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Influence of Plant Growth Regulators on Fruit Quality Attributes of Zucchini (*Cucurbita pepo* L.)

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Author's contribution

The sole author designed, analysed, interpreted and prepared the manuscript.

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Original Research Article

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Abstract

Plant growth regulators (PGRs) are known to exert diverse and often dose-dependent effects on the biochemical composition and quality of cucurbit fruits. Ethephon, an ethylene-releasing compound, has been widely investigated for its capacity to modify sex expression, accelerate fruit development and alter the biochemical composition of fruits in cucurbitaceous crops. A field investigation was conducted at the experimental field of the Department of Agriculture, Khalsa College, Amritsar, during the Rabi season of 2018–2019 (more precisely 'late Rabi–Zaid transition season) to study the influence of ethephon and maleic hydrazide on the fruit quality attributes of zucchini (Cucurbita pepo L.) cv. Dark Green. The experiment comprised nine treatments — ethephon at 50, 100, 150 and 200 ppm; maleic hydrazide at 50, 100, 150 and 200 ppm; and an untreated control — laid out in a Randomized Complete Block Design (RCBD) with three replications. Both regulators were applied as foliar sprays at the two- and four-leaf stages. Three quality parameters were assessed: ascorbic acid content (mg per 100 g), total soluble solids (TSS, °Brix), and flesh thickness (mm). Ethephon at 200 ppm (T4) recorded the highest values for all three quality parameters — ascorbic acid of 16.93 mg per 100 g, TSS of 6.33 °Brix, and flesh thickness of 30.66 mm — whilst the untreated control (T9) recorded the minimum values of 11.90 mg per 100 g, 4.73 °Brix and 22.15 mm,

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respectively. Statistical analysis revealed that TSS was significantly influenced by the treatments (CD at 5% = 0.18), whilst ascorbic acid and flesh thickness showed consistent numerical trends though were not statistically significant. The enhancement of TSS under ethephon application was attributed to the influence of ethylene-related physiological processes on nutrient absorption and accumulation in fruit pulp. These findings indicate that foliar application of ethephon at 200 ppm at the two- and four-leaf stages represents an effective strategy for improving the biochemical quality of zucchini fruits under subtropical conditions.

Keywords: Ascorbic acid; Cucurbita pepo; ethephon; flesh thickness; fruit quality; maleic hydrazide; plant growth regulators; total soluble solids; zucchini.

1. Introduction

Plants are highly sensitive to the environmental conditions during all growth and development stages due to their sessile origin. The presence or absence of light acts as an environmental stimulus that regulates plant growth and development during the entirety of plant ontogenesis. The perception and transmission of light via specific receptors modulate hormone levels and their interplay, which trigger signals that alter plant molecular, biochemical and physiological processes including cell growth and division. Zucchini (*Cucurbita pepo* L.) is one of the most widely cultivated cucurbitaceous vegetable crops in tropical and subtropical regions of the world, and its immature fruits are consumed as a fresh vegetable, either boiled, fried, stuffed or incorporated into a wide variety of culinary preparations (Petrova et al., 2025; Soniya & Arivazhagan, 2023). The species belongs to the family Cucurbitaceae, possesses a chromosome number of 2n = 40, and is known to be highly polymorphic in fruit colour, shape and size (Kathiravan et al., 2006). Beyond its culinary importance, summer squash has been identified as an economically valuable plant with medicinal potentials and is considered a suitable candidate for cultivation under the diverse agro-climatic conditions of Iran and, by extension, many comparable subtropical environments (Bannayan et al., 2011).

The fruit of zucchini possesses a notable nutritional profile, providing dietary fibre at 1.2 g per 100 g fresh weight, protein at 1.31 g per 100 g, carbohydrates at 3.2 g per 100 g and calories at approximately 17 Kcal per 100 g, along with folate at 24 µg per 100 g, potassium at 261 mg per 100 g, pro-vitamin A and ascorbic acid (Food and Agriculture Organization of the United Nations, 2011). Given the low caloric content and high nutritive density of zucchini, its quality attributes — particularly ascorbic acid content, total soluble solids (TSS) and flesh thickness — are of primary importance for consumer acceptance, post-harvest shelf life and commercial market value (Tamer et al., 2010; Bannayan et al., 2011; Souza et al., 2020).

Growth regulators are regarded as one of the most important treatments, used nowadays in agriculture, which in most cases modify the plant growth and the subsequent fruiting. They are utilized to catalyze seed germination, vegetative growth, flowering and fruiting in several vegetable crops. Available determination confirms that best yield can be accomplished by utilizing different concentrations of growth regulators (Dobhal et al., 2022; Sure et al., 2012). Plant growth regulators (PGRs) are known to exert diverse and often dose-dependent effects on the biochemical composition and quality of cucurbit fruits. Ethephon, an ethylene-releasing compound, has been widely investigated for its capacity to modify sex expression, accelerate fruit development and alter the biochemical composition of fruits in cucurbitaceous crops. Ethylene signalling has been demonstrated to play a critical regulatory role in sex determination in *Cucurbita pepo*, and its exogenous application as ethephon can profoundly influence the developmental physiology of the plant (Manzano et al., 2011). Maleic hydrazide is a plant growth retardant that inhibits meristematic activity; at lower concentrations, it may promote female flower expression and improve fruit quality indices, while at higher doses it can suppress vegetative and reproductive development (Kaur et al., 2016).

Several earlier investigations with related cucurbit species have documented that ethephon application at appropriate concentrations significantly increases TSS, ascorbic acid content and other biochemical quality attributes. Hidayatullah et al. (2009) reported that maleic hydrazide at 450 µmol l^{-1} produced the maximum increase in TSS of cucumber fruit (3.23 °Brix), while Chaurasiya et al. (2016) documented that ethrel at 200 ppm recorded the maximum TSS (11.30 °Brix) and total sugars (11.35%) in muskmelon. Vadigeri et al. (2001) found that ethrel at 400 ppm produced the highest ascorbic acid content in cucumber cv. Poinsette. Despite this body of evidence in related crops, specific documentation of PGR effects on the quality attributes of zucchini under the agroclimatic conditions of Punjab, India remains limited.

The present investigation was undertaken to systematically evaluate the influence of foliar applications of ethephon and maleic hydrazide on the fruit quality attributes of zucchini cv. Dark Green, with particular attention to ascorbic acid content, total soluble solids and flesh thickness. The work aims to generate data that can inform the targeted use of PGRs in zucchini cultivation with the dual goal of improving yield and nutritional quality.

1.1 Scope and Objectives

The investigation was designed with the following objectives: (i) to determine the effects of ethephon and maleic hydrazide at varying concentrations on the principal quality attributes of zucchini fruits, namely ascorbic acid content, total soluble solids and flesh thickness; (ii) to compare the relative efficacy of ethephon and maleic hydrazide in enhancing biochemical and physical quality indices; and (iii) to identify the most appropriate concentration and type of growth regulator for improving fruit quality under the prevailing conditions of Amritsar, Punjab.

2. Review of Literature

The following section reviews published research pertaining to the effects of plant growth regulators on the fruit quality attributes of cucurbitaceous vegetables.

2.1 Effect of Growth Regulators on Total Soluble Solids (TSS)

Hidayatullah et al. (2009) conducted a study at the Vegetable Crop Research Programme, National Agricultural Research Centre, Islamabad, Pakistan, to evaluate the effects of ethrel, gibberellic acid (GA3) and maleic hydrazide on sex expression and phytohormone levels in monoecious cucumber. Their results revealed that all concentrations of ethrel (except the very highest doses of 700 and 1,750 μmol l^{-1}), GA3 and maleic hydrazide significantly increased the TSS of cucumber fruit compared with the water-sprayed control. The maximum TSS increases of 3.23 °Brix and 3.19 °Brix were observed with maleic hydrazide at 450 μmol l^{-1} and GA3 at 60 μmol l^{-1}, respectively. These findings underscore the broad-spectrum ability of growth regulators to enhance fruit soluble solids.

Chaurasiya et al. (2016) investigated the influence of plant growth regulators on growth, sex expression, yield and quality of muskmelon (*Cucumis melo* L.) and reported that TSS was significantly increased by foliar application. The maximum TSS of 11.30 °Brix was recorded with ethrel at 200 ppm, which was statistically at par with ethrel at 100 ppm and 150 ppm, while the control recorded the lowest TSS of 8.4 °Brix. The total carotenoids were found to be highest (0.867 mg) with GA3 at 60 ppm, followed by GA3 at 90 ppm (0.853 mg), with the lowest value (0.667 mg) in the control. The authors proposed that the increase in carotenoid content attributable to plant growth regulators was due to increased biosynthesis of carotenoids under PGR treatment.

Kadi et al. (2018) evaluated the effects of different plant growth regulators on growth, yield and quality in cucumber under polyhouse conditions in Indore, Madhya Pradesh. Their results indicated that GA3 at 50 ppm showed better results for quality attributes, including TSS and fruit texture, compared with controls. The study provided useful comparative data on how different PGRs affect TSS in protected cultivation settings, noting that optimal results in terms of quality are obtained at lower concentrations of growth regulators.

Shafeek et al. (2016) conducted a two-season experiment with summer squash (*Cucurbita pepo* L.) cv. Eskandarani in which several bio-regulators, including GA3 at 15–60 mg l^{-1} and ethereal at 150–250 mg l^{-1}, were evaluated for their effects on plant growth, sex expression, fruit set, yield and nutritional supplementation. The study reported that different levels of GA3 and ethereal had distinct effects on the nutritional supplement of squash fruits, with higher concentrations of ethereal generally producing superior quality parameters. The results are relevant to the interpretation of TSS and other biochemical responses in related cucurbit species.

2.2 Effect of Growth Regulators on Ascorbic Acid Content

Vadigeri et al. (2001) conducted an experiment on the effect of ethrel and gibberellic acid on yield and quality of two cucumber varieties (Poinsette and Belgaum Local) in Karnataka. Their results indicated that ethrel at 400 ppm produced the highest ascorbic acid content of 9.23 mg per 100 g in cucumber cv. Poinsette, while Belgaum Local showed an increase in reducing sugars (3.13 g per 100 g) and total sugars (3.43 g per 100 g) with the same treatment. The maximum TSS was also recorded in ethrel-treated plants of cv. Poinsette. This study established an important benchmark for the expected range of ethephon-induced quality improvements in cucurbits.

Devi and Kumari (2015) reported that the combined treatment of NAA at 150 ppm and ethrel at 250 ppm, as well as other growth regulator combinations, produced measurable improvements in quality attributes of muskmelon fruits, including fruit diameter. Their study demonstrated that the effects of growth regulators on fruit quality were not limited to a single biochemical compound but could simultaneously improve multiple fruit quality indices, supporting the multi-faceted nature of PGR interventions in cucurbit quality management.

Hidayatullah et al. (2012) studied the effect of ethrel, gibberellic acid and maleic hydrazide on sex expression and quality of bottle gourd cv. Faisalabad Round, and reported that maleic hydrazide at optimum concentrations improved fruit quality parameters along with increased fruit set. The differential responses of these two major growth regulator classes (ethylene-releasing agents and growth retardants) to quality traits suggest that the mechanism of quality improvement is distinct for each compound and that optimising concentration is critical to achieving the desired outcome.

Nagamani et al. (2015) comprehensively evaluated the effects of PGRs on sex expression, fruit setting, seed yield and quality in the parental lines of bitter gourd hybrids. Their study demonstrated that growth regulators — particularly GA3 at 50 ppm, NAA at 200 ppm and ethrel at 50 ppm — effectively enhanced not only vegetative growth and seed yield but also the qualitative attributes of fruit. The study confirmed that growth regulators can modulate multiple aspects of fruit development simultaneously, including both biochemical composition and physical structure.

Hossain et al. (2006) highlighted the role of gibberellic acid in altering the balance between endogenous hormones in cucurbits. The phytohormone balance established by exogenous application of PGRs influences not only sex expression but also the rate of carbohydrate metabolism and the accumulation of biochemical compounds, including ascorbic acid, in developing fruits. This mechanistic perspective is relevant to the interpretation of PGR-induced ascorbic acid changes in zucchini.

2.3 Effect of Growth Regulators on Flesh Thickness

The flesh thickness of cucurbit fruits is an important textural and quality attribute that determines the proportion of edible flesh and influences the culinary and processing value of the product. The relationship between plant growth regulator application and flesh thickness in cucurbits has received comparatively less attention than TSS or ascorbic acid, but available evidence suggests that growth regulators can positively influence this parameter as well.

Sedghi et al. (2008) investigated the effects of plant growth regulators on biochemical and agronomic characteristics of medicinal pumpkin (*Cucurbita pepo* L.). Their findings showed that gamma-tocopherol accumulation in grains was positively affected by GA3 treatment. The study also reported that the number of female flowers per plant was significantly enhanced by NAA treatment (10.1 flowers per plant), contributing to better fruit development outcomes including improved physical fruit characteristics. These findings support the argument that PGR treatments that enhance female flower number are likely to also improve individual fruit developmental parameters including flesh thickness.

Kadi et al. (2018) reported that GA3 application in cucumber under polyhouse conditions improved several physical fruit parameters alongside yield. These observations, while not specifically measuring flesh thickness, provide a context for understanding how growth regulators can simultaneously influence both the dimensional and biochemical attributes of cucurbit fruits.

2.4 Nutritional Importance and Medicinal Value of Zucchini

The quality attributes of zucchini are of particular relevance in the context of the crop's emerging significance as a medicinal and functional vegetable. Tamer et al. (2010) highlighted the importance of pumpkin and its relatives as sources of bioactive compounds and demonstrated the significant relationship between cultivar selection, maturity and biochemical quality indices in Cucurbita species. Their work is broadly applicable to summer squash quality research, as the Cucurbitaceae family shares many biochemical characteristics across genera.

The classification of zucchini as a crop with medicinal potential is further supported by the work of Bannayan et al. (2011), who identified the specific climatic requirements and adaptability of summer squash and noted that its value as a medicinal plant is closely linked to its biochemical composition, including ascorbic acid and antioxidant compounds. These authors emphasised that the nutritive and medicinal quality of zucchini is expected to respond to management interventions such as growth regulator application.

Hayashi et al. (2001) provided a mechanistic framework for understanding how ethylene, released from ethephon, influences the general physiological condition of the plant by inhibiting gibberellin action and promoting certain biosynthetic pathways. Since gibberellins are known to regulate several aspects of fruit development including cell expansion and biochemical accumulation, the interaction between ethylene and gibberellin signalling pathways is relevant to understanding how ethephon modulates fruit quality attributes such as TSS and ascorbic acid.

Manzano et al. (2011) established that ethylene exerts a stronger influence than brassinosteroids on sex expression and flower development in *Cucurbita pepo*, confirming ethylene's primary role in the crop's reproductive physiology. The modification of sex expression towards femaleness by ethephon has downstream consequences for fruit quality, as it concentrates the plant's metabolic resources on fewer but better-developed individual fruits, potentially resulting in higher individual fruit quality indices.

3. Materials and Methods

3.1 Experimental Site and Climate

The investigation was conducted during the *Rabi* season of 2018–2019 (more precisely 'late Rabi–Zaid transition season) at the experimental field of the Department of Agriculture, Khalsa College, Amritsar (31°38′ N, 74°52′ E, elevation 236 m above mean sea level). The climate of the region is sub-tropical and humid, receiving approximately 745 mm of annual rainfall predominantly between July and September. Summer temperatures approach 45 °C in the months of May and June, whilst the winters are characterised by near-freezing conditions in December and January, with the experimental period (February–June) experiencing progressively increasing temperatures suitable for zucchini cultivation.

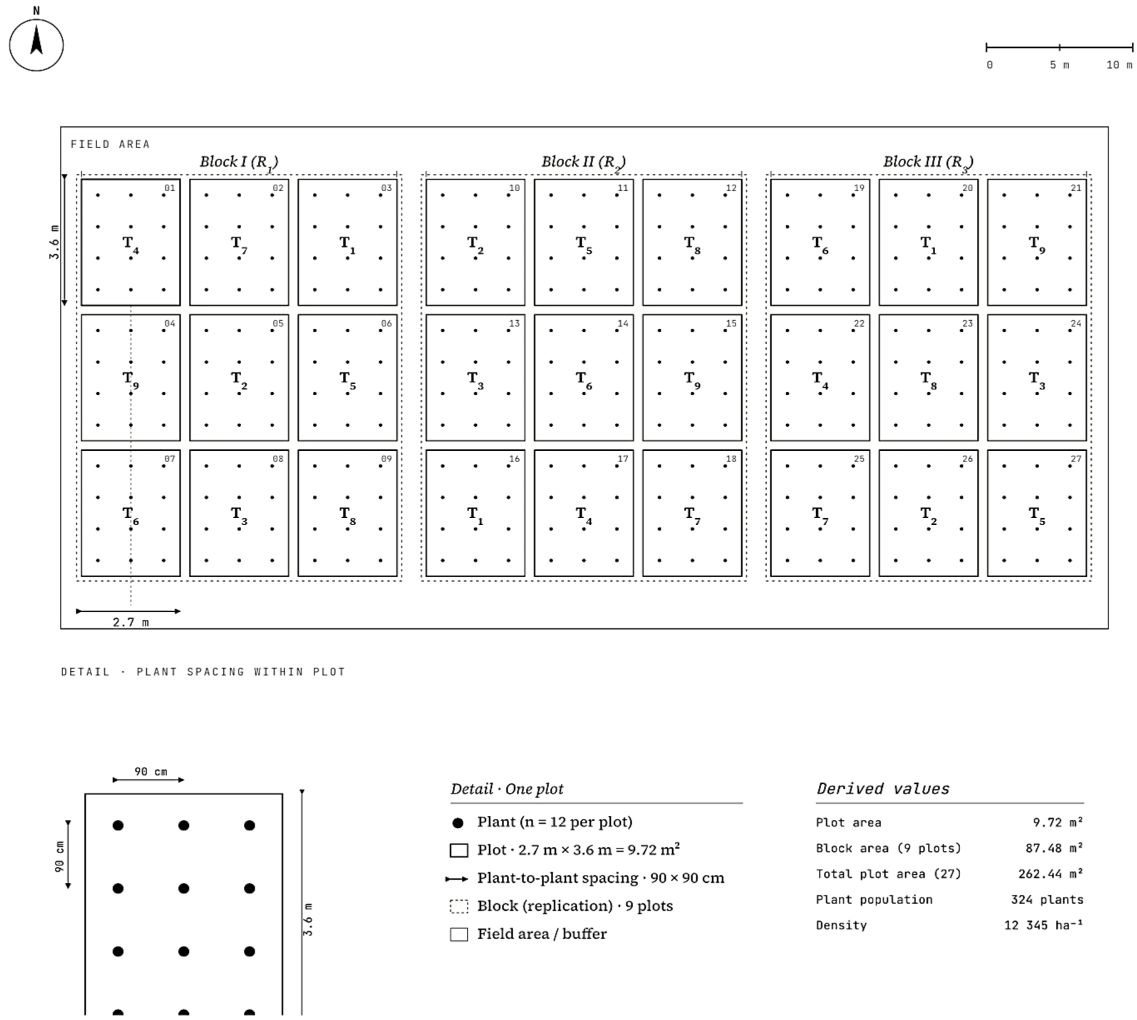
3.2 Soil Characteristics

The soil at the experimental site was sandy loam in texture, with pH 6.5, electrical conductivity of 0.8 dS m^{-1}, organic carbon of 0.42%, total nitrogen of 0.28%, available phosphorus of 17.00 kg ha^{-1} and available potassium of 278.00 kg ha^{-1}. These values were within the acceptable range for cucurbit production.

3.3 Experimental Design, Plant Material and Treatments

The variety Dark Green Zucchini was used throughout the experiment. Seedlings raised at the Centre of Excellence for Vegetables, Kartarpur, in a cocopeat, perlite and vermiculite substrate (3:1:1), were transplanted on 17 February 2019 at a spacing of 90 cm × 90 cm. The experiment was arranged in a Randomized Complete Block Design (RCBD) with nine treatments and three replications (27 plots in total; plot size 2.7 m × 3.6 m). Details of the experimental design is provided in Fig. 1. The nine treatments were: T1 — Ethephon 50 ppm; T2 — Ethephon 100 ppm; T3 — Ethephon 150 ppm; T4 — Ethephon 200 ppm; T5 — Maleic Hydrazide 50 ppm; T6 — Maleic Hydrazide 100 ppm; T7 — Maleic Hydrazide 150 ppm; T8 — Maleic Hydrazide 200 ppm; and T9

— Control (100% recommended dose of fertilisers, no growth regulator). Both growth regulators were applied as foliar sprays at the two- and four-leaf stages of crop development.



DESIGN	TREATMENTS	REPLICATIONS	PLOTS	PLOT SIZE	SPACING
RCBD	9 (T_1–T_9)	3	27	2.7 × 3.6 m	90 × 90 cm

Fig. 1. Schematic field layout of the experiment laid out in a Randomized Complete Block Design (RCBD)
Nine treatments (T1–T9) were randomly allocated within each of three blocks (Block I–III), giving a total of 27 experimental plots. Each plot measured 2.7 m × 3.6 m (9.72 m²) and accommodated 12 plants arranged in a 3 × 4 grid at a uniform spacing of 90 cm × 90 cm between rows and within rows. Blocks were oriented perpendicular to the principal source of field heterogeneity. The hatched border represents the surrounding buffer / non-experimental field area. Treatment allocation within each block was independently randomized

3.4 Cultural Practices

Farm yard manure at 25–30 tonnes ha^{-1} was applied before transplanting. Fertiliser doses of 80–100 kg N, 50–80 kg P_2O_5 and 50–60 kg K_2O ha^{-1} were incorporated in shallow furrows. The crop received ten irrigations over its duration, with the first application at transplanting and subsequent irrigations based on soil moisture assessment. Plant protection against red pumpkin beetle and fruit fly was accomplished using Thiacloprid at 70–80 ml per acre. The field was maintained weed-free by regular manual weeding.

3.5 Determination of Quality Attributes

3.5.1 Ascorbic Acid Content

Ascorbic acid content (expressed as mg per 100 g fresh weight) was estimated using the Indophenol dye titration method. A freshly prepared stock solution of sodium 2,6-dichlorophenolindophenol (0.04%) was standardised against a known concentration of ascorbic acid solution. Samples were prepared by extracting 10 g of zucchini juice in 3% metaphosphoric acid and the filtered extract was titrated against the standardised dye solution. The ascorbic acid content was calculated using the formula: Ascorbic acid (mg per 100 g) = (Titre × Dye equivalent × Dilution factor) / Sample weight.

3.5.2 Total Soluble Solids

Total soluble solids (expressed as °Brix) were determined by measuring the refractive index of the expressed juice using a hand refractometer. The instrument was calibrated with distilled water before each set of measurements. TSS represents the combined concentration of sucrose and other soluble components including carbohydrates, organic acids, proteins and minerals in the fruit. Measurements were performed immediately after harvesting to minimise post-harvest losses.

3.5.3 Flesh Thickness

Flesh thickness (expressed in mm) was determined by measuring the thickness of the edible mesocarp from the outer skin to the inner seed cavity of each harvested fruit using a calibrated metre scale and digital Vernier scale. Measurements were taken at the transverse midpoint of the fruit. The average value from five tagged plants per plot was used for statistical analysis.

3.6 Statistical Analysis

Data were subjected to statistical analysis using analysis of variance (ANOVA) for a Randomised Completely Block Design (Shieh & Jan, 2004; Panse and Sukhatme, 1985). The critical difference (CD) at the 5% probability level was computed for pairwise mean comparisons. Non-significant results (NS) are reported where the F-test showed no statistically significant treatment effect at the 5% level (SPSS Statistics from IBM).

4. Results and Discussion

The data pertaining to the three quality attributes of zucchini as influenced by foliar application of ethephon and maleic hydrazide are presented in Tables 1, 2 and 3, and are discussed in detail below. All three parameters showed consistent numerical trends, with ethephon at 200 ppm recording the highest values and the untreated control recording the lowest values throughout.

4.1 Ascorbic Acid Content

Ascorbic acid (vitamin C) is a water-soluble antioxidant that plays an important physiological role in plant metabolism and is a key nutritional quality indicator in vegetables. The data on ascorbic acid content of zucchini fruits as influenced by plant growth regulator applications are presented in Table 1.

Table 1. Effect of ethephon and maleic hydrazide on ascorbic acid content (mg per 100 g) of zucchini fruits

Treatment	Ascorbic Acid (mg per 100 g)
T1 (Ethephon 50 ppm)	13.41
T2 (Ethephon 100 ppm)	14.78
T3 (Ethephon 150 ppm)	16.15
T4 (Ethephon 200 ppm)	16.93
T5 (Maleic Hydrazide 50 ppm)	14.21
T6 (Maleic Hydrazide 100 ppm)	13.53
T7 (Maleic Hydrazide 150 ppm)	13.28
T8 (Maleic Hydrazide 200 ppm)	12.74
T9 (Control)	11.90
CD (p = 0.05)	NS

The data revealed consistent numerical differences in ascorbic acid content across treatments, though these differences did not attain statistical significance (NS at 5% level). The maximum ascorbic acid content of 16.93 mg per 100 g was recorded in T4 (ethephon 200 ppm), followed by T3 (ethephon 150 ppm) at 16.15 mg per 100 g and T2 (ethephon 100 ppm) at 14.78 mg per 100 g. Among maleic hydrazide treatments, T5 (50 ppm) and T6 (100 ppm) produced intermediate values (14.21 and 13.53 mg per 100 g, respectively), while higher maleic hydrazide concentrations (T7 and T8) showed progressive decline to 13.28 and 12.74 mg per 100 g, respectively. The minimum ascorbic acid content of 11.90 mg per 100 g was recorded in the untreated control.

Although the treatment differences were not statistically significant, the consistent numerical trend — with ethephon-treated plants recording higher ascorbic acid contents than the control — is consistent with patterns reported in the literature for related cucurbit species and merits interpretive attention. The biologically plausible mechanism involves the role of ethephon in encouraging the biosynthesis of ascorbic acid or in protecting already-synthesised ascorbic acid from oxidation through modulation of the enzyme ascorbic acid oxidase. Vadigeri et al. (2001) documented that ethrel at 400 ppm produced the highest ascorbic acid content of 9.23 mg per 100 g in cucumber cv. Poinsette. Similarly, Hidayatullah et al. (2012) reported improvements in fruit quality parameters with maleic hydrazide treatment in bottle gourd, while Kadi et al. (2018) found that GA3 application influenced quality indices in cucumber.

The non-significance of the treatment effects on ascorbic acid in the present study may partly be explained by the inherently low caloric and nutrient content of zucchini cv. Dark Green, which has a narrow absolute range of variation, making it statistically difficult to demonstrate significance for small absolute differences. Tamer et al. (2010) emphasised that the biochemical composition of cucurbit species can vary considerably among cultivars and in response to environmental conditions, which suggests that the lack of statistical significance in the present study may reflect cultivar-specific rather than treatment-related limitations. Notwithstanding the non-significance, the overall direction of the effect — with ethephon-treated fruits consistently recording higher ascorbic acid contents than the control — is consistent with the broader literature.

4.2 Total Soluble Solids (TSS)

Total soluble solids reflect the combined concentration of sugars, organic acids, proteins, and other dissolved substances in the fruit juice and serve as a proxy for the overall sweetness and flavour profile of the fruit. TSS is also an important parameter in determining post-harvest quality and shelf-life suitability. The data on TSS (°Brix) of zucchini fruits as influenced by the treatments are presented in Table 2.

Table 2. Effect of ethephon and maleic hydrazide on total soluble solids (°Brix) of zucchini fruits

Treatment	TSS (°Brix)
T1 (Ethephon 50 ppm)	5.27
T2 (Ethephon 100 ppm)	5.68
T3 (Ethephon 150 ppm)	5.92
T4 (Ethephon 200 ppm)	6.33
T5 (Maleic Hydrazide 50 ppm)	5.47
T6 (Maleic Hydrazide 100 ppm)	5.36
T7 (Maleic Hydrazide 150 ppm)	5.10
T8 (Maleic Hydrazide 200 ppm)	4.91
T9 (Control)	4.73
CD ($p = 0.05$)	0.18

The TSS content of zucchini fruits was significantly influenced by the treatments (CD at 5% = 0.18). The maximum TSS of 6.33 °Brix was recorded in T4 (ethephon 200 ppm), followed by T3 (ethephon 150 ppm) at 5.92 °Brix. A clear dose-dependent increase in TSS was observed across the ethephon concentration series, from 5.27 °Brix at 50 ppm to 6.33 °Brix at 200 ppm. Among maleic hydrazide treatments, T5 (50 ppm) recorded the highest TSS of 5.47 °Brix, with a progressive decline as the concentration increased through T6 (5.36), T7 (5.10) and T8 (4.91 °Brix). The minimum TSS of 4.73 °Brix was recorded in the untreated control.

The enhancement of TSS in ethephon-treated plants can be explained by the influence of ethephon-derived ethylene on the physiological processes within the plant, particularly its effect on the absorption of plant nutrients and minerals from the soil. Ethephon-derived ethylene is believed to enhance carbohydrate metabolism by promoting the hydrolysis of starch to soluble sugars and by facilitating the translocation of photosynthates towards the fruit. As a result, the pulp of ethephon-treated fruits accumulates greater concentrations of soluble solids, resulting in higher TSS readings. Chaurasiya et al. (2016) similarly documented that the TSS of muskmelon fruits was significantly increased by foliar application of plant growth regulators, with a maximum TSS of 11.30 °Brix recorded with ethrel at 200 ppm, whilst the control recorded only 8.4 °Brix. Hidayatullah et al. (2009) also reported that maleic hydrazide and GA3 significantly increased the TSS of cucumber fruit, with the maximum increase observed with maleic hydrazide at 450 µmol l^{-1}.

The decline in TSS with increasing maleic hydrazide concentration is consistent with its role as a growth retardant at higher doses. At concentrations exceeding 100 ppm, maleic hydrazide appears to broadly suppress plant metabolic activity, including carbohydrate metabolism and sugar accumulation in developing fruits. This pattern is consistent with the observation in the present study that T5 (maleic hydrazide 50 ppm) and T6 (maleic hydrazide 100 ppm) produced TSS values superior to the control, while T7 and T8 (maleic hydrazide 150 and 200 ppm) produced values progressively lower than those of lower concentrations, though still generally above the control. Kadi et al. (2018) documented a similar nuanced relationship between growth regulator concentration and quality attributes in cucumber, where optimal concentrations of GA3 were associated with improved quality while excessive doses showed diminishing returns.

The findings on TSS in the present study are broadly in agreement with those documented for other cucurbit species treated with ethephon, providing further evidence that ethephon-induced physiological modifications — primarily mediated through ethylene signalling pathways (Manzano et al., 2011) — have a consistent and positive influence on soluble solids accumulation in developing fruits across the Cucurbitaceae family.

4.3 Flesh Thickness

Flesh thickness is an important physical quality attribute of cucurbit fruits, as it determines the proportion of edible mesocarp relative to the pericarp and the inner seed cavity. Greater flesh thickness is generally associated with higher market value and enhanced culinary utility. The data on flesh thickness of zucchini fruits under the experimental treatments are presented in Table 3.

Table 3. Effect of ethephon and maleic hydrazide on flesh thickness (mm) of zucchini fruits

Treatment	Flesh Thickness (mm)
T1 (Ethephon 50 ppm)	23.27
T2 (Ethephon 100 ppm)	27.73
T3 (Ethephon 150 ppm)	29.10
T4 (Ethephon 200 ppm)	30.66
T5 (Maleic Hydrazide 50 ppm)	26.80
T6 (Maleic Hydrazide 100 ppm)	25.24
T7 (Maleic Hydrazide 150 ppm)	23.17
T8 (Maleic Hydrazide 200 ppm)	23.05
T9 (Control)	22.15
CD (p = 0.05)	NS

The statistical analysis revealed that the treatment effects on flesh thickness were non-significant (NS at 5% level). Nevertheless, a consistent numerical trend was evident, with ethephon-treated plants exhibiting progressively greater flesh thickness as concentration increased. The maximum flesh thickness of 30.66 mm was recorded in T4 (ethephon 200 ppm), followed by T3 (ethephon 150 ppm) at 29.10 mm and T2 (ethephon 100 ppm) at 27.73 mm. Among maleic hydrazide treatments, the highest flesh thickness was recorded in T5 (50 ppm; 26.80 mm), with values declining at higher concentrations. The minimum value of 22.15 mm was observed in the untreated control.

The non-significance of the treatment effects on flesh thickness may be related to the high degree of natural variability among individual fruits within a treatment, which the three-replication design of the experiment may have been insufficient to resolve at the chosen significance level. Nevertheless, the numerical trend is biologically plausible: ethephon-treated plants, by promoting a greater number of female flowers and ensuring higher fruit set, allow the plant to concentrate metabolic resources on fewer but better-developed individual fruits, each of which potentially has greater flesh accumulation capacity.

The role of growth regulators in influencing flesh thickness is linked to the broader effects of ethylene and growth retardants on cell division and cell expansion within the mesocarp. Ethephon-derived ethylene has been documented to influence cell wall extensibility and plasticity, which can facilitate greater cell expansion in developing fruit tissue, thereby contributing to increased flesh thickness. Sedghi et al. (2008) demonstrated that NAA treatment of medicinal pumpkin significantly increased the number of female flowers per plant, thereby indirectly creating conditions for more favourable individual fruit development. Nagamani et al. (2015) also observed improved fruit quality attributes in bitter gourd plants treated with growth regulators.

The observed differences in flesh thickness among treatments in the present study, while not statistically significant, are consistent with published findings from related species. The absolute differences — from 22.15 mm in the control to 30.66 mm in the best-performing treatment — represent a numerically meaningful improvement of approximately 38% and warrant investigation in future studies with larger plot sizes or greater replication to adequately resolve treatment effects at the statistical significance level.

4.4 Integrated Discussion of Quality Response to Ethephon and Maleic Hydrazide

Taken together, the quality responses of zucchini to ethephon and maleic hydrazide treatments reveal a coherent pattern consistent with the known modes of action of these compounds. Ethephon at 200 ppm consistently produced the highest values for all three quality parameters — ascorbic acid (16.93 mg per 100 g), TSS (6.33 °Brix) and flesh thickness (30.66 mm) — while maleic hydrazide at 50–100 ppm produced intermediate improvements over the control. Higher concentrations of maleic hydrazide (150–200 ppm) tended to reduce quality attributes below the values recorded at lower concentrations, reflecting the compound's growth-retarding properties at elevated doses.

The integrated quality improvement observed with ethephon is attributable to the compound's dual role in promoting femaleness (thereby improving fruit development through more efficient allocation of assimilates to a well-distributed set of developing fruits) and in directly influencing carbohydrate metabolism and biosynthetic pathways associated with ascorbic acid synthesis and sugar accumulation. Hayashi et al. (2001) noted that ethephon, acting through ethylene, influences multiple plant developmental processes including cell division and elongation, which collectively contribute to enhanced fruit quality. Similarly, Hossain et al. (2006) emphasised the significance of the critical two- to four-leaf stage for growth regulator application in cucurbits, noting that PGR treatments at this stage produce the most consistent and substantial effects on both reproductive characteristics and fruit quality.

The pattern of maleic hydrazide response — most positive at lower concentrations and diminishing or occasionally negative at higher doses — is also consistent with the compound's biochemical mode of action. At concentrations of 50–100 ppm, maleic hydrazide selectively retards vegetative growth while having a modest positive effect on female flower production and fruit biochemistry. Kaur et al. (2016), studying cucumber under the influence of maleic hydrazide and ethephon, observed that the application of maleic hydrazide at 200 ppm recorded the maximum number of branches among all treatments, suggesting that at these concentrations the compound promotes lateral development rather than overall growth suppression. This differential response helps explain why lower maleic hydrazide concentrations produced quality attribute values above the control while higher concentrations showed some suppression.

5. Conclusions

The present investigation demonstrates that foliar application of plant growth regulators, particularly ethephon, can improve the fruit quality attributes of zucchini (Cucurbita pepo L.) cv. Dark Green under the sub-tropical conditions of Amritsar, Punjab. Ethephon at 200 ppm (T4) consistently recorded the highest values for all three quality parameters measured — ascorbic acid content (16.93 mg per 100 g), total soluble solids (6.33 °Brix) and flesh thickness (30.66 mm) — and was therefore the most effective treatment for quality improvement. The TSS response was statistically significant (CD at 5% = 0.18), while ascorbic acid and flesh thickness showed consistent positive numerical trends that did not attain significance, likely owing to variability associated with the experimental scale. Ethephon at 150 ppm produced values statistically at par with those of the 200 ppm dose for TSS and may represent a slightly less phytotoxic option. Among maleic hydrazide treatments, lower concentrations (50–100 ppm) produced quality outcomes superior to the control, but were generally inferior to ethephon-treated plants. The mechanisms underlying the quality improvements attributable to ethephon include enhanced carbohydrate metabolism, promotion of nutrient accumulation in fruit pulp, and the modulation of biosynthetic pathways associated with ascorbic acid synthesis and sugar accumulation, all of which are attributable to ethylene-mediated physiological changes in treated plants. Based on these findings, foliar application of ethephon at 200 ppm at the two- and four-leaf stages is recommended as an effective practice for improving the biochemical and physical quality of zucchini fruits under comparable conditions. But readers must remember that while TSS was significantly improved by ethephon at 200 ppm ($p \leq 0.05$), ascorbic acid content and flesh thickness showed consistent numerical improvements that were not statistically significant, and multi-season trials are needed to confirm these trends.

6. Limitations

The present study was conducted over a single crop season (Rabi 2018–2019), which limits the generalisability of the conclusions. Multi-season and multi-location studies are needed to confirm the consistency of quality responses across varying environmental conditions. The investigation employed a single open-pollinated cultivar (Dark Green), and quality responses in hybrid or other open-pollinated cultivars may differ. The non-significance of treatment effects on ascorbic acid and flesh thickness may partly reflect insufficient statistical power owing to the three-replication design, and future studies with larger sample sizes or additional replications may be able to detect these differences at the chosen significance level. The study did not investigate possible residue effects of the applied growth regulators on fruit biochemistry at consumption, which would require further analysis. Additionally, the interactive effects of growth regulator application combined with different fertiliser regimes or irrigation levels on fruit quality have not been addressed.

Declaration

The author of the present research paper, Ravneet Kaur, submitted the thesis in partial fulfillment of the requirements for her degree from the Department of Agriculture, Khalsa College, Amritsar, Punjab, India, during 2018–2019. The present manuscript has been derived from that thesis.

Disclaimer (Artificial Intelligence)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of this manuscript.

Competing Interests

Author has declared that no competing interests exist.

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