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Review

The Effect of Preharvest UV Light Irradiation on Berries Quality: A Review

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Abstract: As a non-toxic, pollution-free, non-residual toxicity, safe, and effective physical method, UV light irradiation can extend the shelf life of fruits, improve the quality of fruits, and conform to the current trend of consumers to pursue green, healthy, and natural food. However, most UV treatments are performed in the postharvest stage. Due to the weak resistance of fresh fruits to mechanical damage, after harvest, UV light treatment of fruits needs to flip the fruits to obtain the full effect of an effective dose, which will inevitably cause different degrees of damage to the skin of the fruits. The research shows that the beneficial effects obtained by UV light treatment are systematic, and the fruits treated by UV light before harvest can obtain similar effects to those treated after harvest. This paper reviewed the effects of preharvest UV light treatment on fruit quality. The effects of preharvest UV light treatment on fruit appearance, flavor, and disease resistance were considered. We conclude that the application of UV light before harvest is of positive significance for the improvement of fruit quality and the extension of shelf life. However, researchers and growers must still correlate the UV light treatment dose with plant response in actual production. Data recording and dose-cultivar-response curve drawing can provide essential guidance for future research and production.

Keywords: preharvest; UV; fruit quality; disease resistance

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1. Introduction

UV radiation is a part of the non-ionizing region in the electromagnetic spectrum. The wavelength range is 10–400 nm, and the energy is 3–124 eV, accounting for nearly 8–9% of the total solar radiation. It can be subdivided into three categories according to wavelength: low-frequency longwave UV-A (320–400 nm), medium-frequency longwave UV-B (280–320 nm), and high-frequency shortwave UV-C (200–280 nm). As abiotic environmental stress, UV irradiation can induce complex metabolic adaptation reactions during plant growth, thus affecting its nutritional characteristics [1] and physiological processes [2]. UV-B and UV-C radiation, as abiotic pressures, have great biological effects on plant growth. The response of higher plants to UV radiation depends on UV wavelength, dose, and plant sensitivity [3,4]. An excessive UV radiation dose will cause excessive production of reactive oxygen species (ROS), causing damage to DNA and plant physiological processes [5,6]. However, a low and suitable UV radiation dose can be used as an inducer or bactericide [7]. The biological phenomenon is defined as a "toxic excitatory effect" by inducing the resistance reaction of living tissue through harmful treatment with a low dose [8]. The toxic excitatory phenomenon has been widely confirmed in living tissues. Harmful treatment with a low dose will not damage living tissues but activate a series of resistance reactions within them, which will benefit the tissues [9].

Fruit is a critical component of the human diet. Among them, fleshy fruits are especially rich in sugar, acid, pigment, minerals, and vitamins. During the ripening process, a series of coordinated changes take place in the fruit's color, texture, flavor, aroma, and chemical characteristics, making the fruit more attractive and nutritious [10]. Although

fresh fruits are rich in nutrients, they are fragile in texture. After harvest, they will suffer significant losses due to diseases, mechanical damage, the shelf life of fruits, etc. According to statistics, these losses reach more than 1/3 of the harvest yield [11]. Postharvest fruits are not resistant to storage and are prone to damage during storage and transportation, damaging the fruit tissue and becoming more susceptible to microbial infection. The disease resistance of fruits will be reduced. It can lead to changes in related metabolic substances, leading to quality deterioration, making the surface lose luster and decay in a short time, seriously affecting the postharvest quality, shelf life, and loss of edible and commercial value. Many cultivation measures, such as nutrient type [12], water supply [13], and harvesting method [14], are also considered factors affecting the quality of fruits before and after harvest. Many preharvest factors cause many postharvest quality losses. Generally, fruits are infected by diseases and pests. Improper irrigation and fertilization result in poor quality before harvest. Therefore, it is vital to know the preharvest factors that can produce high-quality fruit during harvest and use appropriate postharvest treatment and treatment methods to maintain the quality after harvest.

In recent decades, UV light has been mainly used in postharvest fruit preservation. UV light can induce physiological and biochemical reactions in fruits, regulate the production of secondary metabolites and the expression of defense genes to maintain and improve the quality of postharvest fruits [1,15], delay fruit senescence, and improve disease resistance [16]. Many studies have proved that UV has produced sound effects on the preservation of various fruits. UV-C treatment of postharvest fruits will produce local rather than global reactions [17]. Therefore, fruit rotation is required to ensure that all parts are affected by adequate UV light. The UV resistance ability of fruits on living plants is higher than that of fruits in vitro. The former shows a systematic and light response, while the fruits in vitro show a non-systematic but strong response. The unsystematic mode of action of UV-C stimulation is one of the main disadvantages of applying this method in the postharvest stage [17]. However, it can be avoided by applying UV irradiation before harvest [18]. There is little research on applying preharvest UV in fruits [19–22], which is still in the exploration stage. The research shows that the application of low-dose UV-C radiation during the growth of strawberry plants can effectively control the occurrence of gray mold and powdery mildew [23,24]. Obande et al. emphasized the residual effect of preharvest UV-C on postharvest fruits in their research on tomato fruits [18]. The stimulating effect of applying UV-C before harvest increased the disease resistance and delayed the senescence and maturity of the tomato, but the response to the preharvest UV-C radiation was conservative. The response of UV-C light to fruits before harvest is mainly reflected in the accumulation of secondary metabolites, including flavonoids and anthocyanins [25], changes in plant hormone profile [26], activation of antioxidant enzymes [27], and expression of genes regulating transcription factors [28]. Compared with postharvest UV irradiation, which focuses on preventing decay and improving the quality of the fruits picked, preharvest UV irradiation is almost ignored. In addition, UV-C irradiation before fruit harvest has the advantage of not directly handling the product during the treatment process, so the risk of mechanical damage is reduced, which will be conducive to the storage and transportation of soft fruits such as strawberries [29]. At the same time, in comparison to long-term supplemental lighting, supplemental lighting before harvest is a more economical method, which can optimize the metabolites in crops planted in the facility environment [30].

2. Effect of Preharvest UV Light Treatment on Berries Appearance Quality

2.1. Effect of Preharvest UV Light Treatment on Berries firmness

Firmness plays an essential role in the sensory quality of strawberries. Fruits with higher firmness can better withstand transportation and have a longer shelf life [31]. Firmness change is one of the processes of fruit ripening. The firmness values of three strawberry varieties treated with UV-C were higher, indicating that UV-C treatment could slow down the softening time of fruit. This result is consistent with the previous study

on delaying fruit softening by UV-C treatment. The firmness of tomato fruits treated with UV-C at the preharvest stage is higher than that of fruits not treated with UV-C [18,32]. It was also observed that ultraviolet light increased the firmness of strawberry fruit in strawberry fruit grown under the ultraviolet transparent film (280–400 nm). However, the fruit firmness of grapes after UV treatment before harvest is softer, which suggests that UV light treatment before harvest accelerates the ripening of grapes [33]. A certain degree of texture loss can be expected in the maturity process. Accelerated ripening will increase polyphenol content and aroma in grape peel [34]. However, this may affect some taste of fresh grapes [35].

Nevertheless, the quality of grapes is generally acceptable. Considering the stimulation and cumulative effect that the use of UV-C may cause before harvest, the dose and time of treatment should be adjusted to avoid excessive exposure of grapes to UV-C light. Although grapes were treated with a stimulating dose of UV-C less than 10 kJ/m^2 every day before harvest [36], the effect of relatively high-frequency use of UV-C before harvest may have accumulated the dose in plants. The increase in this dosage must directly affect the quality of grapes. In addition, a study [22] showed that the preharvest UV-C treatment increased the fruit firmness of almost all experimental strawberry varieties.

2.2. Effect of Preharvest UV Light Irradiation on Berries Skin Color

Fruit color change is one of the parameters used to evaluate the fruit ripening process. Maturation is a very complex process, involving many physiological mechanisms, and its completion depends on environmental conditions, species, and genera. Low-dose UV-B treatment before harvest accelerated the ripening and coloring of blueberry fruits [37]. Xie et al. used a cumulative UV-C dose of 3.6 kJ/m^2 in the whole stage of fruit development to apply it to strawberry plants according to three cycles of repeated experiments [21]. Meanwhile, preharvest UV radiation significantly affect the fruit color of 'Charlotte' strawberry [22] and a* in the green or mature stage of fully developed tomato fruits when received a short-term dose [18]. a* represents red, and the higher a* is, the redder the fruit will be, which can also be used as a sign of early maturation of strawberry fruit [20]. However, after preharvest UV treatment, the grape color was darker and less yellow and blue. It was believed that preharvest UV light treatment accelerated the ripening of grapes [36]. However, it was inconsistent with the result reported by Obande et al. that "the preharvest tomato fruit after UV-C treatment was delayed to achieve full-color development" [18]. The difference in fruit color under preharvest UV-C irradiation may be related to the difference in UV-C application schemes. Similarly, studies [32,38] showed that a* was often higher in strawberry and tomato fruits grown under continuous UV-B radiation. Xie et al. reported that pre-harvest UV-C could significantly improve the brightness (L*) and color saturation (C) of strawberries, showing more vivid colors [21]. Meanwhile, Dong et al. studied the influence of preharvest UV-B on apples and pointed out that UV irradiation had the potential to enhance the red coloring (a* value) [39].

2.3. Effects of Preharvest UV Light Irradiation on Flavonoids and Phenols in Berries

There is much evidence that polyphenols are substances that absorb UV light. Supplement of UV light can induce the synthesis of polyphenol compounds, especially anthocyanins [40]. Because the target UV light treatment affects the content of polyphenol compounds, this may be an essential tool to improve the beneficial health properties of high-value-added fruits.

The application of low-dose UV-C before harvest had no significant effect on the total phenol content (TPC) of strawberry fruit at maturity. At the same time, the effects of variety and temperature on phenols metabolism were greater than those of UV-C treatment. Preharvest UV-C treatment did not affect the total antioxidant capacity of strawberry fruit measured by TPC, ferric ion-reducing antioxidant power (FRAP), and oxygen radical absorbance capacity (ORAC) [20]. Preharvest UV light increased the content of Procyanidins in blueberries at the green fruit stage [41]. Preharvest UV-C treatment significantly increased

the content of ellagic acid and kaempferol-3-glucuronic acid in strawberries depending on varieties and growing seasons [22].

Several studies have studied the effect of anthocyanin accumulation on the fruit maturity of grapes [42], apples [43], and pears [40]. The potential of apples to produce anthocyanins under UV light varies with fruit maturity. The 5th and 10th days before harvest are the best time to use UV light to induce anthocyanin synthesis of Red Skinned Chinese Sand Pears after harvest [40]. Preharvest UV light significantly increased flavonol accumulation in the early development stage of blueberry fruit and increased the content of anthocyanins and Procyanidins in the late stage of fruit development. Preharvest UV light increased the procyanidins in blueberry fruits at the green fruit stage but had almost no effect on the antioxidant capacity of the fruits [16]. In general, UV irradiation promotes the expression of genes related to flavonoid synthesis in blueberries. Compared with the natural ripening of fruits, the content of Procyanidins in fruits under UV light increased and showed higher antioxidant activity. Ultraviolet irradiation can improve the antioxidant capacity and enzyme activity of blueberry fruits, delay senescence, and reduce postharvest decay of fruits, which is related to the increase of flavonoid accumulation [44,45]. Similarly, activating the antioxidant defense system and secondary metabolic pathway seems to play a crucial role in the response of grapes to UV-B radiation [46]. The anthocyanin concentration in blueberry peels mainly depends on the rate of biosynthesis and degradation/transportation [47]. Preharvest UV-B treatment significantly increased the content of anthocyanins in fruits. UV-B affects anthocyanin accumulation through upstream transcriptional regulation rather than the naturally occurring anthocyanin synthesis and accumulation in mature fruits. Exposure to UV-B light will accelerate fruit color change not only due to the change in ripening time but also the direct impact of UV-B on anthocyanin metabolism. Both short-term and long-term UV-B treatment before harvest can improve the anthocyanin content of blueberries in the green fruit stage and mature stage [41]. The anthocyanin content of mature fruits treated with medium and high doses of UV-B was 50% higher than that of the control. However, the proportion of each anthocyanin component did not change significantly, and the anthocyanin biosynthesis in blueberries was not affected by other light. The effect of preharvest UV light on anthocyanin synthesis may be dependent on varieties and cultivation conditions. Xie et al. had significant differences in total anthocyanin content in the field environment and controlled environment, and the anthocyanin content of the 'Charlotte' strawberry was not affected by preharvest UV light [21], Figure 1.

In apples [47], pears [48], and grapes [49], UDP-glycose flavonoid glycosyl transferase (UFGT) is considered to be the key enzyme for rapid anthocyanin accumulation after UV treatment. Preharvest UV-B and UV-C irradiation significantly promoted the biosynthesis of anthocyanins and the transcription of late biosynthetic genes VcDFR, VcANS, VcUFGT, and VcMYB transcription factors [Figure 1]. The activities of DFR and UFGT in the anthocyanin synthesis pathway were related to UV wavelength and development stage. In blueberries, the expression of VcUFGT was significantly up-regulated after UV-B treatment. The research results of blueberries [37], apples [50], pears [48], and grapes [51] all showed that UV-B induced the expression of HY5 and promoted the synthesis of flavonoids. The expression of VcMYB was positively correlated with the expression of VcANS and VcUFGT and with the response of anthocyanin biosynthesis to ultraviolet radiation. In mature fruits, sugar content increased under UV light before harvest. The reaction of anthocyanins to UV light is mainly caused by the activation of downstream pathway genes of anthocyanins, and VcMYB can up-regulate the expression of downstream pathway genes of anthocyanins [41]. For strawberries, applying 0.6 kJ/m^2 UV-C every two days during the fruit production period did not harm the yield or the time required for fruit ripening and significantly promoted anthocyanin accumulation [52,53].

Preharvest UV irradiation significantly promoted anthocyanin biosynthesis and late biosynthesis gene (LBG) expression. During blueberry development, VcDFR, VcANS, VcUFGT, and transcription factor VcMYB may be up-regulated by VcMYB [16]. These stimulative effects are wavelength and developmental stage-dependent. There are different

reaction mechanisms between preharvest and postharvest UV light irradiation of blueberries, including the systematic reaction of living plants and the non-systematic reaction of postharvest fruits. Notably, the critical factor for the accumulation of final products is not only gene expression but also substrate flow. After the fruit is isolated, the upstream substrate transport is interrupted, and the changes of flavonoids under UV light mainly come from the metabolism of the fruit itself. Therefore, compared with the gene expression level under UV light, substrate flow significantly impacts the flavonoid synthesis of fruits. Research shows that UV-A, UV-B, and UV-C can all induce the increase of flavane-3-ol in the green fruit stage and color conversion stage of grapes in vitro [54]. However, UV light exposure to grapes at maturity will cause a decrease in flavane-3-ol, which may be due to the lack of upstream substrate for anthocyanin synthesis. On the contrary, living plants can still produce photosynthates through photosynthesis and coordinate the flow of photosynthates from photosynthetic organs to fruits, thus providing sufficient upstream substrates for anthocyanin synthesis during UV light irradiation. Therefore, preharvest UV irradiation is more practical than postharvest irradiation.

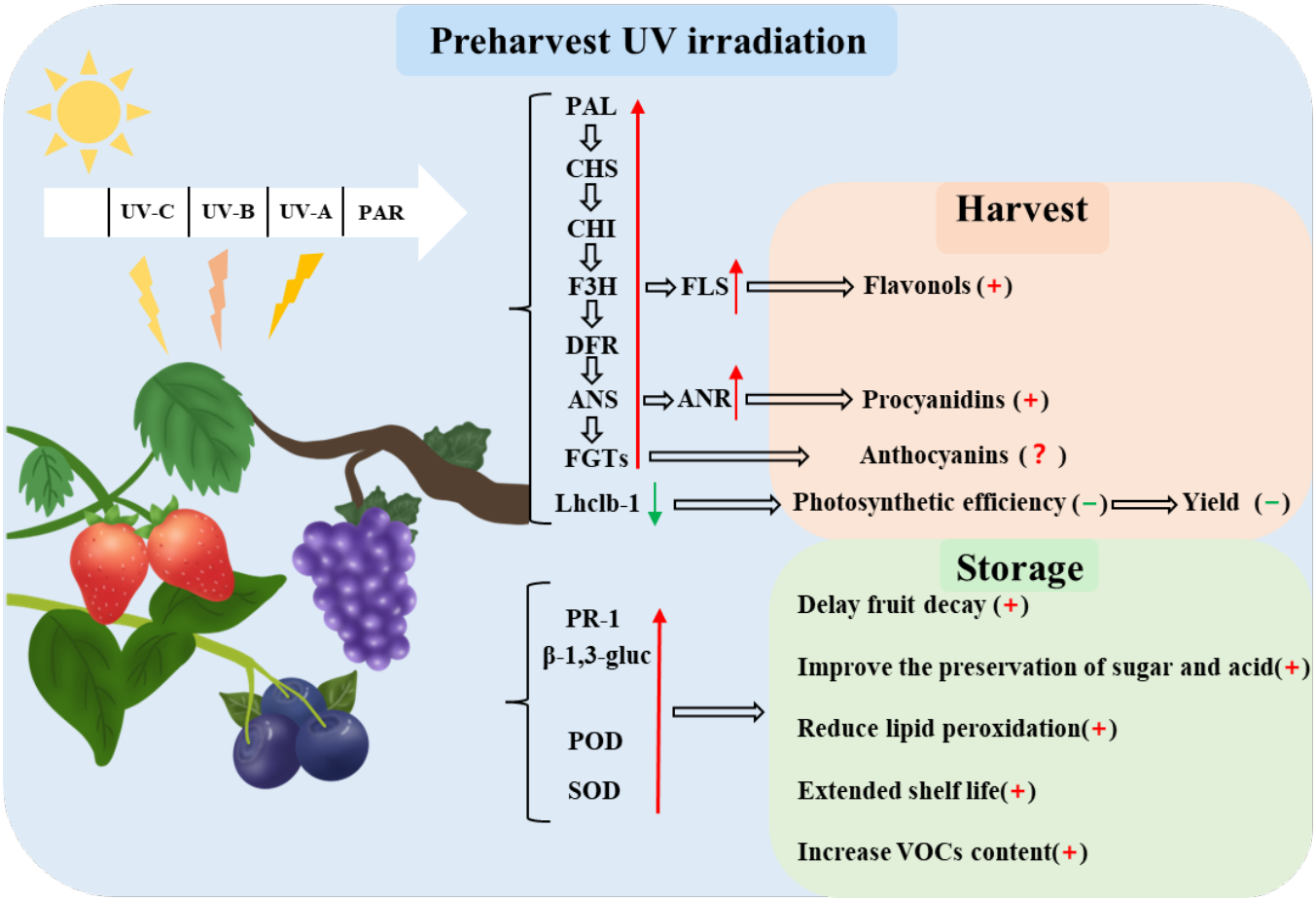

Figure 1. Effect of preharvest UV irradiation on berries. ANS: anthocyanidin synthase; CHI: chalcone isomerase; CHS: chalcone synthase; DFR: dihydroflavonol 4-reductase; F3H: flavanone 3ß-hydroxylase; FGTs: flavonoid glycosyltransferases; FLS: flavonol synthase; PAL: phenylalanine ammonia-lyase; POD: Peroxidase; PR-1: pathogenesis-related protein 1; SOD: Superoxide Dismutase; β-1,3-gluc: β-1,3-glucanase.

The decrease of procyanidin content in young fruits under UV light means that precursor substances used for procyanidin synthesis may flow to other flavonoid synthesis branches such as flavonol. The expression of the flavonoid synthesis gene VcFLS increased under UV light, but the flavonol content did not increase, which may be because the

absorbed carbon flows more to the biosynthetic pathway of anthocyanins and proanthocyanidins than to the flavonol pathway. The regulation of flavonoids and components seems to be closely related to the general phenomenon of overall homeostasis [55]. Therefore, the key synthetic gene expression level determines the accumulation of the final product.

Future work also needs to study the response mechanism of anthocyanin accumulation to preharvest UV light. At the same time, in order to deal with the key compounds synthesized in fruits after UV light irradiation, further research should be conducted on the comprehensive effects of preharvest UV light irradiation on various flavonoid products (such as procyanidins and flavonol) in different development stages and different varieties. These factors need to be discussed from the perspective of the macro metabolic flux of isolated fruits and living plants.

3. Effect of Preharvest UV Light Treatment on Berries Flavor

3.1. Effect of Preharvest UV Light Treatment on Sugar and Acid Content of Berry

The specific sensory characteristics of the fruit are produced by the interaction and combination of various chemicals. In strawberries, sugar and acid have a great contribution to fruit flavor. The sugar content is usually expressed as soluble solids, and the soluble sugar content will increase with the ripening of the strawberry [56], while the titratable acid content is on the contrary.

Xie et al. believed that the preharvest UV-C light treatment would not negatively impact the strawberry's overall taste [22]. The research showed that the content of soluble solids, monosaccharides, titratable acid, and organic acid in strawberry fruits was less affected by preharvest UV-C treatment [22]. It can be considered that preharvest UV-C light treatment will not adversely affect the overall taste of strawberries. However, the titratable acid content of two strawberry varieties, 'Albion' and 'Charlotte', treated with UV-C before harvest is relatively high, which may be related to the delayed fruit ripening process [20]. Preharvest UV-C treatment helped preserve sugar and organic acids during strawberry fruit storage, inhibiting the whole fruit's lipid peroxidation [57]. Vicente et al. found that the content of ascorbic acid and sucrose in the fruit decreased significantly during strawberry storage, while glucose and fructose increased slightly [58]. Even after storage at room temperature for three days, the total sugar content of fruits irradiated by UV-C before the harvest was still high, and the total organic acid content remained low. Preharvest UV irradiation significantly increased the sugar content of blueberry fruits after ripening [41]. Low-dose UV-B treatment before harvest can rapidly promote blueberry fruit growth and sugar accumulation [37]. Low-dose UV-B can promote sugar accumulation in peach fruit by increasing the expression of the sugar transporter gene [59].

3.2. Effect of Preharvest UV Light Irradiation on Volatile Compounds in Berries

During the growth of strawberry plants, increasing UV-C light levels will cause significant changes in the biosynthesis of volatile organic compounds (VOCs). Of the 41 VOCs identified, more than 75% were significantly affected by UV-C light. According to the partial least squares discriminant analysis (PLS-DA) results, three different UV-C doses can produce three different fingerprints of volatile organic compounds in the same crop. The accumulation of volatile organic compounds can bring various benefits to plants.

Volatile organic compounds derived from fatty acids are produced through the LOX pathway through the peroxidation of polyunsaturated fatty acids (such as linoleic acid and linolenic acid) and then reduced downstream under the action of alcohol dehydrogenase (ADH), which converts volatile aldehydes into volatile alcohols [60]. Fatty acid-derived VOCs are the most critical volatile chemicals found in strawberry leaves. They are one of the most severely affected volatile organic compounds by UV-C radiation. PLS-DA shows that with the increase of UV-C radiation dose, the VOCs content gradually increases, which means that VOCs have a solid reaction to UV-C light through the biosynthesis of the LOX pathway. The activation of the LOX pathway after middle and high-dose UV-C irradiation

of fruits indicated that UV-C light stimulated the LOX pathway. At the same time, the content of VOCs derived from fatty acids increased after UV-C irradiation.

In the process of UV-C affecting the synthesis of strawberry VOCs, eight fatty acid-derived volatiles and two isoprene-derived volatiles play a coordinating role between plants and microorganisms, as follows: hexanal, heptanal, nonanal [61], 2-hexenal [62] (E)-2-hexenal, (Z)-3-hexene-1-ol [63], 1-octene-3-ol [64], Cis linalool oxide [65], linalool [66] and 1-hexanol [67]. Most of the VOCs can inhibit the occurrence of *Botrytis cinerea*, one of the major strawberry diseases. The preharvest UV-C treated strawberry fruits had higher ester content at harvest and higher terpene and furanone content after 72 h storage. At harvest time, the accumulation of polyphenols in the UV-C experimental group was relatively high, but it returned to the level of the control group after 24 h of storage [68].

Preharvest UV-C treatment can promote the biosynthesis of fatty acid-derived VOCs in strawberry leaves by increasing the enzyme activity of the LOX biosynthesis pathway. The activities of lipoxygenase and alcohol dehydrogenase were increased under preharvest UV-C treatment. The distribution of VOCs in the samples after preharvest UV-C treatment changed significantly [69], of which 26 volatile organic compounds were the main factor causing the difference. Under medium and high dose UV-C treatment, lipoxygenase and alcohol dehydrogenase activities increased, and strawberries would accumulate up to 18 fatty acid-derived VOCs [70].

4. Effect of Preharvest UV Light Irradiation on Disease Resistance of Berries

UV-C radiation can effectively reduce the development of bacteria in many species, including strawberries (Fragaria × ananassa). Several studies [71–76] show that UV-C radiation is effective not only because of its bactericidal effect but also because it can stimulate plants to defend themselves [77–81].

Preharvest UV-C irradiation is environmentally friendly to control plant pathogens and improve crop quality [82]. UV-C treatment during plant growth will affect the resistance of vegetative organs to pathogens [18,53]. Janisiewicz et al. proved that UV-C treatment before harvest is an effective method to manage *B. cinerea* in strawberry production [83]. Darras et al. showed that UV-C radiation had a substantial impact on the germination of *Botrytis cinerea*'s conidia, and mycelia's growth was significantly delayed [84]. Preharvest UV-C irradiation is an innovative way to increase the content of bioactive substances in strawberries and improve disease resistance of strawberries [70]. UV-C irradiation can reduce the decay of strawberry and tomato fruits inoculated with gray mold spores [72–74,76]. Yao et al. proved that UV-C irradiation of Arabidopsis could affect the disease resistance of non-UV-C irradiated plants in the adjacent control group by producing MeSA, MeJA signal molecules, and other volatiles [85]. The fungal infection will reduce the photosynthetic efficiency and yield per plant. In addition, preharvest UV-C treatment reduced the microbial biomass and the incidence rate of fruit surface in the greenhouse, increased the accumulation of β-1,3-glucanase and pathogenesis-related protein 1 (PR-1), and effectively slowing fruit decay [86], Figure 1. Preharvest UV-C treatment delayed the ripening of tomato fruit and inhibited the growth of penicillium [18].

The effect of preharvest UV-C on the content of bioactive compounds in strawberries seems to be more closely related to varieties [21]. Applying UV-C radiation before harvest can improve the phenylalanine ammonia-lyase activity, anthocyanin, L-ascorbic acid, and other phenolic compounds from the flowering to the harvest stage, and the antioxidant enzymes (superoxide dismutase, SOD; peroxidase, POD) activation of strawberry and the phenol content of treated fruit increased by more than 20% [Figure 1]. However, the preharvest UV-C treatment reduced strawberry photosynthetic efficiency and the reduction of single plant yield by 20% [86]. The application of UV-C light before grape harvest stimulated the synthesis of resveratrol and other stilbene compounds [33,36], increasing the antibacterial property of fruits. Tomatoes treated with UV-C before harvest have a higher hardness and a higher resistance to penicillium during postharvest storage [18]. Similarly, Van Hemelrijck et al. reported that proper interval application of a low UV-C

dose of 0.6 kJ/m^2 was beneficial to the control of powdery mildew of apple seedlings and strawberry plants [24]. Janisiewicz et al. reported that preharvest UV-C light effectively controlled strawberry gray mold, and did not affect leaf photosynthesis and fruit yield and quality [83]. de Oliveira et al. found that the content of phenols, anthocyanins, and L-ascorbic acid in strawberry fruits treated with UV-C light was higher [86]. There are few studies on the use of UV irradiation before harvest [Table 1], and its mechanism of preventing decay and improving fruit quality is still unclear.

Table 1. Application of preharvest UV irradiation in berry crops.

Crops	UV	Dose Rate/Total Dose (kJ/m^2/d)/(kJ/m^2)	Treatment Time	Response	Reference
Grape	UV-C	9.33/9.33, 18.66, 27.99	1, 2, 3 days	Promote fruit ripening and the accumulation of resveratrol and other stilbene compounds, and improves disease resistance	[33,36]
Grape	UV-C	1.92/1.92	1 day	Induce phenol accumulation	[87]
Strawberry	UV-C	0.5/22.5, 42.5	45 days, 85 days	Improve the content of phenols, anthocyanins, and ascorbic acid, and delay the decay of postharvest fruits	[86]
Strawberry	UV-C	0.01236/0.17304	twice/week × 7	Reduce the incidence rate of *B. cinerea*	[83]
Strawberry	UV-C	0.5/14	every 4 days × 28	Improve the content of phenols (especially procyanidins and anthocyanins) and volatile esters	[88]
Strawberry	UV-C	0.6/3.6	twice/week × 3	Increase hardness and ellagic acid content	[20–22]
Strawberry	UV-C	0.6/9.6, 15, 29.4 0.6/6.6	Every 3/2/ 1 days × 16/25/49 Every 2 day × 11	Promote the accumulation of anthocyanins, and polyphenols, facilitate the preservation of sugars and acids Enhance the activity of antioxidant enzymes, promote the accumulation of VOCs, inhibit lipid peroxidation of fruits, and enhance disease resistance	[52,53,57,68,70]
Tomato	UV-C	8/8	1 day	Increase hardness, improve storage, and inhibit the growth of *P. digitatum*	[18]
Tomato	UV-C	-/3.7	1 day	Delay fruit decay and inhibit the growth of *B. cinerea*	[72–74]
Strawberry/Apple	UV-C	0.3/4.8	16 days	Effectively control the growth of *Sphaerotheca aphanis*	[24]
Blueberry	UV-C/B	4.14/12.42	Once/week × 3	Promote the synthesis of anthocyanins and increase the content of sugar, flavonols, and procyanidins.	[16,41]
Blueberry	UV-B	3.528, 4.788/ 24.696~148.176, 33.516~153.216	7~42/32 days	Promote fruit growth, coloring, ripening, and sugar accumulation	[37]
Grape	UV-B	4.75/669.75	141 days	Induce grape berries to produce VOCs (such as aldehydes, alcohols, and ketones, mainly monoterpenes) that protect the tissues from UV-B itself and other abiotic and biotic stresses	[69]
Grape	UV-B	5.98, 9.66/119.6193.2	20 days	Enhance the activity of antioxidant enzymes, preserving leaves from oxidative stress	[89]
Grape	UV-B	86.4/86.4, 172.8, 259.2, 345.6, 432, 604.8	1, 2, 3, 4, 5, 7 days	Increase Flavonols content (particularly quercetin/ kaempferol 3-O-glycosides)	[90]

Table 1. *Cont.*

Crops	UV	Dose Rate/Total Dose ($kJ/m^2/d$)/(kJ/m^2)	Treatment Time	Response	Reference
Peach	UV-B	1.44/30.24, 50.4, 70.56, 90.72, 110.88	21, 35, 49, 63, 77 days	Promote sugar accumulation, increase the anthocyanin contents in peach sarcocarp and pericarp, enhance the sucrose transport to the UV-B-treated fruit	[59]
Strawberry	UV	UV transparent/ opaque film	45 days	Promote fruit coloring, increase fruit firmness, anthocyanin, flavonoid, and phenolic contents	[32]
Tomato	UV-B	6.08/60.8, 109.44	10 d,18 days	Promote fruit coloring, increased the concentration of ascorbic acid and carotenoids	[38]
Apple	UV-A/B	UV transparent/ opaque film	39, 59, 104, 126, 146 days	Increase anthocyanin and flavonol content	[50]
Grape	UV-A/B/C	1.8/1.8	1 day	Increase the content of flavan-3-ol in grape during verasion period and anthocyanin in mature period	[42]
Grape	UV-A/B	UV transparent/ opaque film	Every day	Increase flavonols contents (particularly quercetins and kaempferols), and grape weight and size.	[91,92]
Tomato	UV-A	11.29/-	Every day	Increase VOCs content and acidity	[93]

5. Conclusions

There is limited research on UV light treatment of field plants [20,21,89,94]. These researches mainly focus on vegetative plant organs (such as leaves), rather than reproductive organs (flowers and fruits). Plants showed interspecific and intraspecific differences in UV light tolerance [95,96], which varied with the phenological development stage [97]. The shorter the wavelength is, the higher the photon energy it contains. The positive role of the toxic and excitatory effects of low-dose UV irradiation in agricultural production is mainly proved by the research on UV-B irradiation. A certain dose of UV-B irradiation can promote the secondary metabolism of plants, cause the accumulation of naturally active substances in plants, and induce disease resistance mechanisms. However, to achieve effective treatment doses, UV-A and UV-B radiation treatment generally requires a longer treatment time, usually several hours to several days, which significantly limits the practical application of UV-B radiation [98]. Short-wave UV-C irradiation is an irradiation mode that can achieve an effective dose in a concise time (ten seconds to several minutes). A high dose of UV-C treatment resulted in the browning of tomato peel [99], the dark color of citrus fruit [100], and the scalding of papaya skin [101]. The plant defends against possible damage caused by photosynthetic machinery by the down-regulation of LhcIIb-1, which reduces photosynthetic efficiency and leads to lower yield under the high UV-C radiation treatment [86], Figure 1. Consumers often judge the quality of fruit products by whether they have visual defects. Therefore, the negative impact of UV-C treatment on the appearance may limit the use of this method.

An important goal of future research will be to explore the effect of preharvest UV light dosage on fruit quality. Such research can guide the agricultural practice of using artificial UV light to improve fruits' sensory experience and nutritional quality. In addition, we also need to take into account the impact of the UV light supplement mode on the fruit. For grapes and other fruits in a higher position with leaves above them, it is better to supplement UV light on the side. At the same time, when fruit like strawberry fruit is in a lower position, supplementary lighting from the side or bottom can better illuminate the berry fruit to achieve the desired purpose. However, the current research is not mature, and research on preharvest UV treatment is still rare. The effects of preharvest UV treatment on plant growth and development, fruit quality, shelf life, disease resistance, and other aspects need further research. The effect of the amount of UV toxic stimulants depends on such

factors as temperature, light intensity, production type, variety, maturity, physiological state, harvest season and target pathogens, storage temperature, etc. All relevant factors may adversely affect the beneficial effects induced by UV treatment. Therefore, an effective technical design must be adopted to solve this problem, which requires multidisciplinary research such as postharvest physiology, plant pathology, and engineering. In addition, UV and other physical methods were used to treat the fruit simultaneously, and further study was needed to explore its effects on plant growth and fruit quality. In particular, the relevant planting experiments in the field environment can more truly reflect the impact of UV light dose on the nutritional quality of fruits at maturity under natural conditions and the relevant adaptability induced by these reactions.

In addition, determining the impact of preharvest light quality on the different functions of different plants will be a challenge. The theoretical accumulation of plant response to UV light will be a springboard for further research on the potential molecular mechanism of plant adaptation to light. However, there is no consensus on the mechanism of the influence of plants on preharvest UV light response in the academic community. According to the current research progress, this is the first review on the impact of preharvest UV light on fruit quality, reflecting the lack of relevant research. There are still two problems that cannot be ignored regarding whether some experimental methods to study the response of plants to changes in preharvest UV light are reasonable: (1) Whether the UV light receptors can detect small changes in UV light intensity under low and medium UV radiation in the complex background of a large amount of solar radiation; (2) Lack of dose-cultivar-response curve for the effect of preharvest UV light on fruit quality. When assessing the possible impact of UV radiation dose level changes on plants, drawing a dose-cultivar-response curve should be vital in this research area. Moreover, the future experimental setting needs to be more refined. Individual irradiation treatment should be carried out for each tissue, and the elaborate response curve of each plant tissue to preharvest UV light should be drawn, so as to obtain the mechanism of whether the response of each tissue to UV light can effectively affect the fruit quality to better guide the actual production.

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