fruits stored in ambient conditions and supplied with low K developed less color intensity compared to the fruits that were fed with high K, though not significant (Figure 6). This was probably due to the positive effect of K on color ripening development of the stored fruits as was stated by Constán-Aguilar et al. (2014). Rising K fertilization was reported to increase lycopene content in tomato fruits (Fanasca et al., 2006; Javaria et al., 2012). The red color of a tomato results from chlorophyll breakdown and the subsequent synthesis of lycopene (Fraser et al. 1994). In terms of the influence of K on the lycopene content we argue similar to Arias et al. (2000) that a*/b* qualifies as the best prediction of lycopene content in tomatoes. The fruit color intensity of Yellow Submarine was also enhanced with rising K-fertilization in stored fruits under ambient conditions (Figure 6B). The formation of yellow color is a consequence of the reduction of lycopene content in parallel with rising ß-carotene and lutein content

(Hart and Scott 1995). Hartz et al. (2005) found the highest °H value in tomato fruits which were ripened under low K fertilization, while Taber et al. (2008) reported a decreasing in ß-carotene with high K supply. The results from the present study are in contrast to those of Hartz et al. (2005) and Taber et al. (2008) as rising K fertilization increased though not significantly °H value in the Yellow Submarine fruits.

With respect to B fertilization, there was no clear effect on the color intensity in both cultivars (Figure 6). Singh et al. (2012) reported a significant decrease in carotenoids accumulation in carrots with increasing B application. Considering using different crops, this could probably interpret the non-effect of B on the fruits' color intensity in both studied cultivars.

Loss of Fresh Matter and Dry Matter

The LFM is one of the most important factors under postharvest conditions. During storage, the fruits lose weight and if this weight loss reaches 3 – 10 % they become unmarketable products (Ben-Yehoshua and Rodov 2003). Many studies confirmed that high K application reduces LFM in tomato fruits during the postharvest period (e.g. Almeselmani et al. 2009; Constán-Aguilar et al. 2014). The microelement B was demonstrated to have a major role in cell wall structure conservation, which results in reduced skin crack incidence (Broadley et al. 2012; Davis et al. 2003). Moreover, B has a positive impact on the reduction of LFM by alleviating the membrane's permeability, as reported by Cakmak et al. (1995) in sunflower plants. In this study, neither K nor B had a significant effect on LFM as the maximum LFM was 3.24% at K2+B and the lowest value was detected with 2.70% at K2-B. However, LFM is still lower than that was suggested by Chomchalow (1991) who described that mature-green tomatoes stored under 20°C lost about 5% weight, which might be due to the function of K and B in mitigating LFM and this could also be an elucidation for our observations. Under a constant temperature of 20°C and a dark environment, respiration is high in coincidence with the high metabolic rate to achieve the maturity of the fruits. Another reason could be fruits cracking under high K fertilization, as proposed by Huang and Snapp (2009), which maximizes the electrolyte leakage from the fruits, resulting in high LFM. In addition, the combination of high K and high

B fertilization had highest LFM in both cultivars that is likely because of the higher accumulation of K and B in the cytosol, which increases the osmotic pressure and causes fruit skin tension.

The results of DM showed a significant increase with K supply in both cultivars stored at ambient conditions. Hawkesford et al. (2012) reported that K elevates the DM in tomatoes due to the increment of assimilates accumulation in the cytosol. Furthermore, Davis et al. (2003) concluded a positive influence of B on the DM in tomatoes but such an effect was not revealed in our study.

Total Soluble Solids and Titratable Acids

The sugar content is influenced by pre- and postharvest conditions such as temperature, fertilization, and light (Dorais et al. 2008). A positive impact of K on the TSS content in tomatoes was stated in earlier studies (e.g. Auerswald et al. 1999; Javaria et al. 2012). This effect is most likely due to the reinforcement role of K in carbon assimilation and photosynthesis translocation from the leaves to the fruits (Kanai et al. 2007). It has been reported that B involves in sugar-borate complex and, hence, can relocate the sugars more easily compared to non-borate sugars (Woods 1994). Consequently, the effect of K fertilization revealed a significant increase in the TSS content with a high K dose, which is in line with findings of Constán-Aguilar et al. (2014). In contrast, the impact of the high B led to a diminution in TSS content in both cultivars which confirms the results of Naz et al. (2012), as they found a significant decrease in TSS in tomato fruits with rising B supply.

The other factor influencing the TSS content is the cultivar background (Beckles 2012). Cultivar differences with regard to TSS were observed as Yellow Submarine had higher TSS content compared to Primavera, which was stated by Kanski et al., (2020) as they found significant differences in TSS content among the studied cultivars.

TA in fresh tomatoes contributes around 15% to the TSS, along with the sugar content and aroma compounds that constitute the flavor of tomatoes (Beckles 2012). The results showed a significant influence of K and B on the TA content in both cultivars. This was presumably due to the high K concentration in the cytosol, which elevated the production of organic acids to balance the cation-anion ratio as well as the pH value (Etienne et al. 2013; Hawkesford et al. 2012). Boron as a boric acid in the cytosol comprises the esters mono-, di- and polyhydroxy compounds (Broadley et al. 2012). The esters are derived from acids. With increasing B, the acids content enhances the achievement of ester formation. Consequently, the increasing B supply elevates the acid content, which is congruent with our findings. The decrease in the TA content during ripening is a consequence of the metabolic activity, which results in decreased organic acids and an increased in sugar content (Pila et al. 2010). In our stored fruits, the metabolic activity was probably lower as it was interrupted after the harvest. Similar to the TSS results, the cultivar effect was noted with higher TA values in Yellow Submarine compared to Primavera as was also found by Sonntag et al. (2019).

Effect of Potassium and Boron Supply on Fruit Quality Stored in Refrigerated + Ambient Conditions

Color Intensity of Fruits

The effect of K supply did not display any significant variations in the color intensity of stored fruits in both cultivars, which disagreed with the results of Constán-Aguilar et al. (2014). It has been demonstrated that K mitigates the stress susceptibility in plants by producing more antioxidants, such as carotenoids (Wang et al. 2013). A range of optimal temperatures between 16 – 26 °C was suggested for lycopene synthesis by Brandt et al. (2006), whereby they found that the lycopene production in tomato fruits at breaker stage were suppressed outer the suggested range. Primavera fruits were stored for three weeks under 4°C which could be the reason of diminishing the color intensity a*/b* as Brandt et al. (2006) pointed out a linear relationship between a*/b* and lycopene concentrations. The values of °H of Yellow Submarine fruits exhibited no significant alterations with the fertilization levels. The concentrations of ß-carotene are highly affected by the temperature and the length of storage as Kumkong et al. (2018) stated in their study on baby-jack fruit powder which was stored under 4°C for 30 day. They found that after 15 days the values of

°H were decreased indicating a diminution in ß-carotene contents as it corresponded to °H values (Arias et al., 2000). The fruits of Yellow Submarine were stored for three weeks at 4°C, in which the synthesis of ß-carotene was not catalyzed by neither K nor B due to the inadequate temperature conditions. All in all, increasing the production of carotenoids with rising K supply (Taber et al., 2008) or higher B application (Singh et al., 2012) was suppressed by the insufficient storage temperatures of 4°C for carotenoids production in both cultivars.

Loss of Fresh Matter and Dry Matter

The fruits were stored for three weeks in refrigerated conditions (4°C) and then transferred to ambient conditions (20°C) for one week in which they lost weight as their metabolic rate increased to reach the maturity stage. Mutari and Debbie (2011) reported that the metabolic rate increases with rising surrounding temperature of tomato fruits and results in the loss of water with an associated decrease in weight. Neither K nor B supply had a significant influence on reducing the LFM of both cultivars in this research. Nevertheless, the highest LFM in this experiment was 4.15% at low K level, where Chomchalow (1991) suggested that mature-green and round tomatoes typically lose about 5% weight during ripening at 20°C. In the present study the LFM was lower than the results of Mutari and Debbie (2011) (about 7%) and Roberts et al. (2002) (4.9%). This is likely due to the function of K and B in diminishing LFM, as suggested by Almeselmani et al. (2009) and Davis et al. (2003).

The DM content of the fruits revealed differences among the various K and B fertilizations. Fruits from plants with deficient K and high B showed the lowest DM content while sufficient K supply combined with low B showed the maximum DM content in the stored fruits. The positive effect of K was stated to increase DM in stored tomato fruits at 4°C (e.g. Constán-Aguilar et al. 2014; Javaria et al. 2012) which was probably due to the function of K in translocating and accumulating the photosynthesis assimilates in the cytosol (Hawkesford et al. 2012). With respect to the B and its effect on DM, Davis et al. (2003) reported a positive increase with rising B fertilization in fresh tomato fruits, however, this effect was not revealed in our results. This was presumably due to the role of B in cell wall maintenance under cold stress conditions, which requests the transportation of some substrates into the cell wall as a defense mechanism in plants (Brown et al.,2002).

Total Soluble Solids and Titratable Acids

The results of TSS altered with K and B fertilization and the highest TSS was at K2-B in both cultivars. Under the cold storage conditions, restrained sugar development in the harvested tomato fruits was pointed out by Díaz de León-Sánchez et al. (2009) and Gómez et al. (2009). With respect to the K effect on TSS, we observed rising K application yielding the highest TSS content. This was due to the higher sugar accumulation as one of the major functions of K in the plants (Zörb et al. 2014) which was confirmed by many studies on tomatoes (e.g. Amjad et al. 2014; Javaria et al. 2012). In the present study, the application of B revealed no clear effect on TSS, which was possibly due to the stronger effect of K on photosynthesis translocation in comparison to B.

The content of TA showed a significant increase of K2 in the stored fruits of both cultivars. The effect of B was revealed as a decrease in TA content. K has a positive increasing effect on the TA content in tomatoes as it was shown in several studies (Afzal et al. 2015; Tavallali et al. 2017). However, Gómez et al. (2009) reported that cold temperatures decreased the TA content in stored cherry tomatoes under 4°C for 15 days . This is in contrast to our research and might be due to a positive influence of K and B to maintain the TA content under cold conditions by increasing the pH value of the cytosol.

Effect of Potassium and Boron Supply on Fruits Cold Tolerance Attributes during Refrigerated Conditions

Polyamines and Chilling Injuries

PA are antioxidants and they help plants adapt to and resist abiotic stress conditions, e.g., cold stress (Alcázar et al. 2010). In the present study, the PA results showed a significant decrease in PUT, increase in SPD, and no significant changes in SPN in both cultivars (Figure 8A); this might indicate an increase of SPD and SPN oxidation into PUT, resulting in an accumulation of PUT. Wang (1994) stated in his study on zucchini squash without rising K supply that PUT increased while SPD and SPN decreased under cold storage conditions (5 °C). This could be not comparable to our research because of different used crops and the fertilization applications, however, it could give an indication regarding the positive effect of K on mitigating cold stress effects. The application of K catalyzes the antioxidant system and elevates some secondary metabolite transcripts that are associated with cold tolerance such as PUT (Zörb et al. 2014). B, on the other hand, has a significant role in the maintenance of membranes and the cell wall (Broadley et al. 2012); likewise, B deficiency impairs the development of primary cell walls; hence, decreases the cold tolerance of trees (Lehto et al. 2010). It has been suggested that the plants tend to produce more PUT under abiotic stress, e.g. the deficient of minerals such as K and B (Bouchereau et al. 1999; Camacho-Cristóbal et al. 2005).

Although, the PUT content lowered under the low K as an indicator for abiotic stress, as was anticipated, CI symptoms did not reveal any significant differences between fertilization applications in both studied cultivars. High K application could not prevent electrolyte leakage by lowering the osmotic potential of cells as proposed by Wang et al. (2013) and elevated the PUT levels but could not mitigate CI as was suggested by Sharma et al. (2017). Moreover, B did not play a role in maintaining the cell wall as anticipated by Broadley et al. (2012).

Fatty Acids

FA are very important components in the plant for the mechanical barriers against the environment, such as cellular membranes and suberin (Beisson et al. 2007). They have an essential role in remodeling membrane plasticity under stress conditions (Iba 2002). Changing levels of unsaturated fatty acids by the regulated activity of fatty acid desaturases is a feature of stress acclimating plants (Upchurch, 2008).McKersie and Lesheim (2013) stated that the ratio of unsaturated/saturated FA is an useful indicator of plant cold tolerance and a high ratio leads to more cold stress-tolerant tissue. In the present study, the unsaturated/saturated FA ratio increased at low K fertilization supply combined with +B significantly in Yellow Submarine fruits while in Primavera fruits, high K combined with +B had the highest ratio, though it was not significant. Moreover, a study by Hakerlerler et al. (1997) demonstrated that K supply enhanced plant cold resistance by increasing the membrane permeability and phospholipids, which was not clearly shown in this study. Kanski et al. (2020) suggested in their study on five tomato cultivars stored under 4 °C and 7 °C unremarkable changes in FA composition during the cold storage.

Conclusion

Regarding to the main objectives of this study, the following conclusions can be drawn: (i) The application of both high K and B did not mitigate the LFM under both storage conditions. The color, TSS, TA, and DM of non-stored fruits increased with rising K application in both cultivars. The fruits stored under ambient as well as under refrigerated + ambient conditions displayed increments in DM, TSS, and TA with high K supply. The first hypothesis can be partly confirmed as the effect of B was not perceptible on these parameters. (ii) Fruits stored under ambient conditions were able to develop higher skin color intensity, and higher contents of DM, TSS, and TA than the fruits stored under refrigerated + ambient conditions, which confirms the second hypothesis. (iii) The effect of K with regard to cold tolerance was mainly notable on the PUT content as increased K supply resulted in a reduction of the PUT content. The incidence of CI was not influenced by either K or by B supply. Additionally, the ratio of saturated/unsaturated FA was not affected by increasing K fertilization. Our outcomes emphasize that the fruits performance under different storage conditions is cultivar depended, with Yellow Submarine having higher DM and TSS with lower LFM and CI compared to Primavera.

4. Assessment of sensory profile and instrumental analyzed attributes influenced by different potassium fertilization levels in three tomato cultivars

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Abstract

BACKGROUND

Sensory properties are an essential quality aspect when the consumption of fresh tomato is under consideration. The flavor of tomato is defined as a combination of taste sensations (sweetness, sourness), aroma (volatile compounds), and texture (firmness, mealiness), some of which are proven to be affected by insufficient nutrient supply—especially of the element potassium (K). This study intends to undertake a holistic assessment of the K fertilization effect on the flavor of tomato by connecting the use of sensorial and instrumental methods.

RESULTS

An optimal K supply significantly increased the sensory descriptors sweetness, sourness, tomato-typical aroma, and spiciness as well as the instrumental estimated color, firmness, total soluble solids (TSS), titratable acids (TA), and dry matter (DM) in a cultivar-specific manner. No significant increment of rising K fertilization was found on the composition of the pattern of volatile organic compounds (VOCs).

CONCLUSION

The evaluation by the panelists confirmed the results of the instrumental analyses, by which an increment in the fruit quality with the rising K supply could be detected. An optimal K supply of 3.66 g/plant could be suggested to increase tomato flavor in the cocktail cultivars studied: Primavera and Yellow Submarine. Cultivar effects should, therefore, be considered for defining the optimal K fertilizer dose that favors high tomato fruit quality and, hence, better flavor.

Keywords: *Solanum lycopersicom* L., potassium, sensory evaluation, instrumental analyses, volatile organic compounds

Introduction

The tomato is one of the most important vegetables in the world. In 2019, around 181 million tons of tomatoes were produced (1). The increasing annual demand for tomato can be attributed to its versatility and suitability for several dishes (2), as well as its fruitfulness in nutrients like minerals and antioxidants (3). In the European Union, 40% of tomatoes are consumed fresh and 60% are processed for different products (4). As regards the consumption of fresh fruits, the extrinsic characteristics (e.g. color, shape, and firmness) as well as the intrinsic ones (e.g. taste and aroma) are very important (5). The flavor is a complex attribute and derived from the interaction between the volatile compounds, such as hexanal and 2-isobutylthiazole, and nonvolatile components like sugar, acids, and minerals (6). The flavor of tomato is frequently described as a sweet–sour taste accompanying special aromatic aspects like ‘fruity’ and ‘floral’ (7). However, consumers have often complained about the flavor of fresh tomato (8). Therefore, the flavor of the tomato needs to be comprehensively considered, and not only for the consumers, but also for the producers (9). Moreover, the extrinsic and intrinsic characteristics of the flavor are remarkably influenced by many factors like weather conditions and the nutrient status of the plant and soil (10).

This study focused on the effect of K nutrition on the flavor of tomato. Being an essential macronutrient, K is involved in many physiological and biochemical processes in plants (11). Cellular K plays a role in catalyzing many enzymes, apart from having major functions in osmotic pressure adjustment (12). Furthermore, sufficient K nutrition reinforces the resistance of the plants against biotic stresses like diseases and insects (13). K is also involved in the relocation of photosynthetic assimilates to sink organs, resulting in an increment in the sugar content in the cytosol (14). Consequently, a positive enhancement on total soluble solids (TSS), titratable acids (TA) (15), dry matter (DM) (16), and firmness (17) by the K fertilizer dose has been demonstrated. Serio et al. (2007) (18) and Taber et al. (2008) (19) could state a significant influence of K supply on the lycopene content and, hence, on skin color. The positive effect of K fertilization for increasing yields and fruit quality has been pointed out by many studies (e.g. 3,20). Volatile organic compounds (VOCs) have been considered sensory indications for flavor preferences (21). Though around 400 volatile compounds have been detected in tomatoes, only 15–20 compounds, such as hexanal, 2-isobutylthiazole, and 6-methyl-5-hepten-2-one, have been found to characterize the flavor of the tomato (22). Most volatile compounds are derived from essential nutrient precursors like amino acids, carotenoids, and fatty acids (23). Apart from instrumental analyses, e.g. to measure TSS, TA, and color, the sensory evaluation has been used to characterize the flavor of tomatoes. On these lines, several studies investigated the interaction between sensory evaluation and instrumental analyses in tomatoes (24,26). Nevertheless, these correlations between sensory attributes and instrumental analyses influenced by the K application are the topic of actual investigations. Despite several reports (3,27) dealing with the influence of K nutrition on the instrumental analyzed attributes of the tomato, knowledge of the impact of K on the sensory quality is limited. Our work attempts to investigate the effect of K fertilization on sensory and physicochemical traits. It also aims to verify whether the results obtained by instrumental methods can be confirmed by the human senses. Finally, it intends to combine the instrumental analyzed and sensory descriptors. We hypothesize that: (i) increasing the K supply modifies the values of instrumental analyzed traits and the intensity of sensory quality; (ii) the effect of K fertilization on the sensory quality can be recognized by human senses; (iii) instrumental analyzed traits will distinctly correlate with sensory quality; and (iv) the effect of K fertilization will be cultivar-dependent.

Materials and Methods

Experimental Set-up

In summer 2016, an outdoor experiment was conducted with three tomato cultivars. Two cocktail tomato cultivars—Primavera and Yellow Submarine (Kiepenkerl, Everswinkel, Germany)—and one salad tomato cultivar—Lyterno F1 (Rijk Zwaan, De Lier, Netherlands)—were chosen. The cocktail cultivars were used in previous experiments and showed a good response to K fertilization (15). The salad cultivar was chosen based on the breeders' description highlighting this cultivar as being high in lycopene. Therefore, it was expected that Lyterno F1 would respond well to varying K supply as regards its color, which has been shown for high lycopene cultivars by Taber et al. (2008) (19) and Serio et al. (2007) (18). All the cultivars were sown on March 30 in planting trays with capacities of 0.1L. After three weeks, the seedlings were transplanted into 11 cm pots with capacities of 1 L in a greenhouse. Greenhouse conditions comprised 16 hours of daylight, with a mean temperature of 22 ˚C during the day and 18 ˚C at night. The soil in the trays and pots was a mixed peat ('A 400', Stender, Schermbeck, Germany). The final transplantation to the outdoor location took place after seven weeks of sowing on May 25. The seedlings were planted into 20 cm Mitscherlich vessels with capacities of 6.2 L filled with peat substrate (Gartentorf, Naturana, Vechta, Germany). Three different concentrations of K—K1 low with 0.5g K/plant; K2 medium with 2.19 g K/plant; and K3 optimal with 3.66g K/plant—in the form of liquid K_2SO_4 were applied weekly during the growing season. Nitrogen (N) was applied on a weekly basis along with K—as a mixture of NH_4NO_3 and $Ca(NO_3)_2 \bullet 3H_2O$—for K3 treatment and every two weeks for K1 and K2 treatments. Another N solution—$(NH_4)_2SO_4$—was applied for K1 and K2 treatments, alternating with the previous mixture every two weeks to balance the sulfate supply. Other plant macro- and micronutrients were applied at the final transplantation and two more times during the season (Table A6). The plants were irrigated with distilled water when required and were pruned to one shoot weekly. They were arranged in a randomized design, with four blocks representing four replicates per cultivar and K level. During harvest, the fruits of each sample were split into three subsamples. One sample set was used for the sensory evaluation by the panelists; the second subsample was used for extraction of VOCs; and the third for instrumental analyses. The number of fruits used for each type of quality analysis is given in the Table A7

Instrumental Analyses

The K concentration, color, firmness, TA, TSS, DM, and volatile compounds were estimated at fruit maturity. Based on the method of Koch et al. (2019) (26), the K concentration was determined by digesting 100 mg fine powder of lyophilized tomato fruits in 4 mL of 65 % nitric acid and 2 mL of 30 % hydrogenperoxide for 75 min at 200 °C and 40 bar in a microwave (Ethos terminal 660, Milestone, Sorisole, Italy). Subsequently, the samples were analyzed using inductively coupled plasma-optical emission spectrometry (ICP-OES; Vista-RL ICP-OES, Varian, Palo Alto, USA).

Fruit color was determined by Minolta Chroma Meter CR-400 (Konica Minolta Optics, Japan) at the two equatorial sides of each fruit in the *Lab* modus, where the *a* value represents the red color intensity of Lyterno and Primavera fruits, while the *b* value represents the yellow color intensity of Yellow Submarine fruits. Afterwards, the firmness was estimated by a penetration test (5 mm staple micro cylinder, speed: 6 mm/s, distance: 6 mm) on the equatorial side of these fruits with a texture analyzer (TA.XT2, Stable Micro System, Surrey, UK).

TSS, TA, and DM were estimated for the same fruits. The fruits were mixed for two minutes with a kitchen blender (MQ 5000 Soup, Braun, Neu-Isenburg, Germany) to achieve a homogenized puree. An amount of 10 g of this puree was dried for estimating DM, and the rest of the puree was centrifuged for 20 minutes at room temperature and at 5000 g (Centrifuge 5804 R, Eppendorf, Hamburg, Germany) to estimate TSS and TA based on Sonntag et al. (2019) (15).

Immediately after harvest, VOCs were extracted from fresh fruits, as described by Ulrich and Olbricht (2013) (27). The fruits were rinsed with distilled water, cut into quarters, and homogenized in a solution with 20 % (m/v) NaCl by a kitchen blender (MQ 5000 Soup, Braun, Neu-Isenburg, Germany). The homogenate was centrifuged for 30 minutes at 4 ˚C and 3000 g (Centrifuge 5804 R, Eppendorf, Hamburg, Germany). To 8 mL of the supernatant and 4 g of NaCl, 16 µL of the internal standard (5 µL octanol + 10 mL ethanol) were added. The samples were vortexed and stored at -20 ˚C until analysis by gas chromatography–FID, as previously described by Ulrich and Olbricht (2013) (27).

Sensory Evaluation

A group of 12 panelists had been trained weekly over two months, resulting in eight training sessions in accordance with the ISO 13299 sensory analysis guidance (28), by focusing especially on the quantitative descriptive analysis of the type of tomato fruits used in this study. The sensory descriptors color and odor intensity, juiciness, sweetness, sourness, bitterness, spiciness, skin strength, tomato–typical aroma, and aftertaste were elaborated with the sensory panel (Table A3). The scale from 0 % (minimum intensity) to 100 % (maximum intensity) was used to determine the intensity of all the descriptors that were studied. The final sensory evaluation was performed during the second week of August on fully ripe fruits for three consecutive days, with a single cultivar being evaluated each day. The evaluation was accomplished in a sensory laboratory that provided separated cabins, in accordance with ISO 8589 (2007). The fruits of cocktail cultivars were cut into halves, while those of the salad cultivar were cut into quarters immediately before being served in transparent plates that were coded with three-digit numbers. Between the served samples, the panelists were directed to consume a piece of bread and tap water to naturalize the basic tastes.

Statistical Analyses

Statistical analyses were performed mainly by using the SPSS Software, Version 22 (IBM Corporation, New York, United States). Data were proven to be normally distributed with the Shapiro–Wilk test (p<0.05), and the variance homogeneity was verified with Welch's test. General fertilizer effects were tested at the significance level of p<0.05 with one-way ANOVA before separating the means of each fertilization treatment within the cultivars by using Tukey's post-hoc test. In order to connect sensory and physicochemical traits, Pearson's correlation analysis was calculated with SPSS and a principal component analysis (PCA) was calculated with the Statistica Software, Version 13.3 (TIBCO Statistica, Tulsa, United States). The panel performance was calculated by a 2-way ANOVA with assessor and sample as main effects with the Software PanelCheck V1.4.0.

Results

Fruits K-concentration

The fruits' K concentration was significantly influenced by the fertilization level (Table 5). As anticipated, the level K1 significantly displayed the lowest values. Compared with the medium fertilization K2, the supply of the fertilizer level K3 could only raise the K concentration in the two cocktail tomatoes.

Instrumental and Sensory determined Color

Instrumental analyzed color values increased significantly with rising K fertilization only in the cocktail cultivars, where the color – *b* value (yellow) of Yellow Submarine fruits and the color – *a* value (red) of Primavera fruits were more intense in K3 (Table 5). Based on the panelists' evaluation, color intensity was increased significantly only in Primavera (Table 7). Consequently, the cultivar had a remarkable effect on the evaluation of color by instruments and human senses. The principal component analysis (PCA) in three cultivars confirmed the ANOVA results. In the PCA, color intensity and instrumental determined color were located closely to each other in Primavera (Figure 15) but distanced from each other in Lyterno F1 (Figure 14) and Yellow Submarine (Figure 16). Additionally, the correlations of color intensity with the instrumental determined color were low and nonsignificant: color – *a* (r = 0.23) and color – *b* (r = 0.45) (Table A10).

Volatile Organic Compounds and Odor Intensity

Around 16 known volatile organic compounds (VOCs) were distinguished in this study and they comprised around 80 % of all the detected VOCs (Table 6). Most of them were not influenced significantly by K fertilization, while the main variations were related to a cultivar effect. For instance, in Lyterno F1, hexanal, (*E*)-2-hexanal, octanal, and ß-ionone decreased significantly with rising K supply, while these compounds exhibited no alterations as regards K levels in Primavera and Yellow Submarine. In addition, some of the detected VOCs were only found in red-colored cultivars, e.g. ß-ionone, ß-cyclocitral, and (*E*)-geranylacetone, or only in yellow-colored cultivars like methylsalicylate (Table 6). Odor intensity was not affected by K application along the cultivars that were studied. These observations could be visualized with the previously mentioned PCA plots (Figures 14, 15, and 16), in which the odor intensity and most of the VOCs were less related to K3. Interestingly, odor intensity correlated in a significantly positive manner with only a few compounds—in particular, ß-ionone (r = 0.57**), (*E*)-2-hexenal (r = 0.64**), and benzaldehyde (r = 0.40**) (Table A10).

Texture Parameters

Similar to the VOCs, the cultivar background influenced the textural parameters analyzed by instruments or evaluated by the panelists. The firmness determined by a texture analyzer increased significantly only in Lyterno F1 and Yellow Submarine with rising K levels (Table 5). In terms of the sensory descriptors, skin strength increased significantly in Yellow Submarine, while a significant reduction in Primavera was found (Table 7). On the other hand, juiciness did not exhibit any significant alterations with K fertilization (Table 7). In Figures 1 and 3 of the PCA plot, the firmness and skin strength exhibited a significant increase with K application and were associated closely with K3.

Overall, the firmness correlated in a positively significant manner with skin strength (r = 0.42**), while juiciness did not significantly correlate either with firmness or with skin strength (Table A10).

Relationship between Instrumental Analyses and Taste Attributes

TSS and TA positively increased with rising K fertilization in the three cultivars (Table 5). DM was significantly rising in the cocktail cultivars, while in Lyterno F1 only a positive trend was observed (Table 5). From the panelists' perspective, sweetness and sourness increased significantly with higher K levels, though only in the cocktail cultivars (Table 7). Apparently, the cultivar effect was evident in the instrumental and sensory determined taste attributes. For instance, in Lyterno F1, TSS, TA, sourness, and

DM grouped with optimal K3, while sweetness was decreased with rising K dose; consequently, it dissociated from K3 and approached the low K1 (Figure 14). Sweetness correlated significantly positively with TSS ($r = 0.81^{**}$); likewise, sourness with TA ($r = 0.76^{**}$) and DM correlated in a significantly positive manner as well with TSS ($r = 0.95^{**}$), TA ($r = 0.63^{**}$), sweetness ($r = 0.79^{**}$), and sourness ($r = 0.63^{**}$) (Table A10).

Retronasal Attributes (Aroma)

The aroma of the fruits was finally estimated by the panelists at the end of the sensory evaluation represented by aftertaste, tomato-typical aroma for red fruited cultivars—Primavera and Lyterno F1—and spiciness for Yellow Submarine. Application of K increased aftertaste in the studied cultivars though not significantly (Table 7). Tomato-typical aroma increased with rising K supply; significantly in Primavera and not significantly in Lyterno F1. In contrast, spiciness significantly rose with K application in Yellow Submarine (Table 7). These observations were visually acknowledged by PCA plots (Figures 14, 15, and 16). Aftertaste was associated with K3 in all cultivars. In the same way, tomato-typical aroma (Figures 14 and 15) and spiciness (Figure 16) were linked to K3, confirming the ANOVA results.

Correlations among tomato-typical aroma, spiciness, and the instrumental attributes as well as the VOC's were identified. Tomato-typical aroma associated in a significantly positive manner with TSS ($r = 0.83^{**}$), TA ($r = 0.51^{**}$), DM ($r = 0.74^{**}$), sweetness ($r = 0.82^{**}$), sourness ($r = 0.67^{**}$), odor intensity ($r = 0.76^{**}$), hexanal ($r = 0.44^{*}$), and (*E*)-2-hexenal ($r = 0.48^{**}$). Interestingly, spiciness correlates significantly neither with instrumental nor with sensory determined attributes (Table A10).

Table 5. Mean values and standard deviation of taste-related attributes calculated for each K level (n=4) within the three cultivars Lyterno F1, Primavera, and Yellow Submarine. TSS: total soluble solids, TA: titratable acids. Color–a: estimated for Lyterno F1 and Primavera. Color–b: determined for Yellow Submarine. n.d. not determined. Letters indicate significant differences at $p<0.05$ between the K treatments. K1 low 0.5; K2 medium 2.19; and K3 optimal 3.66 g/plant.

Instrumental analyzed Attributes	**Lyterno F1**			**Primavera**			**Yellow Submarine**		
	K1	**K2**	**K3**	**K1**	**K2**	**K3**	**K1**	**K2**	**K3**
K-content (%)	1.42^{b} ± 0.11	2.48^{a} ± 0.12	2.44^{a} ± 0.17	1.21^{c} ± 0.07	2.34^{b} ± 0.07	2.66^{a} ± 0.15	1.60^{c} ± 0.11	2.29^{b} ± 0.07	2.54^{a} ± 0.15
Color – *a*	21.09^{a} ± 0.92	20.32^{a} ± 0.7	20.77^{a} ± 0.71	12.16^{b} ± 0.45	16.81^{a} ± 1.72	17.67^{a} ± 1.25	n.d.	n.d.	n.d.
Color – *b*	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	44.82^{b} ± 2.71	49.48^{a} ± 1.33	50.24^{a} ± 1.94
Firmness (kg/cm)	1.21^{b} ± 0.34	1.59^{ab} ± 0.08	1.79^{a} ± 0.32	0.69^{a} ± 0.03	0.82^{a} ± 0.09	0.70^{a} ± 0.11	0.75^{b} ± 0.01	0.95^{a} ± 0.10	1.03^{a} ± 0.14
TSS (%)	5.80^{b} ± 0.43	6.45^{ab} ± 0.44	7.30^{a} ± 0.62	6.75^{b} ± 0.3	8.45^{a} ± 0.44	8.52^{a} ± 0.19	8.25^{b} ± 0.01	9.05^{b} ± 0.01	10.45^{a} ± 0.00
TA (%)	0.26^{c} ± 0.03	0.48^{b} ± 0.03	0.53^{a} ± 0.01	0.25^{b} ± 0.02	0.48^{a} ± 0.04	0.51^{a} ± 0.02	0.34^{c} ± 0.02	0.51^{b} ± 0.08	0.65^{a} ± 0.08
DM (%)	7.76^{a} ± 1.18	7.94^{a} ± 0.73	8.99^{a} ± 0.64	8.35^{b} ± 0.42	9.92^{a} ± 0.3	9.95^{a} ± 0.61	10.18^{b} ± 0.66	10.93^{b} ± 0.76	12.44^{a} ± 0.26

Table 6. Mean values and standard deviation of identified and unknown VOCs calculated for each K level (n=4) within the three cultivars Lyterno F1, Primavera, and Yellow Submarine. Values below the limit of detection (LOD) were indicated. Letters indicate significant differences at $p<0.05$ between the K treatments. K1 low 0.5; K2 medium 2.19; and K3 optimal 3.66 g/plant.

VOCs	**Lyterno F1**			**Primavera**			**Yellow Submarine**		
Identified (%)	**K1**	**K2**	**K3**	**K1**	**K2**	**K3**	**K1**	**K2**	**K3**
hexanal	32.82^{a}± 4.93	19.86^{b} ± 6.19	19.46^{b} ± 2.47	40.29^{a} ± 7.47	40.47^{a} ± 1.55	39.24^{a} ± 1.72	27.27^{a} ± 2.64	26.72^{a} ± 2.45	27.38^{a} ± 1.28
(*E*)-2-hexenal	4.22^{a} ± 0.81	3.65^{ab} ± 0.32	3.01^{b} ± 0.39	8.08^{a} ± 3.73	6.67^{a} ± 1.85	7.01^{a} ± 1.47	9.12^{a} ± 2.73	10.76^{a} ± 3.01	9.89^{a} ± 3.08
octanal	5.26^{a} ± 0.82	4.04^{ab} ± 0.68	3.96^{b} ± 0.35	4.48^{a} ± 1.11	3.64^{a} ± 0.31	4.14^{a} ± 1.89	1.35^{a} ± 0.96	1.73^{a} ± 0.21	1.59^{a} ± 0.12
β-ionone	1.06^{a} ± 0.23	0.36^{b} ± 0.42	0.16^{b} ± 0.33	1.98^{a} ± 0.68	1.73^{a} ± 0.23	1.83^{a} ± 0.73	<LOD	<LOD	<LOD
β-cyclocitral	0.67^{a} ± 0.45	0.15^{a} ± 0.3	0.20^{a} ± 0.4	1.91^{a} ± 0.59	1.52^{a} ± 0.27	1.05^{a} ± 0.7	<LOD	<LOD	<LOD
(*Z*)-3-hexen-1-ol	0.42^{a} ± 0.51	0.18^{a} ± 0.36	0.61^{a} ± 0.43	3.04^{a} ± 0.28	2.41^{a} ± 0.39	2.63^{a} ± 0.57	0.38^{a} ± 0.47	0.57^{a} ± 0.66	0.81^{a} ± 0.71
linalool	0.67^{a} ± 0.45	0.77^{a} ± 0.55	0.57^{a} ± 0.75	0.41^{a} ± 0.47	0.27^{a} ± 0.32	0.25^{a} ± 0.29	1.23^{a} ± 0.42	1.67^{a} ± 0.84	1.46^{a} ± 0.6
2-isobutylthiazole	17.11^{a} ± 3.49	27.28^{a} ± 7.23	27.77^{a} ± 7.61	11.57^{a} ± 1.59	11.49^{a} ± 1.53	11.30^{a} ± 2.25	24.43^{a} ± 3.21	22.64^{a} ± 4.97	23.58^{a} ± 4.01
eugenol	0.48^{a} ± 0.39	0.47^{a} ± 0.4	0.77^{a} ± 0.47	1.18^{a} ± 0.94	0.77^{a} ± 0.82	0.88^{a} ± 1.07	0.22^{a} ± 0.25	0.38^{a} ± 0.25	0.36^{a} ± 0.04
1-hexanol	<LOD	<LOD	<LOD	1.7^{a} ± 0.28	1.63^{a} ± 0.39	1.34^{a} ± 0.97	0.19^{a} ± 0.39	0.43^{a} ± 0.51	0.51^{a} ± 0.44
β-damascenone	0.31^{a} ± 0.36	0.86^{a} ± 0.77	0.66^{a} ± 1.11	0.86^{a} ± 1.05	0.64^{a} ± 0.81	0.68^{a} ± 0.78	0.75^{a} ± 0.67	1.50^{a} ± 1.09	1.71^{a} ± 1.17
(*E*)-geranylacetone	10.19^{a} ± 1.99	8.05^{a} ± 2.2	6.98^{a} ± 1.29	4.58^{a} ± 1.83	6.32^{a} ± 1.69	5.94^{a} ± 0.75	<LOD	<LOD	<LOD
6-methyl-5-hepten-2-one	19.93^{a} ± 4.22	28.05^{a} ± 4.62	28.71^{a} ± 5.83	14.39^{a} ± 5.3	17.67^{a} ± 1.58	16.72^{a} ± 5.78	27.59^{a} ± 2.93	23.84^{a} ± 3.69	23.25^{a} ± 2.84
benzaldehyde	2.84^{a} ± 0.79	1.82^{a} ± 0.59	2.51^{a} ± 1.01	3.07^{a} ± 0.85	1.99^{a} ± 0.64	4.29^{a} ± 5.21	6.62^{a} ± 6.52	7.37^{a} ± 5.54	7.00^{a} ± 2.18
citral	3.81^{a} ± 1.39	3.20^{a} ± 1.17	3.09^{a} ± 1.29	2.25^{a} ± 1.14	2.83^{a} ± 0.61	2.29^{a} ± 0.93	<LOD	<LOD	<LOD
methylsalicylate	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD	0.54^{a} ± 0.36	0.80^{a} ± 0.62	1.07^{a} ± 0.34
unknown (%)	18.98^{a} ± 1.88	17.45^{a} ± 3.05	15.55^{a} ± 3.22	22.91^{a} ± 3.73	20.38^{a} ± 4.71	22.26^{a} ± 12.27	23.29^{a} ± 7.55	22.44^{a} ± 7.46	17.85^{a} ± 1.66

Table 7. Mean values and standard deviation of the sensory evaluation calculated for each K level (n=4) within the three cultivars Lyterno F1, Primavera, and Yellow Submarine. 0 % refers to minimum intensity and 100 % to maximum intensity. Tomato-typical taste was not determined (n.d.) for Yellow Submarine and spiciness was not determined for Lyterno F1 and Primavera. Letters indicate significant differences at $p<0.05$ between the K treatments. K1 low 0.5; K2 medium 2.19; and K3 optimal 3.66 g/plant.

Sensory Descriptors (%)	**Lyterno F1**			**Primavera**			**Yellow Submarine**		
	K1	**K2**	**K3**	**K1**	**K2**	**K3**	**K1**	**K2**	**K3**
Color intensity	63.5^{a} ± 12.1	64.2^{a} ± 12.2	64.8^{a} ± 12.7	55.9^{b} ± 12.1	73.2^{a} ± 12.9	73.3^{a} ± 15.3	58.9^{a} ± 11.7	60.5^{a} ± 11.4	58.4^{a} ± 8.4
Odor intensity	39.0^{a} ± 15.5	43.1^{a} ± 17.5	42.6^{a} ± 18.3	49.2^{a} ± 14.6	53.3^{a} ± 13.5	52.5^{a} ± 10.9	52.0^{a} ± 18.9	53.7^{a} ± 16.4	53.8^{a} ± 14.8
Juiciness	67.5^{a} ± 13.9	66.1^{a} ± 15.2	64.7^{a} ± 16.11	78.8^{a} ± 14.1	78.2^{a} ± 14.1	77.5^{a} ± 12.9	72.1^{a} ± 14.5	75.0^{a} ± 14.4	74.7^{a} ± 12.9
Skin strength	56.8^{a} ± 15.7	59.3^{a} ± 14.7	62.4^{a} ± 18.5	58.9^{a} ± 12.5	56.9^{ab} ± 12.5	51.6^{b} ± 10.4	56.7^{b} ± 13.0	55.5^{b} ± 13.1	65.1^{a} ± 12.6
Sweetness	15.1^{a} ± 12.9	13.6^{a} ± 11.7	12.5^{a} ± 8.1	33.9^{b} ± 15.5	40.0^{ab} ± 15.6	43.7^{a} ± 16.9	50.7^{b} ± 17.1	57.2^{ab} ± 15.7	59.7^{a} ± 13.4
Sourness	17.6^{a} ± 12.5	20.4^{a} ± 14.4	21.9^{a} ± 13.1	16.3^{b} ± 12.3	25.2^{a} ± 11.8	28.4^{a} ± 15.3	20.3^{b} ± 13.0	29.3^{a} ± 14.1	35.3^{a} ± 13.8
Bitterness	8.2^{a} ± 9.7	7.1^{a} ± 8.1	8.8^{a} ± 11.3	10.1^{a} ± 12.8	7.0^{a} ± 8.7	6.3^{a} ± 6.1	9.87^{a} ± 11.5	9.06^{a} ± 9.7	12.35^{a} ± 14.7
Spiciness	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	46.01^{b} ± 17.8	53.7^{ab} ± 18.8	57.4^{a} ± 17.2
Tomato-typical aroma	32.7^{a} ± 18.3	32.0^{a} ± 17.5	37.6^{a} ± 17.3	36.6^{b} ± 14.4	52.9^{a} ± 14.6	56.2^{a} ± 14.2	n.d.	n.d.	n.d.
Aftertaste	31.7^{a} ± 14.0	35.7^{a} ± 15.1	36.4^{a} ± 15.5	39.0^{a} ± 16.8	42.8^{a} ± 14.0	44.3^{a} ± 13.5	43.2^{a} ± 14.4	46.7^{a} ± 13.1	49.3^{a} ± 14.4

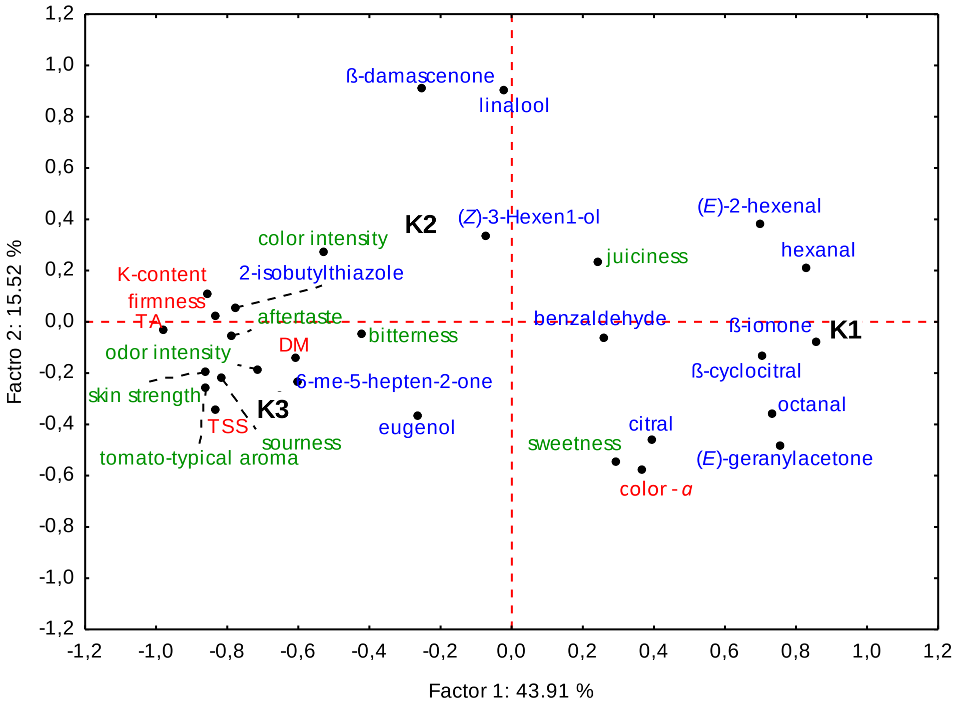

Figure 14. Principal component analysis (PCA) of the sensory evaluation (green), metric data (red), and VOCs (blue) for mature fruits of cv. **Lyterno F1** with K supply as an independent variable. K1: 0.5, K2: 2.19, and K3: 3.66 g/plant weekly K dose, TA: titratable acidity, TSS: total soluble solids. Color intensity: estimated by the panelists. Color – a: measured by Minolta Chroma-Meter.

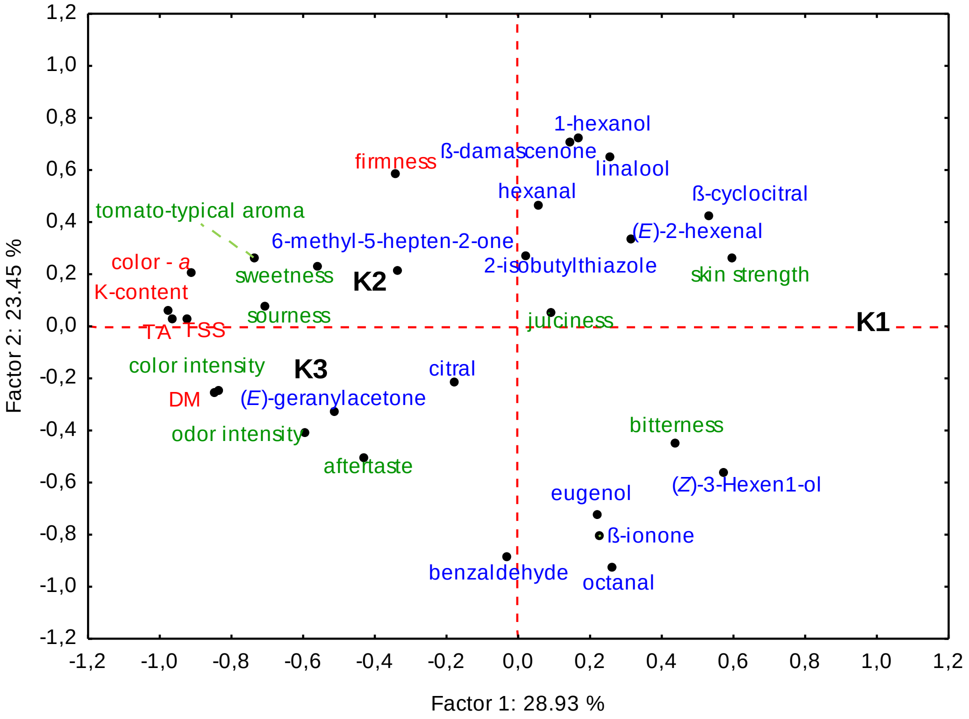

Figure 15. Principal component analysis (PCA) of the sensory evaluation (green), metric data (red), and VOCs (blue) for mature fruits of cv. **Primavera** with K fertilization as an independent variable. K1: 0.5, K2: 2.19, and K3: 3.66 g plant^{-1} weekly potassium fertilization dose, TA: titratable acidity, TSS: total soluble solids. Color intensity: estimated by the panelists. Color – a: measured by Minolta Chroma-Meter.

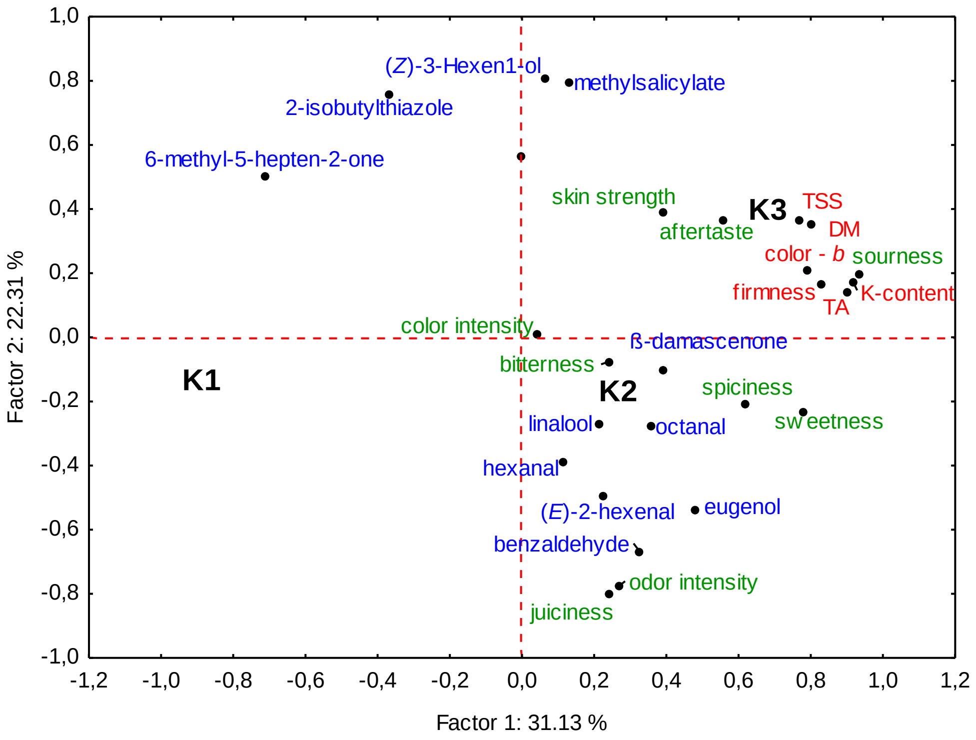

Figure 16. Principal component analysis (PCA) of the sensory evaluation (green), metric data (red), and the VOCs (blue) for mature fruits of cv. **Yellow Submarine** with K fertilization as an independent variable. K1: 0.5, K2: 2.19, and K3: 3.66 g plant^{-1} weekly potassium fertilization dose, TA: titratable acidity, TSS: total soluble solids. Color intensity: estimated by the panelists. Color – b: measured by Minolta Chroma-Meter.

Discussion

In the present study, the effects of different K applications on the instrumental as well as the sensory descriptors on three different cultivars were investigated. In all cultivars, increasing K fertilization to the optimal level significantly ameliorated the K concentrations in the fruits (Table 5). This confirmed our outcomes in the previous research (30), in which the fruit's content of K and the yield of the cocktail tomatoes used in this study were significantly increased by K fertilization. As a major macronutrient, the plants manage to maintain K concentrations in a specific range even under deficient K conditions (12). A constant limitation of K nutrition, however, leads to a decrease in K concentrations; in contrast, sufficient K application increases K concentrations (15), which was confirmed by our results as well (Table 5).

Effect of K Fertilization on Instrumental and Sensory determined Color

The color is the most important external property for the evaluation of tomato fruits (31). In our study, a positive significant effect of K fertilization was exhibited (Table 5 and 7) and compatible results were found between the red color intensity and the instrumental analyzed red color measurement in Primavera. In Lyterno F1 as well, the panelists confirmed the instrumental analyzed color measurement, in which no significant effect of K supply was revealed. Fertilization of K has a positive effect on the color intensity, as has been demonstrated by several researches (e.g. 3,15). Arias et al. (2000) (32) demonstrated high significant correlations between carotenoids content in tomato and color – *a* and color – *b*, such that in this context, a positive increment of K fertilization on lycopene and phytoene in tomato was confirmed (19).

In Yellow Submarine, the sensory analysis of color intensity showed no significant effect of K, which contradicted the instrumental analyzed color evaluation. Yellow tomatoes are not as widely common as the red ones, and one can presume that the panelists in this matter were not be able to differentiate between the yellow color intensity among K fertilization levels, because of their slight experience of yellow tomato consumption. In line with this, the assessor effect on results of sensory descriptor color was proven to be significant for all cultivars (Table A9), indicating a higher variation between the panelists' evaluation compared to the samples derived of different K fertilizer levels.

All in all, the instrumental and the sensory color attribute affected by K fertilization was cultivar-dependent, as the K fertilization significantly increased the instrumental analyzed color in the cocktail cultivars, while in the salad cultivar, no significant effect was detected. Accordingly, several studies pointed out the remarkable cultivar effect on color values under K application (e.g. 15,17).

The instrumental analyzed color did not correlate with the color intensity of sensory results and also Csambalik et al. (2014) (33) did not find that as well in their study on cherry tomatoes.

Effect of K Fertilization on Volatile Organic Compounds and Sensory Determined Aroma

The VOCs were analyzed by GC-FID to gain deeper insights into the possible changes in the aroma of tomato fruits by differing K supply. In combination with the instrumental analysis of VOCs, the odor intensity as a sensory descriptor was estimated by panelists. Of all the VOCs determined, only four were influenced significantly—although negatively—by K application in the salad cultivar 'Lyterno F1'.

The volatile compounds in tomatoes are derived from secondary metabolites such as fatty acids, phenolics, amino acids, and carotenoids (23). Hexanal and (*E*)-2-hexanal, which are being formed from the degradation of fatty acids, showed a significant decrease with increasing K fertilization in Lyterno F1. That could have been caused by the changes in the peroxidation of the fatty acids under stress conditions (K deficiency), as was observed by Wang et al. (2013) (34). In addition, these compounds are classified as green leafy volatiles as they have the fresh aroma of cut grass (35). Presumably, under sufficient K supply, the fruits developed to the full ripe stage better than under K-deficiency and lessened the green grass odor; as was stated, K provokes early maturity of fruits (36).

Similarly, ß-ionone—derived from the apocarotenoids (23)—decreased significantly by K supply but only in Lyterno F1. Apocarotenoids are derived from carotenoids by oxidative cleavage. The cleavage of carotenoid induces rapidly under stress conditions when a non-enzymatic process catalyzed by reactive oxygen species (37). Taking this into account, the studied plants were exposed to stress conditions represented by K deficiency (K1), and, thus, the production of ß-ionone increased in Lyterno F1 at deficient K supply. The cultivar effect was evident for the VOCs, which was confirmed by Wang et al. (2018) (38) and Kanski et al. (2020) (22), as they found differences in aroma profile among different tomato cultivars.

Odor intensity correlated in a significantly positive manner with ß-ionone, (*E*)-2-hexenal, and benzaldehyde. Vogel et al. (2010) (39) pointed out that ß-ionone has fruity and floral perceptions, which can be positively associated with the acceptability of tomato flavor. The significant correlation of (*E*)-2-hexenal with odor intensity is in agreement with Baldwin et al. (1998) (40), as they found a high positive significant correlation ($r = 0.62^{**}$) between (*E*)-2-hexenal and the overall aroma intensity in seven tomato salad cultivars. Benzaldehyde is described as having a peach-like/fruitiness perception (41,42), and it belongs to the group of phenolic volatiles in tomato fruits (23). In our study, benzaldehyde correlated in a significantly positive manner with odor intensity. Baldwin et al., (2015) (41) also found a positive significant correlation of benzaldehyde with tomato flavor along a seven-year study with 38 tomato cultivars.

Effect of K Fertilization on Instrumental and Sensory Determined Texture

With the sense of touch, either when the product is picked up by hand or gets bitten off in the mouth and is chewed, the textural parameters of vegetables and fruits can be perceived. Physiologically, the texture of fruits and vegetables is derived from their turgor pressure, and the combination of individual plant cell walls and the middle lamella, which holds the cells together (43). In this context, it has been stated that K supply can result in an enhancement of the tissue firmness (15,44) by increasing the osmotic potential as a result of the increment of cytosolic K and the accumulation of photosynthetic assimilates (14).

Instrumental determined firmness increased with optimal K dose (K3) in Lyterno F1 and Yellow Submarine. Accordingly, the sensory descriptor skin strength rose significantly in Yellow Submarine and showed a similar—although not significant—trend in Lyterno F1. However, we observed the opposite effect in Primavera (Table 3). Consequently, the results of Javaria et al. (2012) (16) and Tavallali et al. (2017) (17) could be confirmed by our findings that the positive effect of K on the tissues firmness and skin strength was partly revealed. The instrumental determined firmness and the sensory parameter skin strength are highly positive correlated (0.42^{**}). Hence, the effect of K fertilization on the texture in this study has been confirmed by instruments as well as by human senses. Thus, the second hypothesis—the effect of K fertilization on the sensory properties can be recognized by the human senses—can be demonstrated.

Juiciness is one of the most important sensory characteristics and a favorable attribute in most food products (meat, fruits, and vegetables). It is highly correlated to the texture of the plant tissues, in which the juiciness is associated with the cell turgor (43). K has been pointed out to be essential to cell turgor and the accumulation of photosynthetic products into the plant cell (46). Nonetheless, our results exhibited no significant effect of K on juiciness. Chaïb et al., (2007) (47) stated that the firmest tomato fruits with a strengthened skin were less juicy. Accordingly, juiciness correlated in a significantly negative manner with firmness and skin strength in the salad tomato (Lyterno F1). It has to be considered that the descriptor juiciness was elaborated by the sensory panel to distinguish juicy fruits from other fruits with less juiciness and more granular dry tissues. It can be assumed—based on the evaluation of the panel—that fruits of salad cultivars appeared to have a generally more granular tissue than those of cocktail cultivars.

The cultivar effect was also noticeable for the instrumental determined firmness (Tables 5 and 7). Our results confirm that the texture is a complex attribute, which can be affected highly by the genetic background of the cultivars (47).

Effect of K Fertilization on Instrumental and Sensory determined Taste

The taste of tomatoes is mainly derived from reducing sugars, organic acids, and bitter compounds. However, as it is abundant in relatively high concentrations, the higher impact is related to sugar (2.6 g 100 g/FM) (48,49). Many studies have demonstrated that rising K supply increases the contents of sugar and organic acids (e.g. 15,52). In line with this, K dose exhibited a positive significant impact on TSS and TA contents in the three cultivars (Table 1). Likewise, the sensorial sweetness and sourness increased significantly with high K fertilization, though only in Primavera and Yellow Submarine, but not in Lyterno F1 (Table 5). In this context, Kanski et al., (2020) (22) found in their study on three tomato cultivars and two breeding lines that TSS and TA as well sweetness and sourness were highly influenced by the genetic background of the cultivars.

Taking into account the correlations between the instrumental and sensorial attributes, TSS and TA correlated highly positive with sweetness (0.81^{**}) and sourness (0.76^{**}) respectively. Therefore, the outcomes of Kanski et al. (2020) (22) could be confirmed by our findings, as they proved a high positive correlation between TSS and sweetness as well as between TA and sourness.

Apart from TSS and TA, DM is considered to exert a strong influence on tomato taste as it is correlated positively with sugars like fructose and glucose (22,51). The positive effect of K was stated to increase DM in tomato fruits (16,52), which is because of the function of K in translocating and accumulating the assimilated 'sugar' in the cytosol (11). We were able to prove these previous findings, as we showed that increasing the supply of K increased the DM values in the cocktail cultivars but not in the salad one. Here, the water content in the cells and the type of the cultivar have a prominent effect on DM content (6). Interestingly, DM correlated in a significantly positive manner not just with TSS ($r = 0.95^{**}$) and TA ($r = 0.63^{**}$) but also with sweetness ($r = 0.79^{**}$) and sourness ($r = 0.63^{**}$), which could lead to a new approach to enhance cocktail tomato taste under sufficient K fertilization.

The bitter taste is desirable in some products like coffee and beer (21). However, the bitter taste in tomato is not much of a favorite as far as consumers are concerned (53). Interestingly, the sensory evaluation in the present study exhibited no significant increment of K supply on the bitterness. The sweet compounds have been reported to restrain the bitter taste (6), which is compatible with our findings in Primavera, in which K can increase sweet taste and reduce bitter taste. Moreover, bitterness had neither positive nor negative significant correlations with any instrumental analyzed or sensorial attributes.

Effect of K Fertilization on Retronasal Attributes (Aroma)

Tomato flavor is defined by several studies as a complex impression caused by sugar content, organic acids, bitter compounds, and volatile compounds precepted retronasally (22,41,54). In our study, the descriptors tomato-typical aroma and aftertaste correlated in a significantly positive manner with TSS ($r = 0.76^{**}$), TA ($r = 0.46^{**}$), sweetness ($r = 0.71^{**}$), and sourness ($r = 0.68^{**}$), which are in line with the previous studies of Baldwin et al. (2015) (41) and Kanski et al. (2020) (22). The positive correlations between TSS, sweetness and aroma intensity found in the present study are also in accordance with the findings made in the case of strawberries (55,56). However, tomato-typical aroma correlated positively with odor intensity but negatively with hexanal and (*E*)-2-hexenal. This was surprising; hexanal and (*E*)-2-hexenal together comprised a high percentage (in Lyterno F1: 22–37 %, in Primavera: 36–48 %) of the known detected VOCs, and were expected to be associated with tomato-typical aroma. Rambla et al. (2014) (23) reported that the VOCs—hexanal and (*E*)-2-hexenal—have the most abundant volatile compounds produced in tomato fruits. Nevertheless, the influence of these compounds on tomato flavor has been a matter of discussion. Some researchers observed a diminution in the effect of these compounds on tomato flavor and no effect on consumer liking (8,57). In our findings, these two compounds were decreased with rising K fertilization and seem not to contribute to the tomato-typical aroma (Table 5A). Instead, the sugar and acid content seemed to be more relevant for this descriptor.

It was a consensus of the panel that the tomato-typical aroma could be attributed to Lyterno F1 and Primavera, while the flavor of Yellow Submarine was different. Tomato-typical aroma did not match the flavor of the yellow cultivar. Moreover, the panel described Yellow Submarine as having a spicy flavored fruit.

Increasing K supply resulted in a significant increase in the descriptor spiciness in Yellow Submarine. Some VOCs mainly characterize the spiciness in tomato puree (58)—for instance, 4-methyl-1,5-heptadiene and 6-methyl-3,5-heptadien-2-one. In our study, however, these substances were not detected. Among the determined VOCs, eugenol was stated to be associated with the smoky aroma in fresh tomato fruits (59). It was supposed that the attribute spiciness described by the panelists in this research is closely related to the attribute smoky. Nonetheless, eugenol did not significantly correlated to the spiciness as it was found by Tikunov et al. (2013) (59). The reason for this finding might be the effect of K on eugenol,because K fertilization was reported to increase eugenol concentrations (60), which was consistent with our results. Remarkably, the panelists were able to detect the positive increment of optimal K fertilization on tomato-typical aroma and spiciness; this can enhance the possibilities of a new approach in increasing tomato flavor with rising K application.

Conclusion

In this study, the effect of K on instrumental determined and sensory traits could be demonstrated. In this context, the following conclusions are drawn: (i) Optimal K application—3.66 g/plant—increased the instrumental analyzed attributes and some of the sensory descriptors, such as sweetness, sourness, and tomato-typical aroma. Nevertheless, it did not significantly increase the identified VOCs. (ii) The panelists were able to distinguish between the three K fertilization levels with the human senses, as confirmed by the instrumental analyses. (iii) Sugars (sweetness and TSS), acids (sourness and TA), and aroma attributes (odor intensity, hexanal, and (*E*)-2-hexenal) were positively associated with tomato-typical aroma and aftertaste. The cultivar background had a fundamental influence on both instrumental analyzed and sensory attributes and, finally, on tomato flavor. In this study, cocktail cultivars—Primavera and Yellow Submarine—exhibited higher aftertaste and tomato-typical aroma compared to salad cultivar Lyterno F1. Consequently, optimal K supply—3.66 g/plant—could be suggested to increase tomato flavor in the studied cocktail cultivars. The flavor of the tomato is a complex perception and is affected by many factors from seed-sowing to the harvest, which needs further investigations to elucidate it comprehensively.

5. General discussion

Among many factors influencing tomato plants, optimized plant nutrition is an essential factor that has a crucial impact on plant growth and fruits quality (Sainju et al. 2003). Knowledge regarding effect of excessive K fertilization on water use efficiency (WUE), fruits quality, and mineral composition is limited. The effect of K combined with B fertilization on fruits postharvest behavior is not so far studied. Moreover, sensory profile combined with instrumental analyses influenced by K fertilization was rarely pointed out. Therefore, effect of various K fertilizations on tomato was investigated in this study and the outcomes are discussed following.

Effect of K on Yield and Water Use Efficiency

Tomato yield being positively affected by different K fertilizations was markedly studied (e.g. Bidari and Hebsur 2011; Hartz et al. 2005; Mazed et al. 2015). However, the excessive effect of K on marketable yield is not clear, some investigations reported no significant effect on total yield (e.g. Ozores-Hampton et al. 2012; Taber et al. 2008). Therefore, different K levels from deficient to excessive were applied to two cocktail cultivars – Primavera and Yellow Submarine. The marketable yield per plant increased in Primavera with rising K until the optimum supply of K4 (Figure 3). While, in Yellow Submarine the marketable yield was the highest at the excessive supply of K6 (Figure 3). This is likely due to the variations between the studied cultivars – Primavera produces more fruits per plant about 60 fruits per growing season, while Yellow Submarine produces only around 40 fruits per growing season. Both cultivars can grow to a maximum height of 180 cm; however, the fruit weights differ, that is, up to 25 and 20 g per fruit for Primavera and Yellow Submarine respectively (Bio Tomatenpflanze 2018). Additionally, Primavera produced higher biomass compared to Yellow Submarine (Annex, Figure A4), which can also be another reason for the differences in marketable yield with regard to K application. Higher biomass can result in increased yield as reported by Koch et al. (2018) in potato tubers yield. In this context, Afzal et al. (2015)

reported variations in fruit yield of two different medium sized tomato cultivars treated with excessive K fertilizations.

The WUE increased with rising K fertilization levels. However, the response to K supply with regard to WUE varied between the cultivars. The maximum WUE was at optimal K supply (K4) in Primavera, while Yellow Submarine showed the highest WUE at the excessive supply of K (K6) (Figure 2). The WUE is strongly affected by weather conditions, cultivation systems, and crop diversity (Abbate et al. 2004). As both cultivars have different morphological characteristics, that might account for these alterations with regards to WUE.

Effect of K on the Nutritional Composition of Fruits

The content of TSS and TA is associated to the sweet and sour taste of tomatoes (Beckles 2012), which are major contributors to the overall flavor. Three cultivars - one salad; Lyterno and two cocktails; Yellow Submarine and Primavera were grown in 2016 for fruits nutritional analyses, while only the cocktail cultivars were analyzed in 2017. The fruits content of TSS, TA, and DM ameliorated with K application in the two experimental years (Chapter 2 and 4). In 2016, TSS, TA, and DM were higher in Yellow Submarine and Primavera compared to Lyterno (Table 5). That is likely due to the dilution effect in the salad cultivars as they have higher water content compared to cocktail cultivars (Pascual et al. 2013). Additionally, cocktail cultivars have higher TSS content compared to salad cultivars (Gautier et al. 2010; Luengwilai et al. 2010). Here, Yellow Submarine recorded the highest content of TSS, TA, and DM and a significant increase with K supply in both years 2016 and 2017. While Primavera responded positively with rising K only in 2016 regarding TSS, TA, and DM content. That is presumably, due to the different environmental conditions e.g. temperature and light between the two years, as TSS and TA content are highly influenced by those conditions (Beckles 2012).

Fruit mineral composition showed higher content of K, Mg, P, Fe, and Zn with increasing K supply in Yellow Submarine compared to Primavera (Table 1). In this case, the accumulation of these minerals in Yellow Submarine was noteworthy higher, and the application of K stimulates higher uptake of those minerals. It has been reported that K uptake varies amongst plant species as a result of differences in their root structures (Nieves-Cordones et al. 2014). In this study, root structures were not estimated, however, there were varied concentrations of K in the fruits of both cultivars.

Effect of K and B Fertilization on Fruits Postharvest Behavior

The interaction effect of K and B on tomato has been studied (Huang and Snapp 2009); however, in this study, the effect was evaluated on postharvest behavior. The fruits were evaluated under two different factor effects; K and B interaction and different storage temperatures. Antagonism between K and B rarely occurs during plants' uptake, as K is needed in larger amounts compared to B, as well as K transporters in the plants are specific and cannot be blocked by any other nutrients (Horie et al. 2011; White 2012). However, in this study, optimal K combined with low B application exhibited the highest contents in the determined attributes in both cultivars and storage conditions. In refrigerated + ambient conditions, the function of K mitigating the negative effect of cold stress on the fruits was notable especially in putrescine. In this context, many studies have reported that sufficient K is considered to decrease reactive oxygen species load of chilling-stressed plants (e.g. Cakmak 2005; Zörb et al. 2014). The effect of storage temperature on the fruits was higher compared to the effect of K and B, that in ambient conditions (20 °C) the fruits developed higher color intensity, DM, and lower LFM. The content of TSS and TA did not vary between the two storage conditions, and that is probably due to the positive effect of K on TSS and TA content during cold storage (Constán-Aguilar et al. 2014). The stored fruits in refrigerated + ambient conditions lost less fresh matter compared to the fruits stored in ambient conditions. Here, the function of K diminishing these losses was not remarkable as was suggested by Constán-Aguilar et al. (2014). Additionally, metabolite processes are usually suppressed in lower temperatures (Mutari and Debbie

2011). The cultivar effect was noteworthy on the fruits' behavior in postharvest storage. The content of K in Yellow Submarine fruits was slightly higher compared to Primavera, which led indirectly to a considerable development in fruit quality formation. Yellow Submarine fruits produced more TSS, TA, and DM, and less CI and LFM, which qualifies this cultivar for postharvest practice and handling compared to Primavera.

Effect of K on Sensory Profile of Tomato

Knowledge regarding sensory evaluation under conditions of K fertilization is incomplete. In this study, three different tomatoes were used; cocktail cultivars - Primavera and Yellow Submarine and salad cultivar - Lyterno that were fertilized by three levels of K nutrition. The sensory evaluation showed that the cocktail tomatoes recorded the maximum values from the panelists' perspectives (Table 7). This is likely due to that consumers prefer small to medium sized tomato therefore consumption of cocktail tomatoes is higher compared to salad cultivars (Causse et al. 2010). Yellow Submarine was rated the highest in sweetness, sourness, odor intensity, and spiciness as well as showed highest TSS, TA, and DM content. In this context, a good flavor of tomato is defined as having balanced concentrations of sweetness, sourness and aroma (Beckles 2012; Kader 2008). The application of K fertilization was perceptible by the panelists as they could detect the increment in taste of fruits treated by optimal K supply. However, this was not exposed in Lyterno F1, the salad cultivar, which is likely due to the dilution effect as it has low DM compared to the cocktail tomatoes (Table 5). Due to recent consumer complaints and dissatisfaction of poor flavored tomatoes, offering them good flavored cultivars is a priority of producers (Piombino et al. 2013). Therefore, enhancing tomato flavor, in addition to ensuring higher yields and longer shelf life after harvest, are important aspects to consider in tomato (Kader 2008).

Conclusion

Excessive K fertilization decreased marketable yield and conversely increased unmarketable yield. The excessive K supply negatively influenced fruits quality e.g. TSS, TA, DM, which are indirectly affecting the marketable yield. Likewise, deficient supply of K decreased marketable yield, WUE, and nutritional composition of the fruits e.g. TSS, TA, DM, and minerals e.g. K, Mg, Fe, Zn. Consequently, using excessive K fertilization cannot generate acceptable marketable yield, less usage of water, or better fruits quality but it leads to a waste in K fertilization resources.

Fruit quality formation during postharvest period decreased at K and B deficiency level, with stronger influence of K compared to B supply. The LFM, CI, and FA were not affected by the application of K and B, while TSS, TA, and DM increased with high K but not B supply. Only PUT content decreased with rising supply of K fertilization, this is indicative of the role of K inhibiting the negative effect of cold stress. The combination of B and K fertilization did not improve the behavior of the fruits during the postharvest period as hypothesized; rather, the dominant effect was shown by the K application. Nevertheless, it would be interesting to further investigate the effect of B on fruit quality during storage, including the type of B application.

The application of K fertilization has been shown to influence the sensory and the instrumental analyzed attributes as well. Sweetness, sourness, tomato-typical taste alongside TSS, TA, DM, and firmness were ameliorated with increasing K supply. The fertilization of K can enhance tomato flavor in cocktail cultivars.

Finally, the cultivar effect in this study was remarkable on the determined parameters. Yellow Submarine exhibited superiority in nutritional composition of the fruits, sensory evaluation, and considerable performance during postharvest period. However, it generated lower yield and was less efficient in water usage. Overall, in this research, the optimal application of K (3.66 – 4 g plant^{-1}) can contribute positively to tomato yield, postharvest behavior, and sensory profile. The two cocktail cultivars, Yellow Submarine and Primavera, showed positive response to K fertilization. Therefore, with optimal K fertilization, Primavera can be recommended for its high yield and water use efficiency, while Yellow Submarine can be suggested for its high fruit quality formation during postharvest period and acceptable flavor.

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Annex: Supplementary Materials

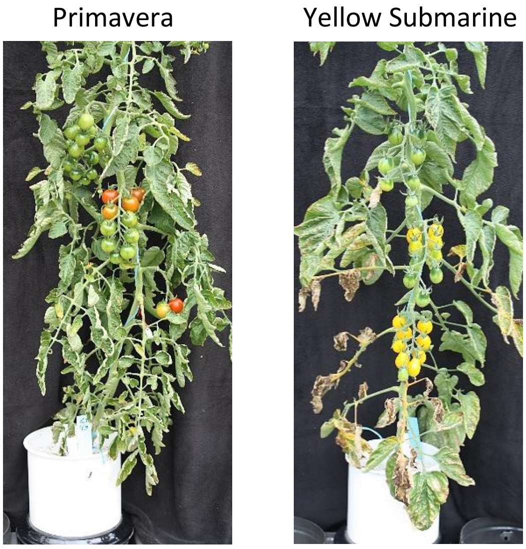

Figure A1. The habitus of the studied cultivars, Primavera and Yellow Submarine, in this present research.

Figure A2. The distribution of gauges (marked by arrows) between plants to estimate precipitation during the growing season.

Figure A3. The fruits in this study. (1) Healthy and intact marketable fruits; (2) BER symptoms; (3) Cracked fruits; and (4) Abnormal and small-size fruits.

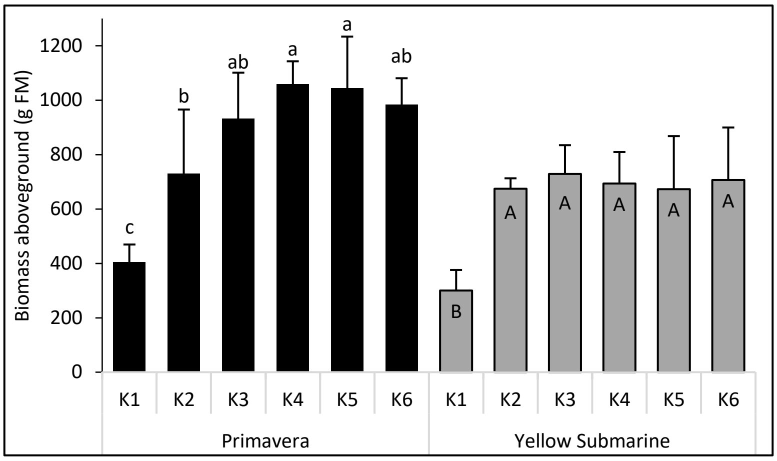

Figure A4. Biomass (stem + leaves) weight in the two cultivars. Values are means (n=6) with standard deviation on each bar. The significance level (5%) was chosen for identifying significant effects of K treatment according to Tukey's test. Lower case letters determine significant differences in Primavera. Capital letters identify significant differences in Yellow Submarine.

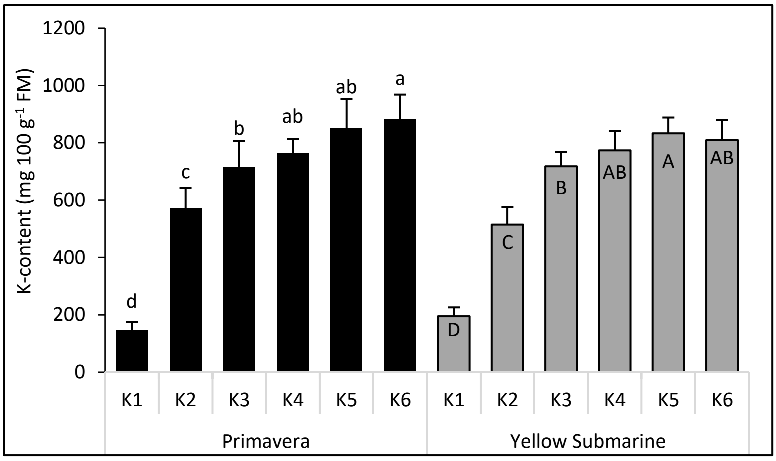

Figure A5. K concentrations in the biomass (stem + leaves) in the two cultivars. Values are means (n=6) with standard deviation on each bar. The significance level (5%) was chosen for identifying significant effects of K treatment according to Tukey's test. Lower case letters determine significant differences in Primavera. Capital letters identify significant differences in Yellow Submarine.

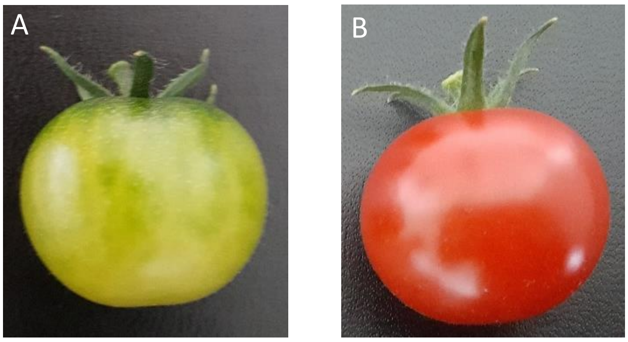

Figure A6. Maturity stage of used fruits -Primavera cultivar- in this study. (A) Fruit in breaker stage. (B) Fruit in full ripe stage.

Table A1. Application of fertilization during the growing season (May - September 2017) for the studied cultivars.

Fertilization	Chemical	g per plant	Application
N	$Ca(NO_3)_2 + NH_4NO_3$	9.22 + 1.56	weekly for levels K3 to K6, each second week for levels K1 and K2
	$(NH_4)_2SO_4$	2.32	Second week for levels K1 and K2 (to balance the Sulfate)
Mg	$MgSO_4•7H_2O$	19	Three times per growing season:
Fe	Fe-EDTA	0.71	- final transplanting 30.05.2017
Mixture of micronutrients	$MnCl_2•4H_2O + ZnSO_4•7H_2O + CuSO_4•5H_2O + Na_2MoO_4•2H_2O + H_3BO_3$	0.26 + 0.05 + 0.02 + 0.0005 + 0.21	- second time 20.07.2017 - third time 25.08.2017
P	$Ca(H_2PO_4)_2 •xH_2O$	17.70	one time at final transplanting
S	K_2SO_4 and $(NH_4)_2SO_4$	Sufficient supply by K and N fertilization	

Table A2. Precipitation (mm) during growing season (May - September 2017). DWD: German Weather Service.

Date	In exposed area	Under plants	DWD
03.06.	16.5	14.41	20.5
06.06.	5.3	4.9	4.3
16.06.	4	3.07	3.1
23.06.	32	29.91	36
29.06.	8.25	10.23	9.4
10.07.	34.35	25.55	16.7
12.07.	11.5	10.04	16.2
17.07.	17	12.31	6.5
19.07.	18	19.16	12.6
01.08.	15.25	17.65	13.2
16.08.	33.5	38.83	35.7
26.08.	31.25	22.83	23
12.09.	8	7.16	7.6
28.09.	8.35	7.14	7
Total	243.25	223.19	211.8

Table A3. Number of fruits used from each cultivar for the conducted analyses; TSS: total soluble solids; TA: titratable acids and DM: dry matter.

Analyses	Primavera	Yellow Submarine
TSS, TA and DM	4 to 6	4 to 6
Minerals extraction	15 to 20	15 to 20
Color	35 to 40	35 to 40

Table A4. Application of fertilization during the growing season (May - September 2017) for the studied cultivars.

Fertilization	Chemical	g per plant	Application
N	$Ca(NO_3)_2 + NH_4NO_3$	9.22 + 1.56	weekly for levels K2-B and K2+B, each second week for levels K1-B and K1+B
	$(NH_4)_2SO_4$	2.32	Second week for levels K1-B and K1+B (to balance the Sulfate)
Mg	$MgSO_4•7H_2O$	19	Three times per growing season:
Fe	Fe-EDTA	0.71	- final transplanting 30.05.2017
Mixture of micronutrients	$MnCl_2•4H_2O + ZnSO_4•7H_2O + CuSO_4•5H_2O + Na_2MoO_4•2H_2O$	0.26 + 0.05 + 0.02 + 0.0005	- second time 20.07.2017 - third time 25.08.2017
P	$Ca(H_2PO_4)_2 •xH_2O$	17.70	one time at final transplanting
S	K_2SO_4 and $(NH_4)_2SO_4$	Sufficient supply by K and N fertilization	

Table A5. Mean of the individual fatty acids FA content in both cultivars.

		Saturated FA (%)				Unsaturated FA (%)				
		C16-0	**C18-0**	**C20-0**	**C22-0**	**C16-1**	**C18-1**	**C18-2**	**C18-3**	**C20-1**
Primavera	**K1-B**	13.67	3.94	0.42	0.18	0.59	15.24	60.05	4.61	0.12
	K1+B	13.49	3.65	0.39	0.17	0.58	14.92	60.75	4.67	0.13
	K2-B	13.81	4.07	0.43	0.18	0.57	16.01	59.09	4.47	0.12
	K2+B	13.18	3.87	0.40	0.16	0.54	15.96	60.30	4.24	0.12
Yellow Submarine	**K1-B**	14.85	4.15	0.44	0.17	0.74	15.43	57.06	5.37	0.13
	K1+B	14.02	3.87	0.38	0.16	0.60	15.28	59.61	4.72	0.12
	K2-B	14.05	4.52	0.42	0.14	0.57	16.52	57.31	4.65	0.12
	K2+B	14.05	4.32	0.38	0.11	0.53	16.34	58.10	4.59	0.09

Table A6. Application of Fertilization during the growing season (May - September 2016) for the studied cultivars.

Fertilization	Chemical	g plant^{-1}	Application
K1	K_2SO_4	0.5	weekly
K2	K_2SO_4	2.19	weekly
K3	K_2SO_4	3.66	weekly
N	$Ca(NO_3)_2 + NH_4NO_3$	9.22 + 1.56	weekly for level K3, second week for levels K1 and K2
	$(NH_4)_2SO_4$	2.32	Second week for levels K1 and K2 (to balance the Sulfate)
Mg	$MgSO_4 \bullet 7H_2O$	19	Three times per growing season:
Fe	Fe-EDTA	0.71	-final transplanting 24.05.2016
Mixture of micronutrients	$MnCl_2 \bullet 4H_2O + ZnSO_4 \bullet 7H_2O + CuSO_4 \bullet 5H_2O + Na_2MoO_4 \bullet 2H_2O + H_3BO_3$	0.26 + 0.05 + 0.02 + 0.0005 + 0.21	-second time 16.07.2016 -third time 26.08.2016
P	$Ca(H_2PO_4)_2 \bullet xH_2O$	17.70	one time at final transplanting
S	K_2SO_4 and $(NH_4)_2SO_4$	Sufficient supply by K and N fertilization	

Table A7. Number of fruits used from each cultivar for the conducted analyses; TSS: total soluble solids; TA: titratable acids and DM: dry matter.

Conducted Analyses	Lyterno F1	Primavera	Yellow Submarine
o Sensory evaluation	4 to 6	12 to 24	12 to 24
o VOCs extraction	3 to 5	8 to 10	8 to 10
o Instrumental Analyses:			
TSS, TA, and DM	2 to 3	4 to 6	4 to 6
Firmness and minerals extraction	6 to 10	15 to 20	15 to 20
Color	15 to 20	35 to 40	35 to 40

Table A8. classification of descriptors according to the kind of sensory impression. The evaluation order was established by the panel and is not equal to order of the classification. Detailed information is given on the evaluation instructions for the panel.

Sensory impression	Order	Descriptor	Evaluation instructions
Appearance	1	color intensity	A self-made reference template with a color standard representing 50% color intensity either for red or for yellow fruits was used by the panelists. The evaluation was carried out on the fruit skin and not on the cross-sectional view of the fruit.
Smell (orthonasal olfactory impression)	2	odor intensity	Odor intensity is defined as the smell of the freshly sliced fruit.
Tactile or haptic impression	3	juiciness	The juiciness of the fruit is represented mainly by the mesocarp, placenta, and myxotesta (pulp and jelly) after biting in. These fruit parts had to be mixed by slight chewing. ʼWeakʻ is defined as a granular dry tissue. ʼStrongʻ is defined either crispy and fresh but watery tissue or a very soft and watery / liquid tissue of a ripe to overripe tomato.
	8	skin strength	ʼWeakʻ means that the peel is easily broken during chewing. ʼMediumʻ (50 %) means that a peel residue is clearly recognizable. ʼStrongʻ also means that a peel residue is clearly recognizable and moreover the peel appears to be very thick.
Taste (gustatory impression)	4	sweetness	For evaluating the taste, it was not differentiated between jelly and pulp. The fruit parts had to be mixed by slight chewing. To compare with samples, the reference fruits were provided with a defined sweetness and sourness. Sweetness was calculated based on the total soluble solids that were measured with a refractometer in advance, while sourness was calculated based on the titratable acidity.
	5	sourness	without instruction
	6	bitterness	without instruction
Retronasal smell (aroma)	7a	spiciness	A spicy-like aroma was recognized only for yellow-fruited cultivars. The panel was trained with a yellow-fruited cultivar (cultivar Yellow Nugget) from a local supermarket set as a standard for this descriptor. The instruction was to taste the standard each day before starting the evaluation of samples.
	7b	tomato-typical aroma	The tomato-typical aroma was recognized only for red-fruited cultivars. The panel was trained with a red-fruited cocktail tomato cultivar (biologically produced date tomato, cultivar unknown) from a local supermarket set as a standard for this descriptor. The instruction was to taste the standard each day before starting the evaluation of samples.
Aftertaste	9	aftertaste	The intensity of aftertaste was evaluated half a minute after swallowing.

Table A9. 2-Way ANOVA of sensory data showing the main effects of assessor and sample deriving of K fertilization level and the interaction of factors assessor*sample. F-values are displayed, and the significance value is indicated by asterisks (*, **, *** significant at p ≤ 0.05, 0.01, 0.001; n.d. not determined).

	Lyterno F1			**Primavera**			**Yellow Submarine**		
Sensory descriptor	**Assessor**	**Sample**	**Assessor*sample**	**Assessor**	**Sample**	**Assessor*sample**	**Assessor**	**Sample**	**Assessor*sample**
Color intensity	12.81***	0.24	1.36	5.41***	26.41***	1.76*	7.49***	1.33	0.39
Odor intensity	18.06***	1.8	0.97	8.55***	2.38	0.84	22.88***	0.5	0.99
Juiciness	10.71***	0.7	1.12	28.37***	0.37	1.26	84.73***	5.79**	0.32
Skin strength	5.73***	2.02	0.85	5.86***	6.26**	1.18	3.56**	7.23**	1.61
Sweetness	6.87***	0.62	2.82***	8.37***	6.33**	1.32	4.63**	3.77*	2.13**
Sourness	12.15***	2.22	1.17	4.44**	8.49**	2.6***	7.36***	17.97***	1.56
Bitterness	8.85***	0.68	0.87	7.97***	1.94	5.43***	9.82***	1.4	1.41
Tomato-typical aroma	30.6***	4.79*	0.97	8.29***	28.37***	2.53***	n.d.	n.d.	n.d.
Spiciness	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	21.26***	12.31***	1.22
Aftertaste	39.59***	6.19**	0.62	11.31***	2.15	2.51***	28.24***	8.68**	0.56

Table A10. Pearson correlations between the studied attributes.

	color Intensity	odor intensity	juiciness	skin strength	sweetness	sourness	bitterness	spiciness	tomato-typical aroma	aftertaste
odor intensity	0.04	1.000								
juiciness	0.16	0.58**	1.000							
skin strength	-0.28*	-0.08	-0.327*	1.000						
sweetness	-0.15	0.79**	0.496**	-0.060	1.000					
sourness	0.17	0.52**	0.197	0.140	0.564**	1.000				
bitterness	-0.26	0.14	0.147	0.392**	0.234	0.198	1.000			
spiciness	-0.51	0.17	0.046	0.366	0.298	0.409	0.395	1.000		
tomato-typical aroma	0.44*	0.76**	0.540**	-0.109	0.824**	0.686**	-0.045	n.d.	1.000	
aftertaste	0,23	0.69**	0.453**	-0.001	0.712**	0.682**	0.257	-0.210	0.529**	1.000
K_content	0.42**	0.23	-0.070	0.145	0.114	0.686**	-0.047	0.487	0.501**	0.331*
color_a	0.23	-0.62**	-0.691**	0.052	-0.640**	0.042	-0.250	n.d.	-0.249	-0.436*
color_b	0.45	0.027	0.115	0.287	0.652*	0.811**	0.171	0.277	n.d.	0.736**
firmness	0.06	-0.522**	-0.579**	0.422**	-0.636**	-0.040	0.015	0.376	-0.386*	-0.335*
TSS	0.09	0.672**	0.268	0.133	0.808**	0.743**	0.102	0.321	0.828**	0.758**
TA	0.23	0.360*	-0.044	0.302*	0.282	0.759**	0.038	0.484	0.512**	0.457**
DM	0.01	0.644**	0.230	0.172	0.785**	0.631**	0.117	0.293	0.740**	0.734**
hexanal	0.21	0.293*	0.620**	-0.480**	0,259	-0.056	-0.223	-0.329	0.436*	0.224
(*E*)-2-hexenal	-0.34	0.642**	0.436**	-0,183	0.745**	0.374*	0.036	0.199	0.477**	0.433**
octanal	0.28	-0.481**	-0.069	-0,082	-0.669**	-0.468**	-0.050	0.410	-0.431*	-0.534**
6-methyl-5-hepten-2-one	-0,23	-0.181	-0.618**	0.425**	-0.132	0.025	0.211	-0.231	-0,280	-0,057
(*Z*)-3-hexen-1-ol	0.28	0.297*	0.516**	-0.180	0.173	-0.044	-0.067	-0.207	0.522**	0,238
isobutylthiazole_2	-0.19	-0.285*	-0.545**	0.435**	-0.172	0.116	0.089	-0.337	-0.361*	0,004
benzaldehyde	-0.05	0.397**	0.382*	-0.081	0.495**	0.312*	0.373	0.461	-0.116	0.422**
linalool	-0.44*	0.188	-0,131	0.058	0.349*	0.190	-0.007	0.370	-0.290	0,138
citral	-0.17	-0.316	-0.431*	0.044	-0,337	-0.255	0.228	n.d.	-0.329	-0,311
ß-damascenone	-0.26	0.194	0.077	0.030	0.276	0.263	-0.189	0.364	0.093	0,134
(*E*)-geranylacetone	0.04	-0.575**	-0.556**	-0.219	-0.527**	-0.324	-0.197	n.d.	-0.49**	-0.489**
ß-ionone	0.11	0.568**	0.589**	-0.536**	0.701**	-0.019	0.126	n.d.	0.31	0.356*
eugenol	0.21	0.179	0.238	0.040	-0.123	-0.044	0.197	0.333	0.13	0.088
ß-cyclocitral	-0.67	-0,192	-0.156	0.760**	0.072	-0.491	0.241	n.d.	-0.08	-0.698**
1-hexanol	0.27	-0.393*	0.285	0.003	-0.531**	-0.287	-0.239	-0.187	0.075	-0.297
methylsalicylate	0.03	-0.41	-0.577*	0.064	-0.313	0.361	-0.253	-0.272	n.d.	0.523*

Table A10. Continue

	K_content	color_a	color_b	Firmness	TSS	TA	DM	hexanal	(*E*)-2-hexenal	octanal	6-methyl-5-hepten-2-one	(*Z*)-3-hexen-1-ol
color_a	0.407*	1.000										
color_b	0.666*	n.d.	1.000									
Firmness	0.281	0.701**	0.616*	1.000								
TSS	0.489**	-0.238	0.681*	-0.304*	1.000							
TA	0.886**	0.372*	0.679*	0.285*	0.676**	1.000						
DM	0.392**	-0.226	0.625*	-0.267	0.955**	0.627**	1.000					
hexanal	-0.285*	-0.620**	0.163	-0.670**	0.023	-0.334*	-0.047	1.000				
(*E*)-2-hexenal	-0.028	-0.635**	-0.077	-0.544**	0.568**	0.150	0.566**	0.278	1.000			
octanal	-0.204	0.004	0.011	0.139	-0.637**	-0.364*	-0.622**	0.131	-0.578**	1.000		
6-methyl-5-hepten-2-one	0.264	0.571**	-0.477	0.478**	-0.014	0.243	0.024	-0.821**	-0.293*	-0.326*	1.000	
(*Z*)-3-hexen-1-ol	-0.102	-0.855**	0.154	-0.533**	0.099	-0.183	0.045	0.729**	0.086	0.296*	-0.654**	1.000
2-isobutylthiazole_2	0.196	0.601**	0.081	0.632**	0.079	0.302*	0.142	-0.837**	-0.187	-0.349*	0.615**	-0.676**
benzaldehyde	-0.022	-0.175	0.060	-0.216	0.416**	0.164	0.446**	-0.053	0.347*	-0.165	-0.149	-0.151
linalool	0.086	0.235	-0.004	0.045	0.270	0.241	0.359*	-0.273	0.602**	-0.633**	0.252	-0.476**
citral	-0.021	0.342	n.d.	0.155	-0.377*	-0.100	-0.333	-0.399*	-0.615**	0.305	0.661**	-0.467*
ß_damascenone	0.223	-0.081	0.116	-0.037	0.272	0.336*	0.296*	-0.002	0.622**	-0.471**	-0.060	-0.122
(*E*)-geranylacetone	-0.066	0.664**	n.d.	0.296	-0.456*	-0.162	-0.410*	-0.419*	-0.608**	0.462*	0.397*	-0.645**
ß-ionone	-0.281	-0.699**	n.d.	-0.858**	0.327	-0.334	0.309	0.697**	0.601**	0.346*	-0.634**	0.800**
eugenol	-0.131	-0.369*	0.379	-0.037	-0.103	-0.097	-0.095	0.257	-0.025	0.492**	-0.482**	0.442**
ß-cyclocitral	-0.454	-0.472	n.d.	0.086	-0.443	-0.494	-0.421	-0.242	0.190	-0.192	0.359	0.153
1-hexanol	-0.044	-0.082	0.311	-0.267	-0.411*	-0.284	-0.519**	0.691**	-0.548**	0.431*	-0.384*	0.772**
methylsalicylate	0.438	n.d.	0.183	0.480	0.281	0.198	0.300	-0.150	-0.186	-0.286	0.198	0.786**

Table A10. Continue

	2-isobutylthiazole	benzaldehyde	linalool	citral	ß_damascenone	(*E*)-geranylacetone	ß_ionone	eugenol	ß_cyclocitral	1-hexanol
benzaldehyde	-0.012	1.000								
linalool	0.316*	0.193	1.000							
citral	0.018	-0.225	-0.220	1.000						
ß_damascenone	0.076	-0.004	0.812**	-0.546**	1.000					
(*E*)-geranylacetone	0.212	0.011	-0.130	0.658**	-0.447*	1.000				
ß-ionone	-0.830**	0.392*	-0.356*	-0.085	-0.160	-0.260	1.000			
eugenol	-0.263	0.117	-0.431**	-0.317	-0.353*	-0.255	0.366*	1.000		
ß-cyclocitral	0.271	-0.715**	0.238	0.226	0.124	-0.272	-0.008	-0.454	1.000	
1-hexanol	-0.620**	-0.631**	-0.648**	0.208	-0.234	-0.137	-0.630*	-0.044	0.619*	1.000
methylsalicylate	0.543*	-0.667*	-0.087	n.d.	0.071	n.d.	n.d.	0.438	n.d.	0.752**

Summary

Tomato (*Solanum lycopersicon* L.) is the most important vegetable in the world consumption and production. The fruits significantly contribute to human health, as they are rich in vitamins, minerals, sugars and antioxidants. Therefore, the high demand on tomato fruits consumption as fresh and processed products necessitates yield increase. However, the focus on yield increase does not consider the fruit's flavor and might dissatisfy the consumers. Most of the consumers store tomatoes after purchasing in household fridge, which decreases the quality and the flavor of these fruits. Nevertheless, an application of particular cultivation management such as optimized plant nutrition could enhance fruit yield and quality. Potassium (K), as one of the essential mineral plant nutrients, is crucially involved in tomato production and fruits quality and has the potential to ameliorate them. It also has a major role in plant-water-relations, e.g. on water-use efficiency WUE. The objectives of the present study were to evaluate the effect of K on the yield production, postharvest behavior, and sensory profile of different tomato cultivars.

The effect of K on yield and water-use efficiency (WUE) was investigated in an outdoor pot experiment with two cocktail tomato cultivars Primavera and Yellow Submarine and six K levels from deficiency to overdose. To study the fruit postharvest behavior, another outdoor pot experiment was conducted with two K levels (K low and K high) and two boron (B) levels (B low and B high) on the same cultivars. The breaker fruits were stored at two different conditions: ambient conditions (20 °C) and refrigerated + ambient conditions (4 °C + 20 °C). In a third outdoor pot experiment, the effect of K on the sensory profile of the fruits was studied at three different K levels (named as K low, K moderate and K high) on three tomato cultivars as Lyterno, Primavera and Yellow Submarine. The sensory evaluation was performed by panelists and subsequently, the taste-related analyses were assessed.

The yield and WUE increased significantly with rising K but they were declined with K overdose. Similarly, the fruit quality attributes as color, total soluble solids (TSS), titratable acids (TA) and dry matter (DM) increased significantly with K application but further supply to overdose did not reveal any enhancement. The effect of K on the fruit's postharvest behavior exposed as a significant increase in TSS, TA and DM in both storage regimes. Boron did not show any significant increase on the studied parameters in this experiment. Potassium had a significant influence on the taste-related attributes and some of the sensory traits but not on fruit volatile compounds.

Generally, optimal K application enhanced the yield, WUE and the fruit quality attributes, while excessive K application did not possess a significant increment effect. The combination of high K and low B fertilization improved the fruit quality performance only under ambient storage conditions. The positive effect of K on the fruits sensory profile was confirmed to be detectable by the human senses as well as with the instrumental analyses.

The conclusions drawn from this study are: that an optimal application of K fertilization on tomato ensures high yields with less water consumption moreover enhances the fruit quality attributes. The adequate application of K on tomato plants reinforces the development process during postharvest of the fruits, which influence positively on the fruit quality under storage conditions. Furthermore, K is important to enhance the flavor of tomato fruits and meet the consumer's preferences. The present study indicates that potassium nutrition is one of many factors that can influence tomato growth and its potential to enhance yield, fruit quality and WUE essentially depends on all factors' integration.

List of papers and manuscripts

Subsequent manuscripts of the present cumulative doctoral thesis are published or Submitted:

1. **Different potassium fertilization levels influence water-use efficiency, yield, and fruit quality attributes of cocktail tomato—A comparative study of deficient-to-excessive supply.**
   By: Bashar Daoud, Elke Pawelzik, and Marcel Naumann
   Published: The journal Scientia Horticulturae, 15 October 2020; 272, 109562.
   https://doi.org/10.1016/j.scienta.2020.109562

2. **Assessment of sensory profile and instrumental analyzed attributes influenced by different potassium fertilization levels in three tomato cultivars.**
   By: Bashar Daoud, Marcel Naumann, Detlef Ulrich, Elke Pawelzik, and Inga Smit
   Submitted: The journal of the Science of Food and Agriculture, February 2021

List of Further publications

Posters

- Frontiers of Potassium Science, Rome January 2017

  Impact of potassium on the abundance and distribution of antioxidants in tomato fruits

  by Bashar Daoud, Frederike Wenig, Elke Pawelzik, and Inga Smit

- 18th International Plant Nutrition Colloquium, Copenhagen 2017

  Effect of potassium nutrition on the sensory profile of tomato

  by Bashar Daoud, Elke Pawelzik, and Inga Smit

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Declaration

1. I, hereby, declare that this Ph.D. dissertation has not been presented to any other examining body either in its present or a similar form.

   Furthermore, I also affirm that I have not applied for a Ph.D. at any other higher school of education.

   Göttingen, ...

   ....

   Bashar Daoud

2. I, hereby, solemnly declare that this dissertation was undertaken independently and without any unauthorized aid.

   Göttingen, ...

   ....

   Bashar Daoud