The Influence of Rootstock on Fruit Ethylene, Respiration, Index of Absorbance Difference, Fruit Quality, and Production of ‘Aztec Fuji’ Apple under a Full-crop Condition

Shahla Mahdavi and Esmaeil Fallahi

Department of Plant Sciences, Pomology and Viticulture Program, Parma Research and Extension Center, University of Idaho, Parma, ID 83660

Gennaro Fazio

Department of Horticulture, Cornell University Geneva, NY 14456

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Abstract. Selection of dwarfing rootstocks that facilitate optimum production of high-quality fruit is crucial in modern high-density apple orchards. In addition to tree growth and yield, rootstocks can influence fruit maturity of scion cultivars in apples. In this study, the impact of 17 rootstocks on fruit maturity, yield, and quality attributes of ‘Aztec Fuji’ apples (*Malus domestica* Borkh.) at harvest were evaluated in a season when all trees were in a “full-crop” condition. Keeping sealed fruit at room temperature, a typical climacteric pattern was observed in ethylene evolution, respiration, and oxygen consumption, peaking after 5–7 days in fruit from trees on all rootstocks. During the ripening period, ethylene evolution and respiration rates in fruit from trees on Supp.3, G.3001, and G.202 were often in the high-range category, whereas those on CG.4004, CG.4214, G.41N, and B.9 were in the midrange category and those on M.9Pajam2, M.26EMLA, and G.11 were in the low-range category. Evolved ethylene and respiration in fruit from trees on M.9T337 steadily and slowly increased from 7 days after harvest (7DAH) to 13 days after which harvest (13DAH) ethylene sharply increased, signaling occurrence of climacteric peak, while respiration declined after the peak of 13DAH. In fruit from trees on most rootstocks, the rates of oxygen consumption had inverse relationships with the rates of respiration, so that fruit from trees on M.9T337 had higher and those on G.41N and Supp.3 had lower rates of oxygen consumption. Trees on G.41N, CG.4004, and M.26EMLA had higher and those on CG.4003 had lower yield per tree than trees on other rootstocks. Trees on B.9 and M.9T337 were most yield efficient among trees on all rootstocks. Trees on CG.4004 had larger fruits than those on other rootstocks. Considering all fruit maturity, quality, and yield attributes, CG.4004 seems to be a good choice of rootstock for ‘Aztec Fuji’ under the conditions of this study.

Autio et al. (2020) evaluated the performance of ‘Aztec Fuji’ apple trees on Budagovsky, Geneva, Pillnitz, and Mallington rootstocks over 8 years and reported that trees on Supp.3 (22%), M.9 NAKBT337 (21%), M.9Pajam2 (19%), B.71-7-22 (19%), and

M.26EMLA (16%) had highest mortalities among all rootstocks tested. They also reported that CG.4004, CG.3001, CG.5222 (G.222), and M.26EMLA produced moderate semi dwarf trees. Based on their results, trees on CG.4004, CG.3001, and CG.5222 displayed the highest yield efficiency and yield per tree for that size category. In their report, trees on G.935N and G.935TC were the most yield efficient and G.935N had the highest cumulative yield per hectare for the large dwarf category. Moderate dwarf rootstocks were CG.4214 (G.214), M.9 NAKBT337, G.11, G.202N, B.10, G.41TC, and Supp.3. In this size category, trees on CG.4214, M.9 NAKBT337, G.11, and B.10 were the most yield efficient and had the highest potential yield per hectare. The trees in small dwarf size category included CG.2034, B.9, and CG.4003 and had similarly yield efficient and projected per hectare yields. In the report by

Autio et al. (2020), B.71-7-22 was classified as sub-dwarf rootstock and produced ‘Aztec Fuji’ trees with high yield efficiency and relatively low projected per hectare yield.

Robinson and Hoying (2011) reported that ‘Honeycrisp’ apple trees on CG.4004 rootstock were significantly more yield efficient, but similar in size to those on M.7. They reported that in the large dwarf category, trees on G.935N performed the best as assessed by yield efficiency. Based on other reports of NC-140 trial, trees on G.935N performed similarly or better than those on M.26EMLA (Autio et al., 2011, 2013; Marini et al., 2014). Robinson et al. (2011) found 7-year-old ‘Golden Delicious’ apple trees on G.11 were more yield efficient than those on M.26 and that 6-year-old ‘Honeycrisp’ trees on G.11 were similarly yield efficient to those on M.9. They reported that trees on CG.4003, B.9, CG.5087, and CG.2034 were the most yield efficient in the small dwarf category and 7-year-old ‘Golden Delicious’ trees on CG.5087 were more yield efficient than those on M.26. They also reported that 6-year-old ‘Honeycrisp’ trees on CG.2034, CG.4003, and B.9 were similarly yield efficient but less efficient than trees on M.9.

Fallahi et al. (1985a, 1985b, 1985c, 1985d) intensively evaluated the influence of six rootstocks (Seedling, M.1, Mallington 106, M.7, OAR 1, and M.26) and fertilizers on ‘Starkspur Golden Delicious’ apple on yield, fruit quality, internal and evolved ethylene during maturation and storage. They revealed that fruit from trees on OAR-1 rootstock had a lower trend of internal ethylene production in the orchard and evolved ethylene after storage (Fallahi et al., 1985a), better color and higher soluble solids concentration and firmness (Fallahi et al., 1985b), whereas fruits from trees on M.26EMLA had the highest internal ethylene (Fallahi et al., 1985a). They reported that field sampling of internal ethylene was an unreliable indicator of predicting harvest time maturity because of variable impact of rootstock and the effects of low field temperature in reducing internal ethylene levels (Fallahi et al., 1985a). Apple rootstocks have also been found to significantly modify internal hormone levels in xylem sap of grafted scions (Lordan et al., 2017), which may in turn set fruit tissues up for different physiological behavior with regards to quality attributes.

Hayat et al. (2019) evaluated the effects of Baleng, Chistock-1, M.26, and M.9 rootstocks on morphological and biochemical changes in ‘Red Fuji’ apples. They reported that morphological and biochemical parameters such as lower plant height, lower mineral nutrient concentrations [phosphorous (P), potassium (K), magnesium (Mg), zinc (Zn), and copper (Cu)], specific hormonal ratios and higher starch content can be considered as preferable indices for the selection of dwarfing apple rootstocks and these characteristics were found in M.9 rootstock. Some dwarfing rootstocks including B.9, M.9, and M.26 were also categorized in the “low” category for boron (B) absorption and transfer to

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grafted scions such as ‘Fuji’ and ‘Honeycrisp’ over multiple years and field trials indicating a rootstock genotype specific influence on mineral nutrient level concentration in grafted scions (Fazio et al., 2015, 2020; Reig et al., 2018). The report by Hayat et al. (2019), to some extent, agrees with earlier reports where fruit quality attributes in the ‘Stark Spur Golden Delicious’ apple fruit on OAR-1 rootstock was superior to those on other rootstocks (Fallahi et al., 1985b), because of their lower nitrogen concentrations (Fallahi et al., 1984).

Important quality attributes in apples include fruit size, flavor, texture, color, shape, and nutritional values (Weiyan et al., 2020). Many quality attributes such as firmness, color, sugar, and volatiles in climacteric fruits are affected by their internal ethylene evolution and/or are interrelated among each other (Bergougnoux, 2014; Bi et al., 2019; Defilippi et al., 2005; Fallahi et al., 1985a, 1985b, 1985c, 1985d; Gunther et al., 2015; Yang et al., 2016).

In climacteric fruit like apple, fruit ripening is controlled by internal ethylene concentration (IEC) (Costa et al., 2005). Hulme et al. (1965) suggested that because of the increased activity of malic enzyme (L-malate NADP oxidoreductase) and carboxylase (2-oxo-acid decarboxylase), the increased CO₂ production of apple fruit occurs just before the onset of visible ripening and called this phase climacteric respiration. Also, Yang and Hoffman (1984) reported two enzymes that are involved in rate limiting step of the pathway leading to the production of ethylene intermediate ACC (ACS; 1-aminocyclopropane-1-carboxylic acid) and ethylene forming enzyme (ACO; 1-aminocyclopropane-1-carboxylase oxidase) which is involved in the conversion of ACC to ethylene.

The index of absorbance difference (I_{AD}) is an indicator that is based on the close relationship between the degradation of chlorophyll and the maturity of the fruit, which is determined by the difference between the absorption at 670 and 720 nm using near-infrared spectroscopy. It directly reflects the actual content of chlorophyll (Ziosi et al., 2008). Although the nondestructive measurement of I_{AD} is not harmful to fruit, the reading is convenient and reliable, and it is more desired than the destructive assays, such as firmness and soluble solids concentration (SSC) (Zhang et al., 2017). Currently, I_{AD} predication has been used on some fruit trees, such as peach (Bonora et al., 2013; Gonçalves et al., 2016; Lurie et al., 2013; Shinya et al., 2013; Zhang et al., 2017), nectarines (Gonçalves et al., 2016), plum (Infante et al., 2011), apples (Anthony et al., 2019), and pears (Goke et al., 2020; Zhang et al., 2016). Research by Gonçalves et al. (2016) on seven peach and five nectarine varieties found a very significant linear regression relationship between I_{AD} values and fruit firmness, which varied according to cultivar while not showing any significant relationship between the I_{AD} value and fruit SSC. Research by Lurie et al. (2013) on both early and late maturity peach varieties, based on measuring I_{AD} at

harvest, reported a nonlinear regression analysis of the change in firmness during shelf time, and established a logistic model of firmness change that could be used to separate peaches in groups with different potential shelf life.

The effects of several rootstocks on performance of ‘Fuji’ apple trees and related fruit quality have been investigated in multiple locations in North America as part of a regional project (NC-140, 1996) aimed at studying rootstock performance and effects on fruit production over several years. However, there is limited information about rootstock effects on maturity of ‘Aztec Fuji’ apples. Thus, our objective in this study was to examine the influence of different rootstocks on apples harvested from ‘Aztec Fuji’ apple scion with regards to I_{AD}, ethylene evolution, respiration, yield, quality, and maturity attributes at harvest. We chose to conduct this study only over the 2020 growing season rather than multiple seasons because trees on all rootstocks had a full-crop load during 2020, and these crops were similar to the long-term averages that were reported in our recent report by Autio et al. (2020). Based on the experience of authors, when crop load of a tree represents a long-term average, ethylene, quality, and maturity attributes of the tree in that year should also represent those of the long-term averages.

Materials and Methods

Orchard establishment and general cultural practices. The experimental trees were planted at 1.8 × 4.27 m spacing on a north-south orientation and trained into tall spindle (Robinson and Hoying, 2011) on a sandy loam soil with an approximate pH of 7.3 at the Parma Research and Extension Center, University of Idaho, Parma, ID (lat. 43.7853° N, long. 116.9422° W) in Apr. 2010. The experimental site was a semiarid climate with an annual precipitation of approx. 297 mm. Climate conditions of this experimental site were similar to those in the Pacific Northwest (Washington State University, 2021).

The orchard ground was prepared and fumigated with Toluene 3 at a rate of 468 L·ha⁻¹ in Fall 2009. General orchard cultural practices such as irrigation and thinning were reported in a different study elsewhere (Fallahi et al., 2018).

Total nitrogen of 60 g/tree as UAN 32 (urea and ammonium nitrate, 32% N) was applied through the driplines. Each year, two fertigation of 30 g/tree N were made: one in late-May and the second one 2 weeks later. Potassium (K) was applied as 30 g K/tree as potassium oxide, via fertigation, once a year in late-May. Phosphorous, as monoammonium phosphate (61% P₂O₅), was applied at the rate of 150 g of formulation to each tree-planting hole, only once at the time of planting. Micronutrients, particularly, iron and zinc, were sprayed twice in spring and once in early summer each year. Calcium (Ca) was sprayed three times with cover sprays during spring every year.

Rootstock treatments. ‘Aztec Fuji’ trees on 17 rootstocks including two named clones from the Budagovsky series (B.9, B.10), four named Cornell-Geneva clones [Geneva[®] 11 (G.11), Geneva[®] 41 (G.41N), Geneva[®] 202 (G.202N), and Geneva[®] 935 (G.935N)], seven unreleased Cornell-Geneva clones (CG.2034, CG. 3001, CG.4003, CG.4004, CG.4214, CG.4814, and CG.5222), one named clone from the Pillnitz series (Supp.3) and three Malling series clones to serve as controls (M.9Pajam2, M.26EMLA, and M.9T337). Additionally, there were three rootstocks produced in the nursery stool-bed, denoted with an N following the rootstock name. These rootstocks included G.41N, G.202N, and G.935N (C & O Nursery, Wenatchee, WA).

‘Snow Drift’ crab apple (*Malus* × ‘Snow-drift’) on M.26EMLA rootstock (C & O Nursery, Wenatchee, WA) was interplanted in each row as a pollinizer after every 10th ‘Aztec Fuji’ tree.

Yield and fruit weight attributes. For evaluating quality and yield, 36 fruits per tree were randomly sampled from each tree on 18 Oct. 2020. Yield and quality attributes were measured according to the procedures described by Fallahi et al. (2020).

Ethylene, respiration, and oxygen measurements. For measuring internal ripening gases, fruit were stored in perforated plastic bags in a regular atmosphere storage at 0 °C. The measurements of evolved ethylene, respiration, and oxygen started 1 week after harvest and continued every other day for a total of six times, until post climacteric curves were reached. Four apples from each replication were randomly picked, incubated in a plastic bag (Zipper bags; GLAD, Ontario, Canada), with 26.8 × 27.3 cm dimension, and sealed with a strong packing tape and kept at room temperature (20 °C). Evolved gases were measured once every other day from 25 Oct. 2020 to 4 Nov. 2020 (7DAH to 17DAH, respectively). We collected 30 mL gas at a flow rate of 80 mL per min from inside of the sealed bags with apples, using a syringe and suction tube in a trigger mode setting (according to the instruction provided by company) and transferred the contents into a Felix Gas Analyzer (Model 940; Felix Instrument, Camas, WA).

The evolved ethylene were measured on mg·L⁻¹ basis and then converted to μL·kg·h⁻¹ and respiration was measured based on the percentage of carbon dioxide (CO₂) and converted to mL·kg·h⁻¹. Also, the amount of oxygen consumption was measured and reported based on percentage of oxygen (O₂) in the sealed bags.

Measuring Index of absorbance difference. The relative pericarp chlorophyll content as an indicator of maturity progression of the fruit was measured with a DA meter. This instrument nondestructively measures the index of absorbance difference (as I_{AD}) of two wavelengths of light between 670 and 720 nm within the range of 0 to 2.2, using the following formula: absorbance difference (I_{AD}) = (A_{670 nm} - A_{720 nm}) (Sinteleia,

Fig. 1. Amount of ethylene evolution ($\mu\text{L}\cdot\text{kg}^{-1}\cdot\text{h}^{-1}$) in 'Aztec Fuji' apples on different rootstocks from Oct. 25 to 4 Nov. 2020 (7DAH to 17DAH).

Bologna, Italy). The I_{AD} value of 2.2 represents green, and 0 represents complete maturity (Zhang et al., 2017; Ziosi et al., 2008). The I_{AD} values of three spots on each apple fruit were read with a DA meter and averaged to have one number for that fruit in each replication (total of four fruit and thus four I_{AD} values per replication).

Experimental designs and statistics. The experimental design was a randomized complete block design with 17 rootstocks and four single-tree blocks. Trees of each rootstock in each block were arranged according to the NC-140 protocol (www.NC140.org). Analyses of variance were conducted using SAS and JMP Pro 15 (SAS Institute, Cary, NC), with general linear model and means were compared by least significant difference at $P \leq 0.05$. Rootstock genotype means were used in multivariate analysis to generate two-way similarity cluster diagrams based on genotype similarity and variable similarity. The Ward's minimum variance criterion was used. Rootstock genotype data were also used to calculate correlation coefficients among variables.

Results and Discussion

General trends of ripening gases and their relations with I_{AD} . Evolved ethylene in bagged fruit increased with time and followed a climacteric peak pattern over the measuring period of 25 Oct. to 4 Nov. 4 (7DAH to 17DAH). Evolved ethylene concentrations in fruit from trees on all rootstocks were at minimum levels on Oct. 27 (9DAH) but reached their climacteric peak between 27 Oct. and 2 Nov. 2 (9DAH and 15DAH) and started to decline then after (Fig. 1).

At second measurement (27 Oct., 9DAH), respiration rates in fruit from trees on all rootstocks were at a minimum and reached their climacteric peaks on Oct. 31 (13DAH) and declined then after (Fig. 2). It has been reported that the increased respiration of apple fruit occurs just before the onset of visible ripening (the respiration climacteric) (Hulme et al., 1965). Based on this study, it seems that fruit from trees on all rootstocks reached their climacteric peak as indicated by their evolved ethylene and respiration. However, the rate of evolved ethylene and respiration during this period varied among rootstocks.

The rates of oxygen in fruit from trees on all rootstocks were at their highest levels at the time of bagging (25 Oct. 2020, 7DAH). These rates declined between the bagging date and climacteric peak, as respiration levels increased. The decline of oxygen during this period is due to the consumption of oxygen for respiration. However, after reaching climacteric peaks, oxygen levels in fruits from trees on most rootstocks started to increase as respiration declined (Figs. 2 and 3). This increasing trend could be because green skins of apple fruit may still be photosynthetically active and fix CO_2 and produce oxygen. Photosynthesis by the skin of these apples may have existed during the preclimacteric period. However, since most of the produced oxygen, together with the available oxygen in the bags were being used for the production of CO_2 , oxygen rates were declining during the preclimacteric period. After climacteric peak, there was no extra demand for oxygen for CO_2 production and thus oxygen levels increased.

Fruit absorbance difference also had significantly strong linear regressions with ethylene

evolution and respiration at the climacteric peak or ripening point, when values over all rootstocks were pooled (Figs. 4 and 5). Regardless of rootstock, high negative correlations existed between fruit absorbance difference (I_{DA}) values at harvest with evolved ethylene and respiration rates during 9DAH to 17DAH (Table 1). Fruit I_{AD} values also had significantly negative correlation with water core incidence (Table 1), which is an indication of over maturity. Further studies are needed to fine-tune these relationships (I_{AD} -ethylene and I_{AD} -respiration) for each scion-rootstock combination and under each climate condition. These estimations provide an excellent, inexpensive, and nondestructive tool for making postharvest management decisions such as time of shipping and approximate shelf life of 'Aztec Fuji' apple fruits based on I_{AD} values.

Rootstock impacts on evolved ethylene, respiration and oxygen. During the ripening period, ethylene evolution and respiration rates in fruit from trees on Supp.3, G.3001, and G.202N were often in high ranges but those on CG.4004, CG.4214, G.41N, and B.9 were in midranges category and those on M.9Pajam2, M.26EMLA, and G.11 were in low ranges (Figs. 1, 2, and 7). Averaging all values revealed that 'Aztec Fuji' fruit from trees on Supp.3 had maximum and Geneva 935N, Geneva 3001 and M.9T337 had minimum amount of average respiration as compared with all other rootstocks. The low levels of evolved ethylene in fruit from trees on M.26EMLA was not consistent with Fallahi et al. (1985a) report, where 'Starkspur Golden Delicious' apple on M.26EMLA had highest fruit evolved ethylene when six rootstocks were compared. In that report, trees on M.26EMLA had lower yield and larger fruit

Fig. 2. Amount of respiration ($\text{mL}\cdot\text{kg}^{-1}\cdot\text{h}^{-1}$) in 'Aztec Fuji' apples on different rootstocks from Oct. 25 to 4 Nov. 2020 (7DAH to 17DAH).

that contributed to their higher ethylene (Fallahi et al., 1985a). An interesting correlation between rootstock induced mean evolved ethylene and percent water core (Fig. 6) which is consistent with the observation by Autio et al. (1996) that rootstocks had an effect on both maturity (ethylene production) and water core formation.

Evolved ethylene and respiration in the fruit from trees on M9.T337 increased steady

and slowly from 25 Oct. to 31 Oct. (7DAH to 13DAH), after which ethylene sharply increased, signaling occurrence of climacteric peak, while respiration declined after the peak of 31 Oct. (13DAH) (Figs. 1 and 2).

In fruit from trees on most rootstocks, the net oxygen consumption concentration had inverse relationships with the rates of respiration, so that fruit from trees on M9.T337 had

higher but those on G.41N and Supp.3 had lower rates of oxygen (Fig. 3). 'Aztec Fuji' fruit on Geneva 41N and CG.5222 had minimum and M.9T337 had maximum oxygen rate compared with those in all other rootstocks (Fig. 3).

Fruit absorbance difference, firmness, and their relations. Fruit from trees on M.9Pajam2, G.11, M.9T337, CG.2034, and M.26EMLA

Fig. 3. Amount of oxygen (%) in 'Aztec Fuji' apples on different rootstocks from Oct. 25 to 4 Nov. 2020 (7DAH to 17DAH).

Fig. 4. Linear regression between index of absorbance difference (I_{AD}) and evolved ethylene at the time of climacteric peak of 'Aztec Fuji' apple on 17 rootstocks at harvest.

had higher than 1.10, whereas those on CG.5222, Supp.3, CG.3001, G.935N, G.41N, CG.4814, and G.202N had 0.87 or lower DA indices (I_{AD}) at harvest (Table 2).

Fruits in trees on CG.4214, CG.2034, G.11, Supp.3, CG.4814, and CG.4003 rootstocks, with a firmness value of at least 80 N were among firmer, whereas those on G.41N and CG.3001 rootstocks, with firmness values lower than 75 N, were among the softest fruit at harvest in this study (Table 2).

In fruit from several rootstocks such as G.41N, CG.3001, G.935N, and CG.5222, both I_{AD} and firmness were lower than other rootstocks at harvest (Table 2). Also, fruits from trees on G.11 and CG.4003 had both high I_{AD}

and firmness values at harvest (Table 2). Thus, the correlations between I_{AD} and fruit firmness in these rootstocks were highly positive. The positive relationship between fruit I_{AD} and firmness in this portion of our study is consistent with previous reports in peach and nectarine cultivars (Goncalves et al., 2016; Zhang et al., 2017). Therefore, in these rootstocks, I_{AD} values can be used in place of firmness measurements, after predictive regression equations between I_{AD} and firmness are developed for each cultivar/rootstock combination. It seems that a DA meter would provide a nondestructive, easier, and faster method for assessing fruit firmness and can ultimately replace a firmness tester.

Despite consistencies in the I_{AD} -firmness relationships in the cases mentioned previously, fruit from trees on Supp.3, had the lowest I_{AD} but highest firmness, whereas those on M.9Pajam2 had the highest I_{AD} but relatively lower firmness than those on several other rootstocks (Table 2). Inconsistent patterns between fruit firmness and I_{AD} among different rootstocks resulted in a weak overall correlation coefficient when values were pooled across all rootstocks (Table 1). A similar inconsistency was observed in early and late-maturing cultivars of peaches by Lurie et al. (2013) who reported that I_{AD} at harvest, had a nonlinear regression, and they established the logistic model between values of I_{AD} firmness changes.

Fig. 5. Linear regression between index of absorbance difference (I_{AD}) and respiration at the time of climacteric peak of 'Aztec Fuji' apple on 17 rootstocks at harvest.

Table 1. Correlation coefficient among maturity, yield, and quality attributes in ‘Aztec Fuji’ at harvest.

DA Harvest	vs.	9DAH C ₂ H ₄	-0.71**	Firmness	vs.	9DAH C ₂ H ₄	-0.57**
DA Harvest	vs.	11DAH C ₂ H ₄	-0.88**	Firmness	vs.	9DAH CO ₂	-0.66**
DA Harvest	vs.	13DAH C ₂ H ₄	-0.83**	Firmness	vs.	% Russet	-0.42*
DA Harvest	vs.	15DAH C ₂ H ₄	-0.62**	Fruit color	vs.	Fruit no/tree	-0.60**
DA Harvest	vs.	17DAH C ₂ H ₄	-0.55*	Fruit color	vs.	Soluble solids	0.51*
DA Harvest	vs.	9DAH CO ₂	-0.14 NS	Fruit color	vs.	Firmness	0.51*
DA Harvest	vs.	11DAH CO ₂	-0.54*	Fruit color	vs.	Yield/tree	-0.57*
DA Harvest	vs.	13DAH CO ₂	-0.70**	Fruit color	vs.	9DAH C ₂ H ₄	0.55*
DA Harvest	vs.	15DAH CO ₂	-0.73**	Fruit color	vs.	9DAH CO ₂	0.53*
DA Harvest	vs.	17DAH CO ₂	-0.78**	Fruit color	vs.	11DAH C ₂ H ₄	0.48*
DA Harvest	vs.	Crop efficiency	0.70**	Fruit color	vs.	11DAH CO ₂	0.54*
DA Harvest	vs.	Yield/tree	-0.008 NS	Fruit color	vs.	13DAH C ₂ H ₄	0.56**
DA Harvest	vs.	Fruit weight	-0.34 NS	Fruit color	vs.	13DAH CO ₂	0.58**
DA Harvest	vs.	Firmness	-0.0001 NS	Fruit color	vs.	15DAH C ₂ H ₄	0.42*
DA Harvest	vs.	SDP	0.60**	Fruit color	vs.	15DAH CO ₂	0.55*
DA Harvest	vs.	Water core	-0.73**	Fruit weight	vs.	9DAH C ₂ H ₄	0.11 NS
Yield/tree	vs.	Fruit red color	-0.57**	Fruit weight	vs.	9DAH CO ₂	-0.44*
Yield/tree	vs.	Soluble solids	-0.73**	Fruit weight	vs.	9DAH O ₂	-0.66**
Yield/tree	vs.	Firmness	-0.89**	Fruit No/tree	vs.	SSC	-0.83**
Yield/tree	vs.	Color	-0.53*	SSC	vs.	DA	-0.41
Yield/tree	vs.	9DAH C ₂ H ₄	-0.52*	SSC	vs.	SDP	-0.33
Yield/tree	vs.	9DAH CO ₂	-0.66**	Fruit No/tree	vs.	Firmness	-0.79**
9DAH C ₂ H ₄	vs.	Water core	0.76**	Fruit No/tree	vs.	Fruit weight	0.47*
Firmness	vs.	Fruit weight	-0.72**	Fruit No/tree	vs.	9DAH C ₂ H ₄	-0.71**
Firmness	vs.	TCSA	-0.75**	Crop Efficiency	vs.	Sun burn	-0.57*

DAH = days after harvest; SDP = starch degradation pattern; TCSA = trunk cross-sectional area; SSC = soluble solids concentration.

NS, *, **Nonsignificant or significant at $P < 0.05$ or 0.01 , respectively.

These inconsistencies could be created by numerous physiological and nutritional factors such as crop load and leaf and fruit nitrogen and calcium status (Fallahi et al., 1985a). Thus, the impact of each of these factors need to be studied before I_{AD} can be fully used in place of regular firmness measurements.

Fruit color and its relations with I_{AD} index. Fruit from trees on CG.4003, Supp.3, CG.4814, and B.10 had higher but those on G.935N lower color than other rootstocks, although differences were not always significant (Table 3). Changes from green to yellow in the background color of apples can be a good indicator of fruit maturity. The amount

of DA (I_{AD}) is related to the actual content of chlorophyll a in fruit mesocarp and ethylene evolution during on tree ripening (Ziosi et al., 2008). According to Ziosi et al. (2008), the consecutive stages of ripening as defined according to ethylene production (preclimacteric, climacteric, and postclimacteric) occurs in same ranges of I_{AD} in different years of study. The robustness of I_{AD} is further corroborated by changes in transcript levels of genes, which are up- or downregulated during fruit ripening and preclimacteric fruit stage, having lowest transcript amount of the upregulated genes and the highest of the downregulated ones and this effect in climacteric

fruit stage was the opposite (Ziosi et al., 2008).

In fruit from trees on all rootstocks, I_{AD} values at harvest had significantly negative correlations with the amount of evolved ethylene at all dates of measurements (Table 1). This result is consistent with a study in peach fruit (*Prunus persica* L. Batsch) ripening progression Ziosi et al., (2008).

Starch degradation pattern, SSC, and relations with I_{AD} . ‘Aztec Fuji’ fruit on G.41N, M.9Pajam2, G.11, and M.9337, with values greater than 3.60, had higher starch degradation pattern (SDP) whereas those on CG.5222 and CG.4214, with values lower than 2.56 had lower SDP than those on all other rootstocks (Table 2). Fruit from trees on Supp.3 and CG.4003 had higher but those on M.26EMLA, M.9Pajam2, and M.9T337 had lower SSC than those on other rootstocks, although differences were not always significant (Table 2).

Starch degradation pattern did not have strong correlation with most maturity indices, including SSC. One might assume that SSC should increase as SDP increases. However, a weak (insignificant) negative correlation existed between these fruit quality and maturity attributes ($r = -0.33$, Table 1). That is because soluble sugars in the fruit tissue are not only supplied by the conversion of fruit starch to these sugars; rather they are also supplied from other sinks. Plants synthesize carbohydrates other than sucrose in source leaves and translocate them to sink organs. Rosaceae, plants synthesize polyols (sugar alcohols) and use them as phloem-translocated compounds (Loescher and Everard, 1996; Noiraud et al., 2001). Polyols are low molecular weight, highly soluble, and nonreducing compounds; thus, they are suitable for translocated compounds. Sorbitol (D-glucitol) is phloem-translocated component

Fig. 6. Clustered correlation coefficient among several measured variables that include ‘Aztec Fuji’ apple fruit quality and yield component parameters.

Fig. 7. Two-way similarity cluster analysis (Ward's minimum variance method) of genotypic means for 'Aztec Fuji' apple fruit quality and yield component parameters influenced by 17 different rootstocks.

in in many Rosaceae trees (Watari et al., 2004). Sorbitol is a major photosynthetic product and a major phloem-translocated component in Rosaceae (e.g., apple, pear, peach, and cherry) (Watari et al., 2004). In apple (*Malus domestica*) phloem, 65% to 80% of the translocated carbon was attributed to sorbitol (Bieleski, 1969; Hansen, 1970; Klages et al., 2001; Kollas, 1968; Marloe and Loescher, 1980).

In our study, no significant correlation existed between I_{AD} and SSC (data not reported), and this result agreed with a previous report on peach fruit by Gonçalves et al. (2016).

Tree growth, yield, and fruit weight and their relations with quality. Trees on G.41N had the highest trunk cross-sectional area (TCSA) than all other trees (Table 3). Trees on G.41N, CG.4004, and M.26EMLA had

higher and those on CG.4003 had lower yield per tree than trees on all other rootstocks (Table 3). The larger tree size resulted in having a relatively lower yield efficiency and crop density, despite their high yield per tree in 'Aztec Fuji' on G.41N (Table 3). Trees on B.9 and M.9T337 had the highest and those on Supp.3 had the lowest yield efficiency compared with those on all others (Table 3).

Table 2. The influence of different rootstocks on evolved ethylene and CO_2 at climacteric peak and internal quality attributes of 'Aztec Fuji' apples at harvest.

Rootstock	Absorbance difference (I_{AD}) ^z	Ethylene at peak ($\mu L \cdot kg^{-1} \cdot h^{-1}$)	Respiration at peak ($mL \cdot kg^{-1} \cdot h^{-1}$)	Firmness (N)	Soluble solids concn (Brix)	Starch degradation pattern (1–6)	Water core (%)
CG.4004	0.94 a-d ^y	22.33 bcd	395.14 a-e	75.07 cd	15.20 cde	3.10 abc	34.38 ab
G.41N	0.86 bcd	27.5 a-d	390.97 a-e	73.99 d	15.10 cde	3.63 ab	50.00 ab
CG.3001	0.87 bcd	33.13 a-d	399.59 a-e	74.676 cd	15.20 cde	3.25 abc	46.88 ab
G.935N	0.86 bcd	27.48 a-d	343.61 b-e	78.79 bcd	15.75 a-d	3.11 abc	21.88 ab
CG.5222	0.85 cd	29.6 a-d	432.18 ab	76.048 bcd	15.00 cde	2.80 bc	53.13 a
B.9	1.06 abc	22.30 bcd	365.09 b-e	78.99 bcd	15.35 a-e	3.08 abc	9.38 ab
B.10	0.96 a-d	18.8 cd	352.29 b-e	77.42 bcd	15.25 b-e	3.25 abc	21.88 ab
CG.4214	0.94 a-d	32.73 a-d	386.92 a-e	84.08 abc	15.90 abc	2.56 c	33.33 ab
G.202N	0.87 bcd	39.25 abc	317.92 de	77.52 bcd	15.70 a-d	2.95 abc	50.00 ab
CG.2034	1.14 abc	20.60 cd	336.21 cde	81.24 a-d	15.60 a-d	3.54 abc	37.50 ab
M.26EMLA	1.20 ab	12.53 d	303.84 e	77.22 bcd	14.25 e	3.60 abc	0.00 b
M.9Pajam2	1.22 a	12.35 d	320.23 de	78.11 bcd	14.70 de	3.85 ab	0.00 b
G.11	1.20 ab	20.5 cd	319.83 de	85.16 ab	15.75 a-d	3.90 a	12.50 ab
M.9T337	1.19 abc	13.13 d	305.43 de	77.62 bcd	14.70 de	3.88 a	28.13 ab
Supp.3	0.70 d	47.00 a	465.64 a	90.16 a	16.50 a	3.08 abc	56.25 a
CG.4814	0.86 bcd	44.13 ab	400.08 a-d	82.42 a-d	15.33 b-e	3.48 abc	20.83 ab
CG.4003	1.08 abc	30.85 bc	422.55 abc	89.57 a	16.40 ab	3.53 abc	41.07 ab

^z I_{AD} measures the index of absorbance difference of two wavelengths of light between 670 and 720 nm within the range of 0 ± 2.2 . The value 2.2 represents green, and 0 represents complete maturity.

^yMean separation within columns in each group of treatments by least significant difference at 5% level.

Table 3. The influence of different rootstocks on physical quality attributes of ‘Aztec Fuji’ apples.

	Yield (kg/tree)	Yield efficiency (kg·cm ⁻² TCSA)	Crop efficiency (fruit no./TCSA)	TCSA (cm ²)	Fruit no. per tree	Fruit wt (g)	Fruit color rank ^z (1–5)
CG.4004	111.1 ab ^y	1.20 bcd	4.66 cd	96.99 b	432 ab	259.2 a	4.13 abc
G.41N	131.7 a	1.14 bcd	4.59 cd	115.59 a	530 ab	248.6 ab	4.00 abc
CG.3001	106.0 abc	1.07 bcd	4.50 cd	101.23 ab	443 ab	242.7 abc	3.88 abc
G.935N	94.8 bcd	1.45 bcd	6.49 cd	67.12 cd	423 ab	229.0 a-d	3.56 c
CG.5222	93.7 bcd	0.98 bcd	4.39 cd	97.19 b	423 ab	220.2 a-e	4.19 abc
B.9	106.0 abc	2.49 a	11.86 ab	46.25 fg	502 ab	214.7 a-e	4.13 abc
B.10	103.0 abc	1.77 ab	8.43 bcd	59.12 def	478 ab	212.6 a-e	4.38 ab
CG.4214	71.4 cde	1.56 bc	7.80 bcd	41.41 g	355 bc	208.8 b-e	4.25 abc
G.202N	85.5 bcd	1.32 bcd	6.83 bcd	64.88 cde	437 ab	199.2 cde	4.31 abc
CG.2034	41.2 efg	1.63 ab	8.58 bc	24.98 h	215 cd	189.6 de	4.13 abc
M.26EMLA	109.1 ab	1.40 bcd	7.55 bcd	77.99 c	582 a	188.2 de	3.75 bc
M.9Pajam2	84.4 bcd	1.31 bcd	6.97 bcd	63.44 cde	434 ab	186.1 de	4.13 abc
G.11	70.0 cde	1.52 bcd	9.15 abc	46.62 fg	412 ab	185.4 de	3.88 abc
M.9T337	103.0 abc	2.47 a	14.06 a	43.20 g	576 a	184.4 de	3.75 bc
Supp.3	26.8 fg	0.63 d	43.99 fg	43.99 fg	141 d	184.0 de	4.50 ab
CG.4814	60.5 def	1.30 bcd	7.61 bcd	50.13 efg	351 bc	177.8 ef	4.50 ab
CG.4003	22.6 g	1.14 bcd	9.26 abc	20.52 h	180 cd	132.2 f	4.56 a

^zColor rank: 1 = most green progressively to 5 = uniform red.^yMean separation within columns in each group of treatments by least significant difference at 5% level.

TCSA = trunk cross-sectional area.

Trees on CG.4004 had the heaviest and those on CG.4003 had the smallest average fruit weight compared with those on all other rootstocks (Table 3).

Auvil et al. (2011) reported that ‘Fuji’ and ‘Honeycrisp’ apples on Geneva rootstocks including G.11, G.935N, G.41N, and G.214 had better yield performance than M9 (Auvil et al., 2011). However, in our study, trees on only G.41N had higher yield than those on M.9Pajam2 (Table 1). Also, Dallabetta et al. (2021) reported that ‘Golden Delicious’, ‘Gala’, and ‘Fuji’ apples on G.969 and G.935N had more yield than M.9T337. Nevertheless, in our study, ‘Aztec Fuji’ on G.935N and M.9T337 has similar yields. These contradictions could be because of different groups of rootstocks were used in our study and those of Dallabetta et al. (2021) and Auvil et al. (2011).

Yield, either expressed as kilograms per tree or number of fruits per tree, had significantly negative correlations with harvest time fruit color, SSC, firmness, and ethylene and CO₂ (Table 1).

In this study, strong negative correlations between firmness and yield, TCSA, fruit number per tree, average fruit weight, and percent of russet were observed (Table 1). The negative correlation between firmness and fruit size/weight and between fruit firmness and yield in this study was consistent with a previous report by Fallahi et al. (1985d). Negative correlation between fruit firmness and fruit size agrees with a previous report (Fallahi et al., 1985c).

Fruit number had positive correlation with fruit size, which is not an expected relationship between these two quality attributes. If we had imposed different crop loads (i.e., different levels of thinning) in trees on a single rootstock, we would have expected to observe a negative correlation between fruit number and fruit size (Fallahi and Simons, 1993). However, in our study, ‘Aztec Fuji’ on a several rootstocks, including CG.4004

had both high or moderately high yield and large fruits, leading to a positive correlation between these two attributes when values over all rootstocks were pooled (Table 1). Producing high yield and large fruit size is a highly desirable genetic feature for any rootstock.

Ethylene was highly and positively correlated with water core (Table 1). Water core is a physiological phenomenon through which sorbitol accumulates in the core area of the apple fruit. Advanced fruit maturity and high levels of ethylene are among the factors that are overwhelmingly associated with water core according to Beaudry (2014).

Crop efficiency correlated with percent sunburn suggesting the possibility that more dwarfing rootstocks (more yield efficient) had more fruit exposed to the sun (Table 1, Fig. 6).

Conclusion

‘Aztec Fuji’ on all rootstocks showed classic evolved ethylene and respiration climacteric curves and reached their climacteric peaks in a week at room temperature. DA meter can be used as a nondestructive tool to monitor the maturity progression and determining the best time of harvest based on estimating maturity of ‘Fuji’ apple fruit. Major differences existed among rootstocks with regards to their impacts on ethylene evolution, respiration, yield, fruit weight, and other quality attributes, and thus rootstock impact must be taken into account when making management decisions in harvestings and shipping ‘Fuji’ apple fruit. Further studies are warranted to find precise prediction equations between I_{AD} and ethylene and respiration for each cultivar/rootstock combination and under each climate condition to have a more precise and nondestructive tool to make management decision in harvesting and shipment of ‘Aztec Fuji’ apple.

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