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REVIEW

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Accelerating abscission of macadamia nuts using ethephon: are there implications for nut quality?

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ABSTRACT

Macadamia is a valuable nut due to its high content of healthy monounsaturated fats, dietary fibre, antioxidants, and essential minerals such as magnesium-B and potassium. One of the major issues affecting industries around the globe is the delayed nut abscission and a prolonged and expensive harvest. A delay in harvesting also reduces the quality of the kernel. To address this challenge, ethephon is used to accelerate abscission, helping to prevent delays in harvesting. Ethephon can cause up to a 15-fold increase in nut abscission within 4 weeks compared to untreated trees. We provide a brief overview of the use of ethephon and its effects on nut quality. The major side-effects of ethephon used to manage macadamia harvesting are associated with ethylene, which is released from ethephon during the acceleration of plant senescence. This process impacts nut quality and shelf life by modulating lipid composition and nut biochemistry. Additionally, ethephon influences the appearance of the nut and the expression and regulation of specific plant genes. This review bridges the information gap between the application of ethephon for harvesting and its effects on the nut quality.

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Introduction

Macadamia is a high-value nut that is cultivated in many countries, including Australia, South Africa, Kenya, USA, China, Guatemala, Malawi, Zimbabwe, and Brazil (Bandason et al., 2022). In 2022, annual revenue was 300 million USD compared with 7.3 million USD in 1996 (Bouarakia et al., 2023). South Africa and Australia accounted for 31% and 23% of exports, respectively (International Nut and Dried Fruit Council, 2022).

Macadamias are native to Australia, where there are four species, two of which produce edible nuts. *Macadamia integrifolia* and *Macadamia tetraphylla* are known as the smooth shell and the rough shell, respectively (Dailey & Vuong, 2015; Nagao et al., 1992). These species are part of the *Proteaceae* botanical family (Canneddu et al., 2016). These nuts stand out for their content of monounsaturated fats, dietary fibre, protein, total sugar, antioxidants, as well as essential minerals such as magnesium and potassium (Figure 1) (Buthelezi et al., 2019; Y. Liu et al., 2022; Rahman et al., 2021; Schlörmann et al., 2017; Yang et al., 2009). The nut in shell contains about 25% moisture on a dry basis and requires drying. Initially dried by natural convection to 10% moisture, it then undergoes forced convection drying to reduce moisture to around 3.5% on a dry basis (Navarro & Rodrigues, 2016).

Though native to Australia, commercial production of macadamia was initiated in Hawaii during the mid-1920s (O'Connor et al., 2019), and cultivars are now grown across the world. Global production reached 78,415 metric tons in 2022 (Figure 2). In 2021, both global exports and imports reached 37,622 metric tons (International Nut and Dried Fruit Council, 2022). Production and trade are influenced by regional harvesting schedules. In Australia, the harvest takes place from March to September (Brinkhoff & Robson, 2021), whereas, in South Africa, harvest takes place from February to August (SAMAC, 2021). Australia and South Africa export up to 99% of their crop to the USA, China, Japan, and Vietnam (Shabalala et al., 2022). The crop is harvested by collecting nuts from the orchard floor following natural nut abscission (D. A. Walton & Wallace, 2009). Harvesting is affected by cultivar type, rapid fruit abscission, lack of harvesting

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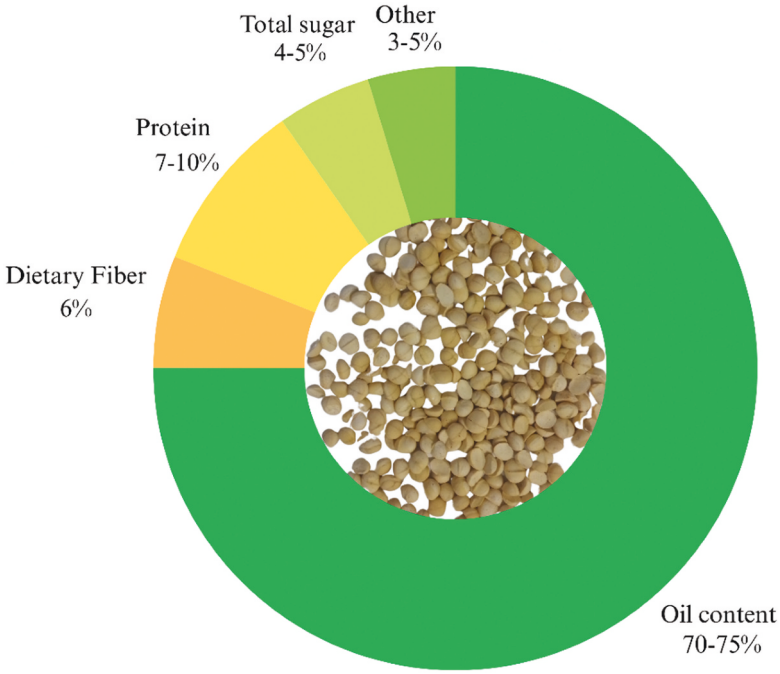


Figure 1. Nutritional composition of macadamia nuts (Buthelezi et al., 2019; Y. Liu et al., 2022; Rahman et al., 2021; Schlörmann et al., 2017; Yang et al., 2009).

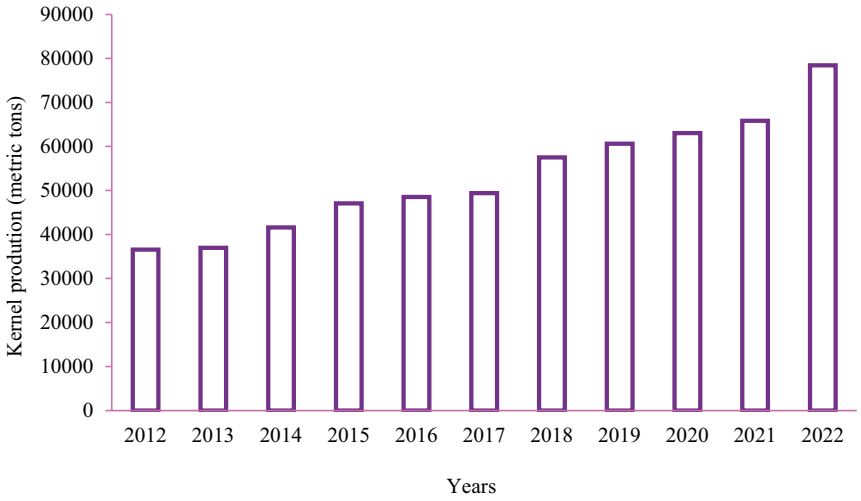


Figure 2. Global macadamia production in metric tons of kernels between 2012 and 2022. Data from the International Nut and Dried Fruit Council (2022).

equipment, inadequate on-farm storage, the inability of processors to receive the product, and weather (Trueman et al., 2002; D. A. Walton & Wallace, 2009). Delayed abscission has been identified as a significant factor contributing to the pattern of commercial nut drop of some cultivars (Trueman et al., 2002). The nuts can remain on the trees for a long period, adversely affecting the quality of the kernels. Hence, there is a need to hasten the abscission process. Macadamia has a high oil content of fatty acids and is susceptible to rancidity and rapid deterioration (Gama et al., 2018). D. A. Walton and Wallace (2009) reported that, when the harvest is delayed, deterioration is more rapid in later-harvested nuts than in those harvested earlier. Kernels from late-harvested nuts have high peroxide values, indicating that lipid oxidation is initiated several months before harvest whilst nuts are still attached to the tree (Gama et al., 2020).

It is crucial to harvest nuts soon after maturity to reduce the loss of quality (Gama et al., 2020; D. A. Walton & Wallace, 2009). However, variations in abscission necessitate the use of cultural practices to hasten nut abscission. This can be accomplished by shaking the trees or by applying ethephon (Quinlan et al., 2008). The combined use of ethephon and shaking has been proven to be the most efficient protocol (Trueman et al., 2002). Ethephon is applied before shaking to reduce the nut removal force, but the use of ethephon alone is the most practical method (D.

Walton & Wallace, 2008). Ethephon releases ethylene after application and accelerates nut abscission (Trueman, 2010). Challenges from delayed abscission and multiple harvests can be mitigated through the use of ethephon.

Therefore, we reviewed current knowledge regarding the effect of ethephon on the harvesting of macadamia. The paper explores possible side-effects of ethephon on kernel quality and shelf life. The findings of this review will help producers make better decisions to maintain profitable macadamia production.

Stages of nut development

The stages of nut development, including ripening and ageing, are closely tied to the tree's growth cycle. This cycle includes floral initiation, flowering, nut set, nut development, oil accumulation, and nut abscission (Figure 3) (Stephenson et al., 2003). Mature trees produce over 10,000 inflorescences (racemes), bearing about 100–300 flowers (Prasannath et al., 2021). Each tree has close to 1–3 million flowers. However, yield does not reflect flower production. Howlett et al. (2015) reported that 0.3% of the flowers resulted in harvestable nuts. This is because a high percentage of flowers drop because they are not fertilised (du Queens et al., 2018). Factors contributing to this issue include inadequate pollination, poor weather, and nutrient deficiencies (De Silva et al., 2022). Identifying the causes of poor nut set can potentially improve yields. Macadamia is partially self-incompatible pollinated and pollinated by bees. Some cultivars are self-compatible; however, they can have higher yields after cross-pollination. Cross-pollination increases yield by up to 95% compared to self-pollination (da Silva Santos et al., 2020; Trueman, 2013). Pollination can be limited by non-pollinator-friendly management and high pesticide use (Grass et al., 2018). Once the fruit have set, nut growth increases until the nuts are mature and have a hard shell (Nortjé, 2018). Subsequently, sugars in the kernals are converted to oil (Nortjé, 2018). Kernels with high sugar content are characterised as immature (Gama et al., 2018; Wall & Gentry, 2007). The highest quality kernels have an oil content of 72–78% (Wall, 2013). Following oil accumulation, the mature nut drops from the trees. However, this stage varies among cultivars and seasons (Trueman, 2013). The extended nut drop poses a challenge to the industry. In the next section, we explore the benefits of plant growth regulators, such as ethephon.

Use of ethephon and other plant growth regulators

Abscission occurs naturally in plants, resulting in the shedding or separation of leaves, flowers, fruit and branches from the parent plant (Meir et al., 2019). The process takes place at the abscission zone and is divided into four phases. The first step includes the differentiation of cells that are present within the abscission zone. This is followed by the second step

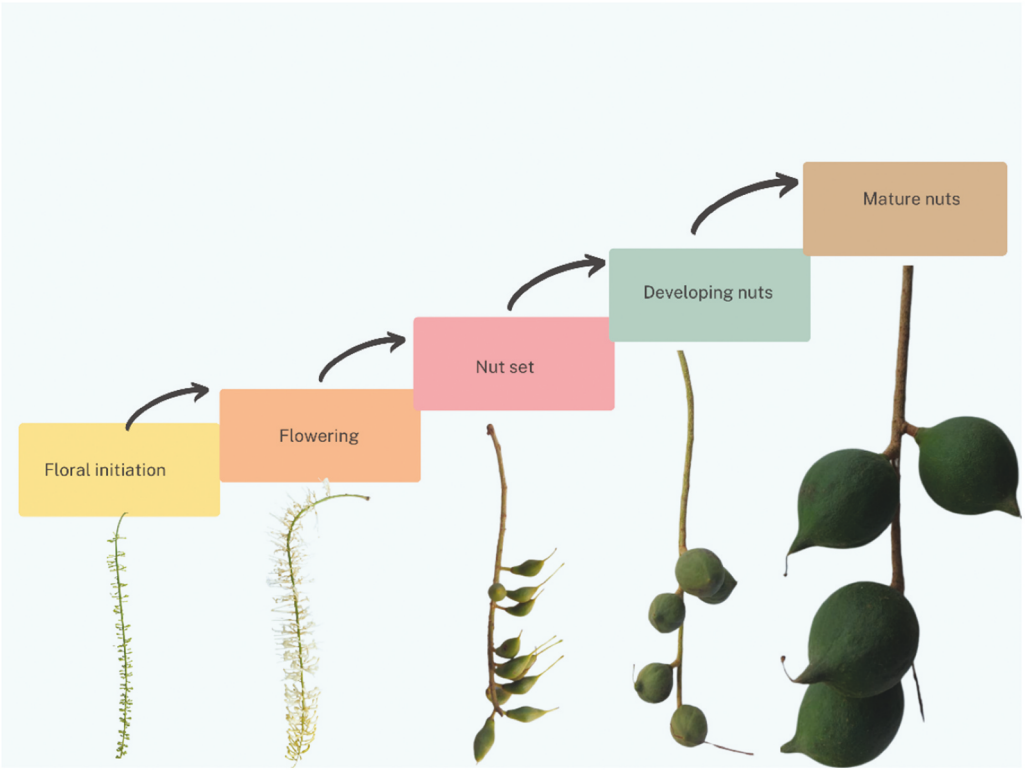


Figure 3. The phenological stages of the macadamia.

where these cells acquire the competence to respond to abscission signals. This is followed by loosening of the cell wall and separation (nut drop). Finally, a protective layer is formed over the abscission zone (J. Kim, 2014; G. Liu et al., 2020a; Patharkar & Walker, 2018; Rai et al., 2021). Two models of abscission have been suggested: senescence-triggered abscission and correlatively driven abscission (Ackerman & Samach, 2015; Bangerth, 2000; Giulia et al., 2013). Senescence-triggered abscission is a natural process that occurs in ripe fruit and leaves where shedding is programmed (Giulia et al., 2013). In this model, as the leaf or fruit matures, ethylene production is triggered, in turn reducing auxin production and basipolar transport of indolyl acetic acid to the abscission zone. This leads to increased sensitivity of the tissue to ethylene, ultimately initiating abscission (Bangerth, 2000). However, this model focuses on mature fruit and doesn't account for the abscission of young fruit. Correlative-driven abscission involves the natural shedding of young fruit, driven by the interplay between neighbouring fruit and nearby shoots (Giulia et al., 2013). This process reflects the regulation of fruit load based on nutritional factors, ensuring effective resource utilisation (Giulia et al., 2013). A fruitlet with a stronger ability to attract and utilise nutrients is more likely to accumulate greater resources compared with neighbour with a lower capacity. The fruitlet possessing higher 'sink strength' has a better chance of surviving (Ackerman & Samach, 2015).

Furthermore, the movement of auxins within fruitlets, encounters specific points termed 'autoinhibitory junctions' along the stem or peduncle (Larson et al., 2022). These junctions act as points of interaction where auxin flow from dominant fruitlets can hinder the movement of auxin from less dominant ones. The reduced downward movement of auxin through the pedicel and heightened sensitivity to ethylene in the abscission zone triggers the abscission of fruitlets (Hagemann et al., 2015). Although ethylene contributes to the final stages of fruit detachment, it is not the initial catalyst for the process, as is the case with abscission prompted by senescence (Bangerth, 2000). The ability of ethephon to release ethylene has made its use practical in accelerating the abscission of macadamia nuts. Ethylene released from ethephon causes the cell inside the pedicel abscission zone to produce cell wall degrading enzymes that are responsible for breaking down the pedicel abscission zone which leads to the detachment of leaves, flowers, fruit, and branches from the parent plant (Hagemann et al., 2015). A systematic process of ethylene-induced abscission is illustrated in Figure 4. Briefly, when

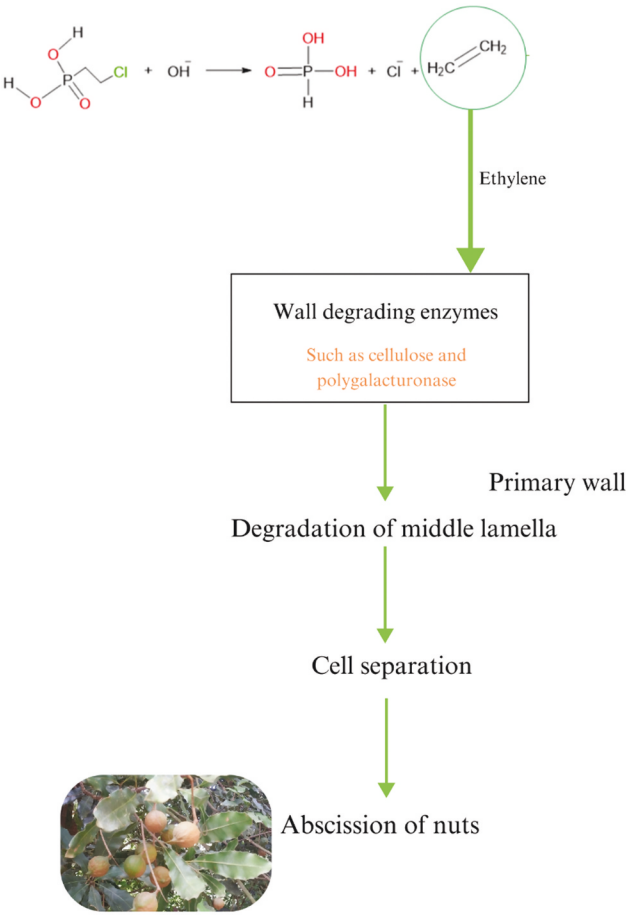


Figure 4. The ethylene-induced abscission process in macadamia (adapted from Yamada et al., 2015).

ethylene is released, it acts as a signal to initiate the synthesis of wall-degrading enzymes, such as cellulose and polygalacturonase. These enzymes are instrumental in breaking down the primary cell wall and the middle lamella, a process crucial for facilitating cellular separation. This step is followed by the breakdown of the cell wall, which results in cell separation and organ shedding (Yamada et al., 2015).

Evaluation of the application of ethephon for macadamia nut abscission

The high costs associated with multiple harvest times and cultivars exhibiting late-season abscission are the major motivations for the use of ethephon to promote nut abscission. Studies done by Trueman et al. (2002) and Trueman (2003) demonstrated that ethephon significantly reduced the harvest duration for macadamia nuts. In the study by Trueman et al. (2002), ethephon-treated plots achieved up to 96% nut drop within 4 weeks, compared to 62% in untreated controls. The study by Trueman (2003) found that ethephon caused up to 86.7% nut drop within the same period, whereas untreated controls saw only 43.2% nut drop (Table 1). These findings collectively demonstrated that ethephon effectively accelerated nut abscission, resulting in a shorter overall harvest period and improved harvesting efficiency. Reports investigating abscission without the use of ethephon revealed that fruit maturation and the timing of abscission are independent in macadamia (Trueman et al., 2000). This necessitates the use of ethephon on cultivars exhibiting delayed abscission. Ethephon applied to 'A16' (a macadamia cultivar exhibiting late-season abscission) effectively induced abscission and had no adverse effects on quality but decreased yields (Trueman, 2003). Ethephon reduced macadamia nut yields significantly, with decreases up to 2.39 kg in unshaken trees mid-season and 2.02 kg (Trueman, 2003). Richardson and Dawson (1993) observed lower yields in the following season when ethephon was applied 2 or 4 weeks after nut maturity (Richardson & Dawson, 1993). This response was primarily attributed to the loss of leaves caused by the chemical (Table 2) (Trueman, 2003). Philips (1970) reported that a decrease in yield is associated with leaf loss. Burns et al. (2003) found that ethephon led to 100% leaf drop after 10 days, providing further evidence of its negative impact on the canopy. When ethephon is applied to plants, it reduces the number of leaves available for photosynthesis. Consequently, the plant's capacity to assimilate carbon dioxide (CO_2) is diminished, in turn resulting in lower yields (Trueman, 2003). However, a recent study by G. Liu et al. (2020b) demonstrated that defoliation does not always lead to yield loss (G. Liu et al., 2020b). Optimized leaf removal can enhance light distribution, subsequently increasing canopy photosynthesis (G. Liu et al., 2020b).

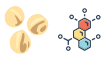
Factors influencing the efficacy of ethephon

In acidic solutions, ethephon remains stable, whereas it hydrolyses in plant tissues with higher pH levels (Torres & Asín, 2022). This hydrolysis releases ethylene, which, upon external application, triggers ethylene-dependent processes such as flower or fruit abscission (Torres & Asín, 2022). In flowers and climacteric fruit, ethephon is exogenously applied but

Table 1. Influence of ethephon concentration on nut drop in various macadamia cultivars.

Ethephon concentration (mg/L)	Cultivar	Untreated trees nut drop	Ethephon treated nut drop %	References
400	'Beaumont'	6%	87%	Richardson and Dawson (1993)
500	'Beaumont'	5%	95%	Kadman and Ben-Tal (1983)
600	'A16'	43.2%	83.6% ± 3.8%	Trueman (2003)
900	'A16'	43.2%	78.9% ± 3.4%	Trueman (2003)
1000	'Ikaika'	–	60%	Nagao and Sakai (1987)
1200	'A16'	43.2%	86.7% ± 3.4%	Trueman (2003)
1600	'A16'	18.29%	93.77%	Jing et al. (2018)

Table 2. Effects of ethephon application on leaf drop, yield, and nut biochemistry in macadamia trees, based on various studies.

Parameter	Effect	Reference
Leaf drop 	Leaf abscission was observed in ethephon treated trees, particularly among older leaves within the canopy, though no specific counts were made.	Trueman et al. (2000)
	Ethephon application was linked to leaf drop, although it was not quantitatively measured.	Trueman (2003)
Yield 	Application of ethephon at 400 mg/L reduced subsequent yield to 48 nuts per tree, compared to 121 nuts per tree in untreated controls.	Richardson and Dawson (1993)
	There was no observed negative impact on the yield following ethephon application.	Jing et al. (2018)
Nut biochemistry 	No significant changes were noted in kernel oil content. However, an increase in nut-in-shell (NIS) weight was observed post-ethephon treatment, although this change was not statistically significant.	Trueman (2003)
	Ethephon application significantly influenced fatty acid composition, total phenolics, and flavonoid content in nuts.	Aruwajoye et al. (2023a) Aruwajoye et al. (2023b)

induces endogenous ethylene biosynthesis. Two distinct systems have been acknowledged in regulating ethylene production. The first is System 1, where ethylene suppresses its biosynthesis during vegetative growth. System 2 operates exclusively during climacteric fruit ripening in specific species and is characterised by an autocatalytic ethylene biosynthesis process that intensifies production (Argueso et al., 2007). Autocatalytic ethylene production involves ethylene-induced upregulation of enzymes such as 1-aminocyclopropane-1-carboxylate synthase and 1-aminocyclopropane-1-carboxylate oxidase, which play a crucial role in the rate-limiting reaction of ethylene biosynthesis (Gorny & Kader, 1997). Marei and Crane (1971) reported that exogenous ethylene stimulates the tissue to produce more ethylene. However, a recent study by Reig et al. (2016) on loquat fruit suggests that the ethylene released by ethephon might have a transient effect, lacking the ability to trigger the autocatalytic biosynthesis of ethylene and, as a result, the subsequent ripening process. The response to ethephon can be inconsistent due to cultivar, weather, chemical rate, time of application and spray additives (Jing et al., 2018; Torres et al., 2021). Some cultivars exhibit a differential response to ethephon. For example, kiwifruit has two commercially important species (*Actinidia deliciosa* and *A. chenensis*). *A. chenensis* exhibit higher endogenous ethylene production (Ampa et al., 2016; Asiche et al., 2016). This may be attributed to genetics and higher levels of ethylene biosynthesis enzymes. Temperature affects the degradation of ethephon, with degradation more rapid at higher temperatures (Ali et al., 2012; Walters & Lopez, 2018). Ethephon applied under low temperatures has been associated with poor abscission, whereas in high temperatures, the growth regulator may cause over-thinning or defoliation (Yuan, 2007). Moreover, research has optimised the use of ethephon for nut abscission, focusing on the solution's pH and effective concentration (Jing et al., 2018). However, as a strong acid, ethephon can alter the final pH of the solution, potentially impacting its effectiveness (Camberato et al., 2014). Higher efficiencies are attained if the age of the nut is also considered (Nagao & Sakai, 1988). The sensitivity to ethephon varies with the stage of nut development. Nuts that are small (3–7 weeks after flowering) and mature nuts nearing maturity (28–30 weeks after flowering) respond to ethephon (Jones, 2002). In contrast, mid-size nuts are not sensitive to the chemical (Jones, 2002). This suggests that the timing to ethephon application can affect the rate of nut drop.

Application of ethephon on nut trees

Ethephon has many benefits but also undesirable side-effects (Table 3; Atli et al., 2021; Grijalva-Contreras et al., 2011; Kamiab et al., 2020; Wang et al., 2016a). Ethephon induces synchronised flowering but also causes massive defoliation (Jhade et al., 2019). Ethephon can induce fruit abscission or loosening, but this can come at the expense of defoliation (Burns et al., 2008). For example, ethephon applied to table olives reduced fruit detachment force but defoliated the plants (Burns et al., 2008). Khalil et al. (2016) reported that high rates of ethephon caused leaf and nut drop and decreased total kernel weight of pecan nuts (Khalil et al., 2016). Similarly, the use of ethephon reduced the size and number of pistachio nuts, reducing market value (Rahemi & Ramezanian, 2007). Ethephon maintained kernel quality when walnuts were harvested within 10–14 days of treatment

Table 3. The effect of ethephon on selected tree nuts.

Tree nut	Concentration of ethephon	Benefits	Side-effects	References
Almonds (*Prunus dulcis*)	75–300 mg/L	Delayed bloom.	Up to 3-fold yield reduction.	Grijalva-Contreras et al. (2011)
Pecan (*Carya illinoensis*)	200, 400, and 600 mg/L	Increased leaf chlorosis and kernel quality.	Reduced total kernel weight, and leaf defoliation.	Khalil et al. (2015)
Pecan (*Carya illinoensis* (Wangenh.) C. Koch)	600 mg/L	Increased fruit set.	Decreased total kernel weight.	Khalil et al. (2016)
Walnuts (*Juglans regia* L)	40, 70, and 100 mL/100 L	Increase in hull-dehiscence.	Slight yellowing of the leaves.	Lang and Evans (2010)
Walnuts (*Juglans regia* L)	0, 10, 500, and 8000 mg/L	Low concentration enhances resistance and retards the decay of fresh in-husk nuts.	High concentration promotes senescence and decay of the fruit.	Wang et al. (2016)
Pistachos (*Pistacia vera* L)	100 and 200 mg/L	Increased size of the nut, floral bud retention, weight of kernel, and decreased % of seedless nuts.	Reduced number of fruit per cluster.	Rahemi and Ramezanian (2007)
Pistachos (*Pistacia vera* L)	1000, 3000, and 5000 mg/L	Improved cluster breaking force from the branch and endocarp removal force from the seed.	–	Atli et al. (2020)
Pistachos (*Pistacia vera* L)	75, 150, and 200 mg/L	Decreased flower bud abscission and increased yield, nuts per ounce, blank and split nuts percentage improved.	–	Kamiab et al. (2020)
Cashew (*Anacardium occidentale* L)	50 mg/L	Increased nut yield and the number of fruit set and decreased fruit drop.	–	Lakshmipathi et al. (2014)

but decreased quality when harvesting was delayed (Lang & Evans, 2010). In some cases, the side-effects of ethephon are minor (Table 3; Lang & Evans, 2010). Ethephon has been studied for its potential application on almond trees since the flowers are vulnerable to frost damage (Omidifard & Gharaghani, 2022). Grijalva-Contreras et al. (2011) assessed the effect of ethephon on delaying bloom and found that application of ethephon at the 10% leaf drop resulted in a delay of bloom by 7, 8 and 9 days at 75, 150 or 300 mg L^{-1}.

Factors affecting the post-harvest quality of macadamias

Nuts, including macadamia, are susceptible to oxidative rancidity and rapid deterioration due to their high oil content and fatty acid composition (Gama et al., 2018). Pre-harvest, harvest, and post-harvest conditions affect nut biochemistry and quality. Gama et al. (2020) reported that macadamias harvested later in the season had a shorter shelf life and lower oil quality than those harvested earlier (higher free fatty acid levels). Similarly, oil extracted from early harvested almonds had superior quality (lower K232 and K270 values and a higher K232/K270 ratio) compared to late-harvested almonds (Kazantzis et al., 2003). Based on Kazantzis et al. (2003) findings, the degradation of oil quality was attributed to the increase in UV absorption coefficients K232 and K270, which are respectively linked to the formation of conjugated hydroperoxides from lipid oxidation and the presence of hydroperoxide breakdown products. On the other hand, in *Torreya grandis*, later harvested nuts had lower free fatty acid levels and peroxide values compared to early harvested nuts (Y. Wang et al., 2021). The findings suggest that the optimal time of harvesting varies with the species and its susceptibility to lipid oxidation. The quality of all nuts, including macadamia, can be revealed by various indices such as oil content, lipid oxidation, moisture content, and rancidity (Buthelezi et al., 2019). Oil content is the most critical quality index in macadamia because the nut has unsaturated fatty acids levels greater than 80% (Buthelezi et al., 2019; Rengel et al., 2015).

The effects of ethephon on the post-harvest quality of macadamias

Ethylene released from ethephon can result in changes in nut quality. The abscission process is regulated by a complex series of structural, physiological, biochemical, and molecular changes, which influence nut biochemistry (Qiu et al., 2020). Aruwajoye et al. (2023b) examined the impact of ethephon, designed to stimulate nut detachment, on the fatty acid composition of macadamias ('Beaumont' and '788') during post-harvest storage. Ethephon increased stearic acid and saturated fatty acids (SFAs) in 'Beaumont' and decreased unsaturated fatty acids (USFAs) (Aruwajoye et al., 2023b). Similar results were observed in *Chlorella vulgaris* (*C. vulgaris*) (S. H. Kim et al., 2016). Exogenouse ethylene increased stearic acid and total saturated fatty acids in walnuts when used for hulling (Farooq et al., 2023). Ethylene-induced fruit abscission in oil palm and increased quality as reflected by lower Free Fatty Acids (FFA) and higher oxidative stability (Chew et al., 2021). The treated fruits had a higher triacylglycerol, which is also found in macadamias (Chew et al., 2021). These observations emphasise the effect of ethylene on the nutrition and storage of macadamias

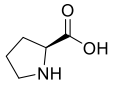
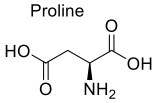
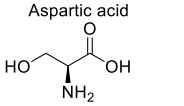
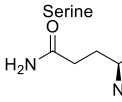
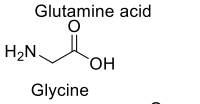
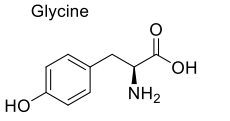
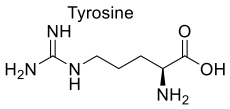
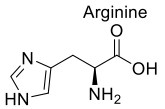
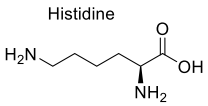
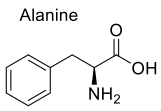
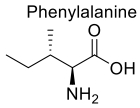
The application of ethephon has been associated with sugar accumulation and changes in phenolic metabolism in fruits and nuts (Aruwajoye et al., 2023a; Li et al., 2002; Wang et al., 2016a). Wang et al. (2016a) indicated that ethephon improved the storage life of walnuts by slowing the role of decay, inhibiting browning-related enzymatic activities, and preserving kernel quality (Wang et al., 2016a). However, at higher ethephon concentrations, a reduction in phenolic content and an increase in polyphenol oxidase activity were observed. This highlights the importance of considering the applied concentration of ethephon.

Effect of ethephon on gene expression and regulation

The impact of ethephon is also evident in its influence on the expression and regulation of specific genes. For instance, Y. Hu et al. (2022) found that exposing *Torreya grandis* nuts to exogenous ethylene enhanced cracking rates, elevated squalene content, and reduced β-sitosterol levels. This indicates an accelerated post-ripening process that influences the biosynthesis of bioactive compounds through ethylene-induced gene expression in the mevalonate pathway, particularly involving TgHMGS and TgHMGR. Ethephon used to induce abscission in *Camellia oleifera* resulted in the upregulation of CoACO1 and CoACO2, which are genes that encode for 1-aminocyclopropane-1-carboxylate oxidase (ACO) enzymes (X. Hu et al., 2021). This is important to note because *Camellia oleifera* has similarities to macadamia nuts; both contain high levels of monounsaturated fats and have a similar fatty acid profile. While the genetic and biochemical responses of *Camellia oleifera* to ethephon are reported (X. Hu et al., 2021), similar responses in macadamia nuts treated with ethephon would need to be investigated.

Moreover, a study by Z. Zhang et al. (2023) found that exogenous ethylene treatment *in Torreya grandis* significantly increased amino acid levels, particularly enhancing umami amino acids

Table 4. The effect of ethylene on the amino acid content of nuts (adapted from Farooq et al., 2023 and Z. Zhang et al., 2023).

Amino acids	Walnuts	*Torreya grandis* nuts
 Proline	–	Decrease
 Aspartic acid	Decrease	Increase
 Serine	Increase	Increase
 Glutamine acid	Increase	Increase
 Glycine	Decrease	Increase
 Tyrosine	Increase	Not significant
 Arginine	Increase	Increase
 Histidine	Increase	Increase
 Lysine	Decrease	Not significant
Alanine	Decrease	Not significant
 Phenylalanine	Decrease	Decrease
 Isoleucine	Decrease	Not significant
Leucine	Decrease	Not significant

like glutamic and aspartic acids (the effect of ethephon on other amino acids is shown in Table 4). This occurred through the upregulation of biosynthesis genes and downregulation of degradation enzymes, ultimately improving post-harvest nut quality. These findings collectively suggest that exogenous ethylene treatment has the potential to improve both the physical and biochemical aspects of *Torreya grandis nuts*, contributing to enhanced post-harvest nut quality.

Conclusions

Ethephon in macadamia production has emerged as a critical tool, promoting uniform nut abscission and easier harvesting. However, a limitation arises when this growth regulator hastens the ripening of the macadamia nuts. Ethephon modulates lipid composition and nut biochemistry. The chemical also affects nut appearance, as well as the expression and regulation of specific genes. Future research should focus on determining optimal application rates and timing for different cultivars. These studies should assess physical, biochemical, and genetic responses. A better protocol for the use of ethephon will help the expansion and viability of this important nut crop.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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Authors' contribution statement

The study was conceptualized by S. Z. Tesfay and N. N. Aruwajoye. The first draft was written by S. Z. Tesfay, N. N. Aruwajoye, and O. O. Olarewaju. The final manuscript was prepared by S. Z. Tesfay, N. N. Aruwajoye, O. O. Olarewaju, and A. E. Oluwalana-Sanusi. Supervision was provided by S. Z. Tesfay, L. S. Magwaza, and A. Mditshwa. Visualization was handled by N. N. Aruwajoye, O. O. Olarewaju, and A. E. Oluwalana-Sanusi.

Data availability statement

Data sharing does not apply to this article since no new data were generated or analysed.

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