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Review

Effect of Magnetic Field and UV-C Radiation on Postharvest Fruit Properties

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Abstract: This review focuses on the recent information on the effect of different types of magnetic fields (MFs) and ultraviolet radiation (UV-C) on the processes that may finally affect fruit quality and its storage potential. Firstly, the biological effect of MFs on every plant's growth and development level is described. The magnetic field interacts with a plant's metabolism and changes the permeability of membranes affecting cells' homeostasis. It also could affect early seedling development, stimulating enzyme activity and protein synthesis, and later on nutrient and water uptake of adult plants. In some cases, it makes plants more resilient, increasing their tolerance to environmental stresses. Also, MF treatment could lower the disease index of plants, thus improving the internal and external fruit quality indices. The second part of this review focuses on interesting perspectives of using UV-C radiation to reduce postharvest fruit diseases, but also to delay fruit ripening and senescence. The application of UV-C light to combat postharvest infections is associated with two mechanisms of action, such as direct elimination of microorganisms located on the fruit surface and indirect triggering of the plant's defense reaction. Moreover, the use of hormetic doses of UV-C can additionally increase the nutritional properties of fresh fruit, lead to the accumulation of desired phytochemicals such as polyphenols, for example, to increase anthocyanin or resveratrol content, or elevate antioxidant activity.

Keywords: magnetic field; UV-C; fruit crops; yield quality; fruit storability

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1. Introduction

Fruits are prone to many postharvest diseases. Among them, fungal pathogens are responsible for very high fruit losses. The most common strategy to control it is the use of synthetic fungicides, which are relatively inexpensive, easy to apply, and have both preventive and curative action against infections [1]. However, the use of fungicides is becoming more limited because of increasing pathogen resistance and environmental and health side effects. Also, the use of the chemicals raises many concerns about the consumers as well as the authorities, resulting in law restrictions, and, finally, shortening the active substances registration list [2]. On the other hand, organic food products are becoming more popular [3]. Therefore, the pursuit of an alternative method of non-chemical techniques to control plant postharvest diseases is a must.

Magnetic field (MF) treatment is considered an effective and emerging tool not only to control plant diseases but also to increase tolerance against adverse stresses (Figure 1). Alongside MF treatment, UV-C irradiation seems to be an efficient way to control many pathogens [4,5]. These physical treatments have gained large interest in recent years to control postharvest pathogens because of many advantages like (i) the total absence of residues in the treated product, (ii) minimal adverse environmental impact, (iii) the direct activity against the pathogens, and (iv) the induction of host resistance [6–8]. What is more important, many of these methods are accepted by organic production law regulations [9]. However, they also reveal some limitations, including lower efficiency, application

problems, and the lack of uniform results. Although many efforts have been made to comprehend the action mechanisms of low-frequency MFs in biological systems, more extensive studies still need to be performed [10–12].

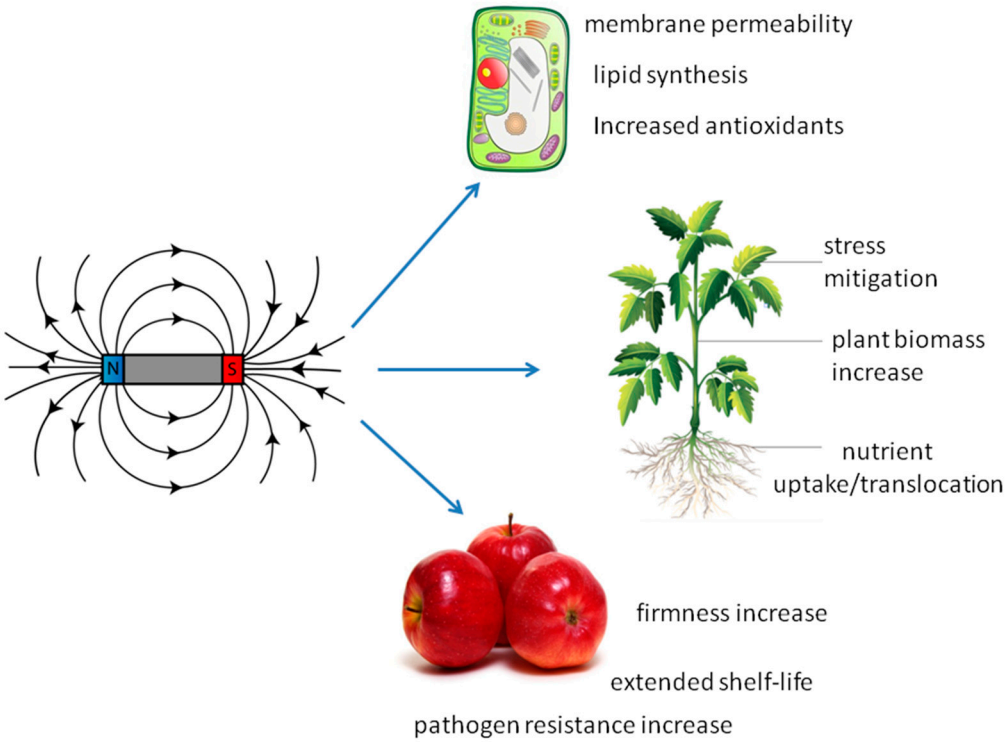


Figure 1. Magnetic field effects on plant physiology.

Therefore, this review aims to gather recent research information on the impact of some electromagnetic wave ranges (MF, UV-C) on plant physiology, emphasize their possible effects on fruit quality and storability, and, finally, enumerate prospects of using electromagnetic fields in fruit production and storage.

2. Magnetic Fields

2.1. Introduction to Magnetic Fields

Recently, the biological effect of electric fields (EFs), magnetic fields (MFs), or electromagnetic fields (EMFs) on pro- and eukaryotes has garnered strong interest as this physical factor could profoundly affect their metabolism, behavior, and even survival [11–16].

However, despite the extensive literature [12,17–19], there is still a lack of a comprehensive view concerning the mechanisms and biological effects of MFs [11]. The literature devoted to the influence of MF on biological systems is very heterogeneous regarding (i) the strength of magnetic field induction (varying from 10^{-7} T to 10 T); (ii) the type of MF (static/oscillating/pulsed magnetic field); and (iii) the duration of the application (exposition) as well as the frequency and polarity of the MF. Research focused on static magnetic fields (SMFs), which are not associated with electrical current, is rare [20]. However, most of the studies are focused on time-varying MFs, which are associated with the changes in the electrical current, while some are with the electric field induced by stationary charges [13]. Thus, some authors postulated that the combination of an electric field and a magnetic field can be viewed as an electromagnetic field (EMF) [21].

Magnetic fields affecting living organisms could be categorized as weak (<1 mT), moderate (1 mT–1 T), strong (1–5 T), and ultra-strong (>5 T of magnetic induction) [18,20]. Strong and ultra-strong SMFs cause changes in animal cells, e.g., differentiation of *Xenopus* frog eggs [22]. It was explained by the possible changes in the orientation of diamagnetic anisotropic organic molecules, such as cells' membrane lipids [20,23,24]. Inflorescences

from *Tradescantia* clones exposed to high MFs showed pink mutations in stamen hair cells [25]. The effect of moderate or low induction static MFs was also studied within numerous eukaryotic model systems, and the noted effects were linked to the changes in Ca^{2+} influx and the permeability of membrane ion channels [22]. MFs also stimulate lipid synthesis in chloroplast, mitochondrial, and other cell membranes [26]. In prokaryotic systems, moderate SMFs affected the growth and survival of bacteria [27] but the results remained inconclusive. However, several attempts were made to use moderate SMFs to eradicate some bacteria and germs [7,28,29].

The Earth's geomagnetic field (GMF) is induced in the fluid outer core by a self-exciting dynamo process [30]. Measured at the ground surface, it ranges from 0.03 mT to 0.06 mT, so it is considered as weak [31,32]. However, there are some differences on the ground in the strength and direction of the Earth's magnetic field. The vertical component of the GMF is at a maximum (about 67 μT) at the magnetic pole and is zero at the magnetic equator, while the horizontal component is at a maximum at the magnetic equator (about 33 μT) and is zero at the magnetic poles [33].

As a magnetic field (MF) is a source of energy, it affects the cell's metabolism [34] and meristem cell division [35]. The GMF can influence many basic physiological functions such as rhythmicity [36], orientation [37], and development [38]. The MF's effect can be explained by ion-cyclotron-resonance (ICR) and the radical-pair model of the magneto-reception mechanism in organisms [39,40]. The different models of the interactions between a weak magnetic field (WMF) and the living organism have been enumerated by Binhi [41]. This included biogenic magnetite and pollution with magnetic nanoparticles; thermal heating and eddy currents; magnetohydrodynamic effects and chemical kinetics with bifurcations; cyclotron, parametric, and stochastic resonances; phase transitions in magnetic fields and the effects of spin chemistry; interference of the quantum states of ions and molecular groups; and coherent excitations or metastable states of water [41].

However, most studies suggested that cryptochromes (CRY), blue-light-absorbing photoreceptors, can sense magnetic stimuli via a CRY-based radical pair [42–44]. The plant cells contain ferritin involved in growth and metabolism [38] with about every 4500 iron atoms. The magnetic rotator moment of these ultimate Fe atoms creates an external MF and collectively generates oscillations, which generate energy and, consequently, re-position the atoms in the direction of the MF. This raises the plant cells' and tissues' temperature, which depends upon the duration and frequency of MF treatment [39]. The WMF affects cryptochrome and phytochrome-mediated plant responses in plants [45]; many other studies confirmed the potential role of cryptochrome as a plant magnetosensor [46,47].

2.2. MF and Plant Development

The MF action mechanism on plant growth and development is still not clear. However, undoubtedly, MFs modulate the initial growth stages and early sprouting of seeds [48,49] (Figure 1, Table 1). The studies confirmed a beneficial effect on seedling elongation [50] and seed germination [51], as well as a strong magnetotropic effect on root stimulation and development [52–64]. Better germination and growth parameters are also linked with increased nutrient acquisition [65,66]. The changes are credited to the activity of Ca^{2+}/calmodulin-dependent cyclic nucleotide phosphodiesterase [67] and cytochrome C oxidase [68], which are altered by the MF. According to Mericle et al. [54], the MF influences the Fe and Co atoms and uses their energy to promote better microelements translocation in root meristems, which results in more vigorous plant growth.

Some authors proved that the pretreatment of seeds by the MF resulted in their vigor, as well as further seedling growth, uptake, mineral nutrient transport, flowering, and, consequently, an increased crop [55,56]. It was proved that MF application affects seed membranes, leading to reduced electron leakage during imbibition [57]. The MF accelerates growth by triggering protein synthesis [55] and involving free radicals [58–61], as well as stimulating the enzyme and protein activity to enhance seed vigor [58]. It also increases

auxin content [62], nutrients [56], and water uptake [63]. It was proved that magnetic fields of low frequency (16 Hz) can be used for postharvest seed improvement [64].

2.3. Plant Productivity

The MF application is a novel approach aiming to enhance the plant's growth and productivity [17,46]. The different levels of MF (4–400 mT) alter the root and stem biomass, as well as the leaf area [12]. What is interesting is that the roots' growth rate is much more sensitive to the MF than shoots [61,69]. The MF promotes root growth in an intensity and direction dependent on increasing auxin concentrations at the root tip [70]. Esitken [49] investigated strawberry plants treated with MFs. He showed that elevated magnetic induction strength (0.096 T) boosted fruit crops by 18%; however, it was associated with a decrease in vegetative growth. Also, Matsuda et al. [71] noted enhanced yield in MF-treated strawberries.

An application of 20–30 mT of MF on vegetable crop plants increased their growth. Taimourya et al. [72] recorded significant increases in vigor (leaves, shoot number, and root length) in tomatoes treated with MFs. The study of Jedlicka et al. [73] confirmed higher crop and biomass of MF-treated (40 mT) tomatoes. MFs may cause changes in the ions, water, metabolites, and growth regulator transport, thus regulating the overall plant growth [74]. The low-intensity MF also impacts the transport of carbohydrates and plant growth hormones from the site of synthesis to the distant growth zones (fruits) [49].

While weak to moderate MFs increase productivity, the lack of a MF is detrimental. Some reported decreased flowering of *Arabidopsis* grown in a "magnetic vacuum" (near null magnetic field) [75]. Barley (*Hordeum vulgare*) seedlings treated with a very low (10 nT induction) MF revealed a decrease in dry biomass of shoots (by 19%) and roots (by 48%) in comparison with GMF controls. From this pioneering study, it was concluded that a very low or close to magnetic vacuum MF was responsible for delaying organ formation and development [76].

Crop productivity could be affected by many detrimental factors, including abiotic stresses. MF treatment mitigates the suppressive effect of heat [77,78] and the chilling stress during maize seed germination [79]. In the first case, higher levels of heat shock proteins are revealed under thermal stress. In the latter, MF exposure stabilizes the membrane permeability and regulates ion transport in stressed seeds to alleviate the detrimental effect. Moreover, MF facilitates biological processes such as photosynthesis, transpiration, and stomatal conductance during stress. Also, increased polyphenol levels induced by MFs in stressed plants could be the reason for preventing ROS production [80].

Table 1. The effect of a magnetic field (MF) on the different plant development processes.

Species	Dose	Parameter	References
Banana	300 mT and 600 mT	Accelerated ripening, increased weight loss	[81]
Lime	10 KHz EMF	Increase biomass of leaves, MDA, proline, and protein content Decrease H_2O_2 and carbohydrates, better health status reduction in phytoplasma in plant tissues (probably)	[82]
Passion fruit	Static MF 200 mT during germination test 14 days	increase in germination speed index, germination %, emergence speed index	[83]
Strawberry	PMF 5–100 mT, AMF 50–150 uT and 5–100 mT t = 5 min, 5 times	Firmness increase up to 30% (for 50–150 uT)	[84]
Strawberry	0.096 T-0.384 T AMF	Increase fruit yield, N, K, Ca, Mg, Cu, Fe, Mn, Na, and Zn in plants Reduce P and S content	[49]

Table 1. *Cont.*

Species	Dose	Parameter	References
Tomato	Static MF 50, 100, 150 mT t = 1 h	Increase in plant height, shoot, and root weight, increased: number of leaves, flowers, and fruits per plant	[85]
Tomato	MF for 50 Hz 20, 40 and 60 mT t = 20 min	Seed germination, growth of young plant, size of fruit, stem length, weight of tomatoes, and earlier fruit setting	[73]
Tomato	100 mT -170 mT SSMF	Enhance plant growth, pigments synthesis, and fruit yield	[86,87]

2.4. Mineral Nutrition

The alternating magnetic field within a wide frequency range (from 0.2 Hz to 100 Hz) also causes changes in the mechanisms of membrane permeability which is responsible for cell, tissue, and whole organ homeostasis. The magnetic field induces the generation of currents, providing the resonance effect, which involves the opening and closing of membrane ion channels [88].

Radhakrishnan et al. [46] noted higher levels of Fe, Cu, Mn, Zn, Mg, K, and Na while lower Ca levels were observed in soybean MF-treated seedlings. Other authors reported enhanced levels of N, K, Ca, Mg, Fe, Mn, and Zn while there was no effect on the amounts of Cu and Na in MF-treated strawberry leaves [49]. The MF affects the membranes and Ca^{2+} signaling in plant cells, and many magnetic effects in living organisms are probably due to the alterations in membrane-associated Ca^{2+} flux [39]. Na-channels are less affected than Ca^{2+} channels [20] and due to the changes in Ca^{2+} channels, the Ca content might be elevated in MF-treated plants.

MF also affects mineral nutrition levels in adult plants. Eşitken and Turan [49] noted that MFs moderate in strength (0.384 T) raised the concentration of macroelements and Zn in tested leaves. However, a decreased level of P as well as S was observed. The mineral nutrition level undoubtedly affects the mineral content of fruits, and, consequently, their storability.

Ercan et al. [89] showed that different MF induction strengths (20, 42, 125, and 250 mT) caused some root cell membrane damage, thus it impacts the macro- and microelement content of investigated tissues. The macroelements P, K, Ca, and Mg were gradually decreased with increasing MF induction level. The reverse was true for microelements Fe, B, Cu, Mn, Zn, and Mo, as measured in roots. Some studies [90] proved the beneficial role of MFs in the alleviation of heavy metals' (Cd, As) toxic effects. Seedlings upon a 600 mT MF revealed a lower level of ROS, but higher overall photosynthetic parameters (amount of total chlorophyll, photosynthetic rate, stomatal conductance, transpiration rate, and intercellular CO_2 concentration) as well as better water use efficiency in Cd stress conditions. Additionally, MFs had a beneficial effect on C and N concentrations in Cd-stressed plants, making plants more resilient.

2.5. Fruit Quality Properties

Fruits reveal high metabolic activity after harvest and, consequently, this leads to the rapid losses of their properties during storage [91] These processes lead to changes in the color, taste, and texture of the fruit [92,93], the latter being most profound. Although the rate of fruit firmness change depends upon the cultivar's genetics, it could also be influenced by environmental factors [94–96]. The main internal factor responsible for the cell wall properties and the intercellular interactions is pectins [97]. Also, cellulase participates in the degradation of cell walls [98], decreasing fruit firmness [99,100].

Puchalski [101] stated that a strong MF (200 mT) increased the firmness of 'Melrose' apples, resulting in 20 days of extended storage capacity. However, surprisingly, in the

case of the Šampion variety, the MF reduced the storage potential. Valentinuzzi [102] pointed out that magnetic fields can have inhibitory properties due to decreased incidence of molecular collisions caused by the orientation of paramagnetic molecules. Boe and Salunkhe [103] in their early study reported that a magnetic field has a positive effect on fruit ripening.

On the other hand, Bourget et al. [104] pointed out that MFs at doses as low as 2.5 mT did not affect the tomato fruit firmness during storage. However, AMF treatment (2.5 mT) of *Cucumis melo* influenced their firmness, increasing by over 50%, as compared to the control. These results indicated that AMFs retarded the fruit softening [105]. Also, Zaguła et al. [106] noted increased firmness of strawberries by 30% after AMF treatment (50–150 uT). MFs penetrate deeper into cells and tissues; therefore, they can influence metabolism at the cellular level [107]. This is in line with other studies. The better firmness retention of MF-treated fruits was noted for tomatoes [108] and persimmons [109].

Some authors [84,110] noted clear selectivity of the MF's impact on monosaccharide (especially fructose) accumulation in strawberries. The increase is observed in the case of the MF within the induction of 50 μT and 100 μT and frequencies of 50 Hz and 100 Hz. It is supposed that this magnetic induction increased enzymatic activity in plant tissue and, consequently, increased the transfer of monosaccharides through cell membranes.

MF-treated apples had up to 25% more glucose [111]. Generally, MFs slightly improved (6–9%) the soluble solids content in strawberries [84]. Boe et al. [103] proved a similar tendency: tomato fruits after a MF dose of 6 mT magnetic induction revealed higher glucose, beta carotene, and lycopene levels. Yusuf and Ogunlela [112] noted higher levels of carotenoids and ascorbic acid in tomato fruits harvested from plants irrigated with magnetic water. It slows down the respiration rate, production of ethylene, and—consequently—the ripening of the fruit. Electro-magnetic fields (700 μT and 900 μT ELF) affected the value of the pH and ascorbic acid level in grapes [113]. To maintain the acidity and vitamin C level in grapes, the effective level of ELF magnetic induction was 900 μT for 2 × 30 min and 2 × 45 min. HVEF efficiently reduced fruit weight loss at the end of storage [105,106]. The use of MFs and EFs has a positive effect on the content of phenolic compounds and antioxidant enzymes [12,13].

However, the mechanism of influence of MFs on fruit ripening is still unclear. Bourget et al. [104] researched the effects of weak static MFs (2.5 mT) on the ripening and senescence of tomatoes. No differences in color or weight loss were observed. On the contrary, Thai cavendish bananas increased mass loss after using MFs (300 mT and 600 mT, 8 days). It also caused hastened ripening as compared to control fruits [81].

The opposite solution, the use of the near null geomagnetic field, for prolonging apple storability was postulated by Zaguła et al. [114]. Authors noted a decrease in respiration of apples 'Jonagold'. The author linked better storability with interactions between the GMF and cryptochrome. It resulted in an inhibition in the enzymatic decomposition of starch and conversion into simple sugars.

2.6. Fruit Protection

In theory, treatment with a strong (electro)magnetic field could be useful as a food preservation method due to its ability to sterilize microbes, as well as the inactivation or inhibition of enzymes engaged in the loss of food property [115,116], Table 2. The MF application could also reduce the harmful effects of pathogens [39]. For instance, citrus plants treated with MFs (10 Hz) revealed a significant enhancement in fresh and dry leaf weight in healthy as well as infected (*Phytoplasma aurantifolia*) plants [82].

A moderate magnetic field (10 mT) can slow down or even inhibit the growth of yeast [117]. It was confirmed that MFs could also enhance the pathogen's resistance. Infected plants treated with MFs revealed higher protein accumulation, alongside the lower carbohydrates. The MF triggers the proline synthesis (a protective osmolyte), which supports cellular structures [118]. The MF also alleviates the biotic stress by reducing H_2O_2 production in infected plants. Conversely, scavenging enzymes control the free radicals,

which alter membrane integrity and increase the resistance in plants against pathogen infection. Similarly, the MF affects polyamine metabolic enzymes such as ornithine decarboxylase (ODC) and phenylalanine ammonia-lyase (PAL), which helps the plant withstand biotic stress [119]. Additionally, MF exposure and the higher resistance could be linked to the accumulation of Ca^{2+}, proteins, and proline in plants. MF usage lowers the plants' disease index due to the modulation of calcium signaling as well as some enzyme (proline and polyamines) pathways.

Table 2. The effect of magnetic field (MF) on the inactivation of fungal pathogens on fruits.

Fruit	Dose	Phytopathogen	References
Blueberry	2 kV/cm 2–6 min	*E. coli*, *Listeria* and native microorganisms	[92]
Strawberry	3.61, 4.56, and 5.13 kV/cm for 1 h	*Botrytis cinerea*	[74]

3. UV-C Radiation

3.1. Introduction to UV Radiation

The ultraviolet (UV) part of the electromagnetic spectrum is divided into four distinct spectral areas including vacuum UV (100–200 nm), UV-C (200–280 nm), UV-B (280–315 nm), and UV-A (315–400 nm) [120–122]. Individual radiation bands (UV-A, UV-B, and UV-C) have different effects on plants and the microorganisms that colonize them. The UV-A and UV-B influence mainly the phototropism and morphogenesis of plants, while the UV-B and UV-C bands are responsible for the plant cells' secondary metabolites production. Short-wave UV radiation (UV-C) is the most energetic, so it is used to inactivate microorganisms, but it can also cause some damage to plants [123].

3.2. Mechanism of Action of UV-C Radiation

It is known from numerous reports that radiation within the range from 200 to 280 nm of wavelength, mostly 254 nm, affects the stability of double bonds between adjacent carbon atoms in nucleic acid components, such as pyrimidines and purines. Inactivation of microorganisms by UV radiation results mainly from the formation of the dimers in the structure of DNA (thymine and cytosine) and RNA (uracil and cytosine) [124]. The most toxic and mutagenic DNA structural changes induced by UV-C radiation include the formation of cyclobutene–pyrimidine dimers (CPDs), such as thymine–thymine and thymine–cytosine dimers, which are formed between two adjacent pyrimidine bases in the same DNA strand [125–127]. This type of lesion accounts for approximately 75% of DNA impairment caused by UV-C radiation. Other severe DNA damage (approximately 25%) generated by UV-C radiation includes the formation of a 6-4 pyrimidine-pyrimidone photoproduct (6-4PP) [125]. Both types of lesions distort the structure of the DNA helix. Changes in the structure of DNA result in errors in the replication of the genetic material and ultimately the interruption of replication and transcription, which in turn leads to cell death [127]. In addition to DNA lesions, due to direct absorption of UV-C, UV radiation can also indirectly affect nucleic acids and other components of a living cell through the production of reactive oxygen species (ROS). It has been reported that in some organisms, oxidative stress can lead to the production of 8-oxo-7,8-dihydro-2′-deoxyguanosine (8-oxo-dG) as well as the formation of strand breaks in the DNA helix [126]. In addition to DNA damage, UV absorption by aromatic amino acid residues can lead to the formation of free thiol groups, which in turn can react with each other to form new disulfide bridges [126].

3.3. Indirect Effects of UV Radiation

The reactive oxygen species (ROS) can also modify the structure of amino acid residues, which may lead to conformational and functional changes in proteins and, consequently, affect protein–protein and protein–nucleic acid interactions [126]. UV radiation can also influence the cell membranes of living cells, which can be damaged by lipid peroxidation [128]. On the other hand, both plants and the microorganisms that colonize them, including phytopathogens, have developed various mechanisms to repair damage generated by ultraviolet radiation [123,126].

3.4. Bactericidal Effect and Application of UV-C Radiation

The bactericidal effect of UV-C radiation is traditionally used, among others, in air purification, surface decontamination, and water treatment, but also in food-related applications, among others, in the disinfection of fresh and fresh-cut fruit and vegetables or cold-pressed juices, nectars, plant-derived milk alternatives, grape musts, wines, and ciders [122,129–142].

A wide group of microorganisms, namely molds, bacteria, and yeast, contribute to fruit and vegetable decay after harvest and food contamination. Kim et al. [128] found that sensitivity to UV-C radiation varied among the tested microorganisms, being the highest in Gram-negative bacteria, then Gram-positive bacteria, and the lowest in tested yeast. Molds are microorganisms considered to be the most resistant to UV-C radiation. Additionally, it is known that spores of fungi and bacteria are more resilient to ultraviolet radiation than vegetative cells. Therefore, much higher doses of UV-C radiation are needed to inactivate bacterial spores than to eliminate non-sporulating bacteria, which are more sensitive [123].

3.5. Factors Influencing the UV-C Efficiency

The effectiveness of disinfection by UV radiation depends on several factors such as the UV-C dose administered, the method of administration, the UV-C wavelength, the type of microorganisms to be eliminated, their sensitivity to UV radiation, the ability of the microbial cells to repair damage made by UV light and the physicochemical properties of the treated food product [122].

3.6. Reduction in Postharvest Diseases and Improvement of Fruit Quality as a Result of UV-C Treatment

The application of UV-C radiation to control postharvest fruit diseases is associated with two mechanisms of action, such as a direct reduction in the population of microorganisms on exposed surfaces, and on the other hand, an indirect mode of action related to the induction of host immunity by stimulating the defense mechanisms of the plant exposed to UV-C [6,143,144] (Figure 2). It was found that when using UV-C to reduce postharvest fruit rot, the UV-C dose is important, the optimal value of which significantly depends on the fruit variety and its physiological age [145].

Examples of the use of UV-C radiation to reduce fruit decay caused by postharvest fungal pathogens are shown in Table 3.

Table 3. The effect of UV-C radiation on the inactivation of fungal pathogens on fruits.

Fruit	Dose	Phytopathogen	References
Apple	4.8 kJ m^{-2}	*Alternaria* [1]	[146]
	7.5 kJ m^{-2}	*Colletotrichum gloeosporioides* [1]	[146]
	7.5 kJ m^{-2}	*Monilinia* [1]	[146]
	7.5 kJ m^{-2}	*Penicillium expansum* [1]	[147]
Grapefruit	2.2 kJ m^{-2}	*Penicillium digitatum* [1]	[146]
	0.5 kJ m^{-2}		[148]
Grape	0.12–0.25 kJ m^{-2}	*Botrytis cinerea* [1]	[149]
	3.6 kJ m^{-2}		[150]
Mandarin	3.4 kJ m^{-2}	*Penicillium digitatum* [1]	[151]

Table 3. *Cont.*

Fruit	Dose	Phytopathogen	References
Peach	7.5 kJ m^{-2}	*Monilinia fructicola* [1]	[152]
Pear	0.36 kJ·m^{-2}	*Alternaria alternata*	[153]
Strawberry	0.25–1.0 kJ m^{-2}	*Botrytis cinerea*	[154]
	0.05–1.5 kJ m^{-2}		[155]
	4.1 kJ m^{-2}		[156]
Tangerine	1.3 kJ m^{-2}	*Penicillium digitatum* [1]	[146]
	0.84–3.6 kJ m^{-2}	*Alternaria citri* [1]	[146]
	0.84–3.6 kJ m^{-2}	*Geotrichum candidum* [1]	[146]
Tomato	3.6 kJ m^{-2}	*Rhizopus stolonifer* [2]	[157]

[1] Fruit artificially inoculated with the tested pathogen after treatment with UV-C light, postharvest UV-C application; [2] fruit harvested at the mature green stage, artificially inoculated with the tested pathogen after treatment with UV-C light.

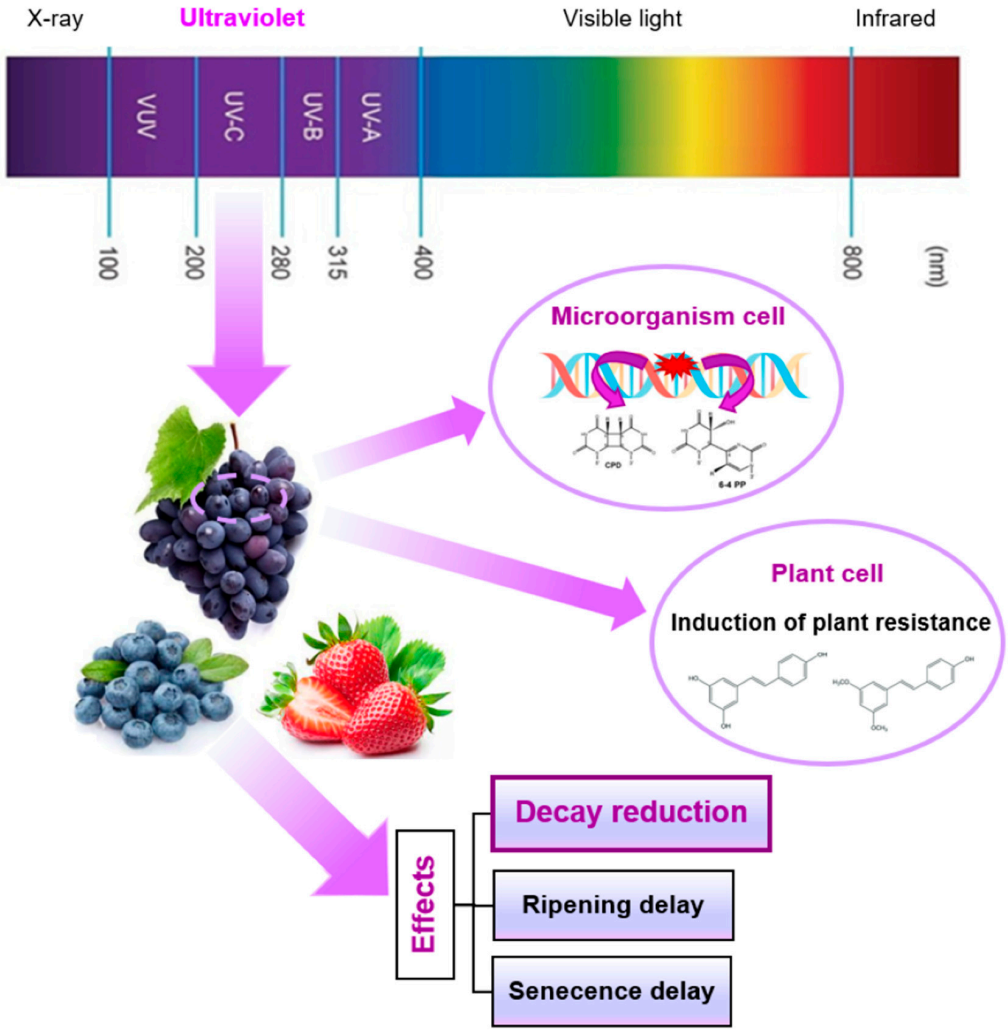


Figure 2. Mechanisms of action of UV-C irradiation to combat postharvest fruit diseases.

The influence of UV-C light (254 nm) on reducing postharvest diseases of pome, stone, and citrus fruit was investigated, and a beneficial effect of such treatment in controlling postharvest decay was noticed [146]. Pre-treatment of fruit with low doses of UV-C, followed by artificial inoculation fungal pathogens, showed reduced postharvest decay. The application of low doses of UV-C reduced the occurrence of apple diseases such as Alternaria rot (*Alternaria* spp.), bitter rot (*Colletotrichum gloeosporioides*), and brown rot (*Monilinia* spp.). There was also a delay in the incidence of brown rot (*Monilinia fructicola*) in peaches, while in tangerines, the occurrence of diseases such as green mold rot (*Penicillium digitatum*), stem end rot (*Alternaria citri*), and sour rot (*Geotrichum candidum*) was reduced [146]. The results of the study showed induced fruit resistance to postharvest decay caused by low doses of UV-C, which were defined as hormetic [146]. Hormesis is a concept introduced by Luckey [158] meaning a stimulation of a beneficial plant response by low or sublethal doses of an agent such as a physical stressor or a chemical inducer. It was observed that exposure to UV-C light was associated with the accumulation of phytoalexins such as resveratrol and pterostilbene in grapes [159], scoparone, and to a lesser extent, scopoletin in citrus fruit [148,160] or 6- methoxymellein in carrots [161]. Moreover, UV-C radiation also induced an increase in phenylalanine ammonia-lyase (PAL) activity in plant tissues (in apples, peaches, citrus fruit, and strawberries) [145,146,162,163]. Similarly, in grapefruit peel, PAL and peroxidase activity increased significantly after exposure of the fruit to UV light [145,164]. The effects of UV-C radiation or magnetic field (MF) on the

activity of enzymes and the production of bioactive compounds in fruits are summarized in Tables 4 and 5.

Table 4. The effects of magnetic field (MF) on the activity of enzymes in fruits.

Fruit	Dose	Effect	References
Persimmon	600 kV/m 30, 60, 90, 120 min	Inhibited pectinesterase activity	[95]
Sapodilla	3 mT, 0.5 h	Decreased activity of pectinase	[93]

Table 5. The effects of UV-C radiation on the activity of enzymes in fruits.

Fruit	Dose	Effect	References
Grape	0, 0.5, 1.0, 2.0, or 4.0 kJ m^{-2}	Increase in antioxidant enzymes activity (SOD and CAT)	[165]
Grapefruit	1.6–6.4 kJ m^{-2}	Increase in phenylalanine ammonia-lyase and peroxidase activities	[164]
Mango	2.46–4.93 kJ m^{-2}	Increase in phenylalanine ammonia-lyase activity Increase in lipoxygenase activity	[166]
Papaya	1.48 kJ m^{-2}	Higher catalase (CAT) activity	[167]
Peach	7.6 kJ m^{-2}	Induction of chitinase Induction of β-1,3-glucanase Increase in phenylalanine ammonia-lyase activity	[168]
Pear	0.36 kJ·m^{-2}	Increase in activities of chitinase, β-1,3-glucanase, peroxidase, superoxide dismutase, catalase, ascorbate peroxidase, and phenylalanine ammonia-lyase Decrease in activities of lipoxygenase and polyphenol oxidase	[153]
Strawberry	0.5–4 kJ m^{-2}	Increase in phenylalanine ammonia-lyase activity	[162]
	0.43, 2.15, and 4.30 kJ m^{-2}	Increase in activities of glutathione peroxidase, glutathione reductase, superoxide dismutase, ascorbate peroxidase, guaiacol peroxidase, monodehydroascorbate reductase, and dehydroascorbate reductase	[169]
Sweet cherry	1.05, 2.10, and 4.20 kJ m^{-2}	Increase in activities of phenylalanine ammonia-lyase, cinnamate-4-hydroxylase, and 4-coumarate-CoA ligase	[170]
Tomato	3.6 kJ m^{-2}	Reduction in cell wall-degrading enzyme activity	[171]

Moreover, the defense response of harvested fruit, exposed to UV-C, decreased with an increase in fruit ripeness, and, therefore, the harvest period also influences the induction of host resistance by UV-C light [143].

Importantly, apart from inducing resistance, UV-C light shows direct activity against plant pathogens and food-contaminating microorganisms. Valero et al. [172] reported that UV-C radiation significantly reduced the germination of conidia of fungi isolated from grapes, such as *Aspergillus carbonarius*, *A. niger*, *Cladosporium herbarum*, *Penicillium janthinellum*, and *Alternaria alternata*. The species *A. alternata* and *A. carbonarius* showed the greatest resistance to UV-C. Similarly, the results of the study by Wenneker et al. [144] indicated that the conidia of the tested fungal species causing apple and pear diseases were completely or partially inactivated by UV-C radiation. It was found that spores of *A. alternata* and *Venturia inequalis* were more resistant to UV-C than conidia of *Penicillium expansum* and *Botrytis cinerea*. UV-C light did not completely inhibit mycelial growth in vitro, but a reduction in growth and sporulation has been observed for most fungal species.

According to Nigro et al. [149], pretreatment of table grapes with low doses of UV-C, followed by artificial inoculation with *B. cinerea*, reduced the incidence of gray rot.

Moreover, no adverse effect on the naturally occurring microflora was observed. It was found that the populations of yeast, yeast-like fungi, and bacteria increased significantly on fruit treated with UV-C doses of 0.25 and 0.5 kJ·m^{-2}. Potentially, some of these epiphytic microorganisms exhibit antagonistic properties towards pathogens. Similarly, Romanazzi et al. [150] showed that UV-C irradiation can be used for postharvest control of gray rot on table grapes and that this method, used alone or combined with chitosan treatment, induced an increased level of catechin and trans-resveratrol (compounds believed to have anticancer and antioxidant properties) in fruit treated with UV-C. According to Erkan et al. [169], strawberries exposed to UV-C radiation for 5 and 10 min (2.15 and 4.30 kJ m^{-2}) were subject to significantly less decay and were characterized by higher antioxidant capacity after storage for 15 days. Furthermore, Liu et al. [173] found that UV-C irradiation with energy of 4 and 8 kJ m^{-2} significantly increased the total phenolic content in ripe green tomato fruit stored at 14 °C for 35 days by 21.2 and 20.2%, respectively. An increase in the total content of phenols and anthocyanins after UV-C irradiation was also observed in blueberries at UV doses of 0.43–2.15 kJ·m^{-2} [174]. Therefore, in addition to the direct elimination of microorganisms from the surface, exposure of fruits to UV light may induce the synthesis of compounds with known health-promoting properties, such as flavonoids including stilbenoids and anthocyanins [175,176]. This phenomenon is related to the UV response mechanism, in which plants exposed to ultraviolet radiation induce the synthesis of specialized metabolites whose role is to protect the plant against photodamage. Flavonoids are among such photoprotective molecules. Some of these compounds also have strong antioxidant, antifungal, and antibacterial properties. Increased production of this type of metabolites may be beneficial from the point of view of the health-promoting properties of fruit or vegetables, and, on the other hand, it may affect the interactions between the plant and the microorganisms inhabiting it and lead to increased resistance to pathogens causing plant diseases and the spoilage of fruit or vegetables during storage [123], Table 6.

Decay reduction and extension of shelf life were also found in the case of mangoes [166,177,178], limes [179], strawberries [155,180], pepper [181,182], peeled garlic [183], lettuce [184,185], or spinach leaves [186].

Moreover, studies on grapes [187], apples [188,189], strawberries [190], blueberries [191], lemons [192], and mangoes [193] also showed that light in the UV-B range induces the flavonoid pathway and can affect the level of many phenolic compounds, such as anthocyanins, flavonols, and proanthocyanidins in fruits. In the case of strawberries, the level of cyanidin 3-glucoside (anthocyanin), as well as quercetin 3-glucuronide and kaempferol 3-glucoside (flavonols), was reduced in fruits grown under film-blocking UV-B radiation compared to strawberries grown in the open field. After using a film partially transmitting UV-B light (about 70% of the radiation), the flavonoid content may increase to a level similar to that in strawberries grown under open field conditions [190]. The study of the synergistic effect of UV-B and UV-C light showed that such a combination of methods covering two subregions of UV spectra can be a highly effective method of pre-treatment for long-term storage of peach fruit [194].

Table 6. The influence of magnetic field (MF) and UV-C radiation on the production of bioactive compounds in fruits.

Fruit	MF/UV-C	Dose	Bioactive compounds	References
Apple	MF	50–150 μT 10–100 Hz 5 min/week	Increase by 8% fructose and 25% glucose	[111]
Blackberry	MF	50 Hz frequency magnetic field of 3 mT for up to 12 h	Increased anthocyanins (up to 6 h) Decreased after longer time	[105]
Blueberry	MF (pulsed)	2 kV/cm 2–6 min	Anthocyanins and phenolic compounds increased by 10 and 25%, respectively	[92]
Cranberry	MF (pulsed)	2–8 kV/cm	Lower respiration rate, no effect on SSC or color	[110]
Embolic fruit	MF	430 kV/m	Increase in vitamin C content	[195]
Melon	MF	2 mT 0–25 min	Reduced organic acid breakdown	[59]
Persimmon	MF (HEV)	600 kV/m 30, 60, 90, 120 min	No impact on the number of total phenols	[95]
Blueberry	UV-C	0.43 kJ·m^{-2}	Increase in phenolic compounds	[174]
		2.15, 4.30 and 6.45 kJ·m^{-2}	Higher antioxidant capacity	[174]
Grape	UV-C	3.6 kJ m^{-2}	Increase in catechin and resveratrol content	[150]
Mango	UV-C	2.46–4.93 kJ m^{-2}	Higher levels of total phenols and total flavonoids	[166]
Mandarin	UV-C	1.5 and 3.0 kJ·m^{-2}	Increase in flavonoids and total phenolic contents	[196]
Orange	UV-C	0.5–3 kJ m^{-2}	Scopoletin and scoparone accumulation	[160]
Papaya	UV-C	1.48 kJ m^{-2}	Increase in flavonoid content in peel	[167]
Peach	UV-C	1.5–4.9 kJ m^{-2}	Increase in polyamines production	[197]
Pear	UV-C	0.36 kJ·m^{-2}	Increase in phenolic compounds	[153]
Sweet cherry	UV-C	4 kJ m^{-2}	Increase in total phenolic content (21–36% in fruit grown under regulated deficit irrigation)	[198]
		1.05, 2.10, and 4.20 kJ m^{-2}	Increase in phenolics, flavonoids, and anthocyanins content	[170]
Strawberry	UV-C	0.5–4 kJ m^{-2}	Increase in ethylene production	[162]
		0.43, 2.15, and 4.30 kJ m^{-2}	Higher antioxidant capacity	[169]
Tomato	UV-C	4 and 8 kJ m^{-2}	Increase in total phenolic content	[173]

The effect of pre-harvest UV-C light treatment on plant growth and the susceptibility of strawberry fruit to major fungal diseases was also investigated. It was observed that exposure to UV-C radiation caused earlier initiation of flowering and reduced the susceptibility of fruits to the development of *Rhizopus* spp. [199].

A study conducted by Syamaladevi et al. [200] analyzed the effect of UV-C radiation on limiting the development of *P. expansum* artificially inoculated on the surface of various organic fruits such as apples, cherries, strawberries, and raspberries. The results of the study showed that UV-C radiation effectively inactivated *P. expansum* on the surface of fresh fruit. However, it was observed that the elimination of the fungal pathogen was significantly correlated with the morphology of the fruit surface. Microorganisms located on fruits with a smoother and even surface (apples) were more susceptible to UV-C exposure and easier to inactivate, while the same pathogen inhabiting fruit that has a rougher and

uneven surface (raspberries) was more difficult to eliminate. Similarly, in another study by Butot et al. [201], moderate effectiveness of UV-C in eliminating bacterial pathogens (*Escherichia coli* O157:H7, *Salmonella*, and *Listeria monocytogenes*) was observed on all three examined types of berries (strawberries, raspberries, and blueberries). The limited inactivation of bacteria on berries could be related to the localization of microorganisms in structures such as stomata, trichomes, irregularities, or cracks on the fruit surface, which are little exposed or inaccessible to UV-C radiation [201].

Moreover, large doses of a stressor, such as UV-C light, may adversely affect fruits and vegetables, cause damage to their tissues, and as a result, lead to increased susceptibility to the development of pathogens [145,146]. For example, visible damage to citrus fruits was reported after the application of large doses of UV-C (approx. > 5–8 kJ m^{-2}) [143,160,202]. Some adverse effects of UV-C radiation at high doses have also been described for peaches [197], grapes [203], broccoli [204], and strawberries [155].

Although high doses of UV-C may negatively affect the color of fruits and vegetables, causing undesirable changes that indicate wilting or spoilage of fresh produce, on the contrary, lower doses of UV-C radiation appear to have no significant influence on the product's color or may even have a positive effect on this parameter by preventing color degradation, e.g., in green vegetables [205]. Undoubtedly, the degradation of chlorophyll is a beneficial change for many fruits, but the same process for some vegetables means a loss of quality [206].

Fruit treatment with hormetic doses of UV-C light can also delay softening. It was found that ethylene production was reduced in tomatoes exposed to UV-C, which resulted in a decrease in the expression of genes encoding cell wall-degrading enzymes and, in consequence, a reduction in their activity and delay in the softening of tomato fruit [171,207]. A similar effect of delaying fruit softening through reduced degradation of cell walls was demonstrated in strawberries exposed to UV-C [208].

In addition to combating fruit fungal pathogens, another benefit of using UV-C light may be the reduction in mycotoxin levels. UV-C radiation with a dose ranging from 14.2 to 99.4 mJ/cm^2 reduced the level of patulin in fresh apple cider [209]. On the other hand, it has been observed that fructose in fruit juices may be decomposed under the influence of UV-C radiation, which may ultimately result in the formation of toxic furan [210]. However, the study by Fan et al. [211] showed that UV-C radiation can induce the formation of furan (mainly from fructose) when used to pasteurize juice. It induced a small amount of furan in apple cider. The influence of the magnetic field (MF) and UV-C radiation on quality characteristics and the occurrence of physiological disorders in fruits is presented in Table 7.

Table 7. The influence of magnetic field (MF) and UV-C radiation on quality characteristics and the occurrence of physiological disorders in fruits.

Fruit	MF/UV-C	Dose	Effects	References
Apple	MF	200 mT 5 × 30 min	Change in firmness depending on cultivar (Melrose increase Šampion decrease, Cortland no change)	[101]
Banana	MF (HEV)	430 kV/m	Respiration rate suppression in the pre-climacteric period	[212]
Blueberry	MF	2 kV/cm 2–6 min	Increased softening, improved safety, quality, and nutritional value	[92]
Mandarin	MF (HEV)	105 kV/m for 1 h	Delayed chlorophyll degradation	[213]

Table 7. *Cont.*

Fruit	MF/UV-C	Dose	Effects	References
Pear	MF (HEV)	430 kV/m	Respiration rate suppression in the pre-climacteric period	[212]
Persimmon	MF (HEV)	600 kV/m 30, 60, 90, 120 min	Delay in weight loss, decreasing hardiness rate	[109]
Plum	MF (HEV)	430 kV/m	Respiration rate suppression in the pre-climacteric period	[212]
Strawberry	MF (Alternate)	AMF for 50–150 uT	Increase in firmness up to 30%	[106]
Grape	UV-C		Delayed ripening and senescence	[214]
Lime	UV-C	7.2 kJ m^{-2}	Delayed ripening and senescence	[215]
Mandarin	UV-C	3.4 kJ m^{-2}	Burning and browning on the fruit surface	[151]
Mango	UV-C	4.0, 8.3, and 11.7 kJ·m^{-2}	Delayed in ripening, reduced endogenous ethylene production, suppressed respiration rate, and lowered chlorophyll content	[178]
Oranges	UV-C	0.5–3 kJ m^{-2}	Delayed ripening and senescence	[160]
Peach	UV-C	1.5–4.9 kJ m^{-2}	Reduced breakdown and chilling injury	[197]
		0.72 kJ m^{-2}	Reduced weight loss, decay, TSS (total soluble solids) of fruits, improved physicochemical and sensory properties during storage	[194]
Pear	UV-C	0.36 kJ·m^{-2}	Reduction in accumulation of mycotoxins released by *Alternaria alternata*	[153]
Strawberry	UV-C	0.25–1.0 kJ m^{-2}	Lower respiration rate, delayed softening, higher anthocyanin amount	[154]
	UV-C	4.1 kJ m^{-2}	Delayed softening and anthocyanin accumulation	[156]
Tomato	MF (HEF)	2 kV cm^{-1}	Delayed softening, respiration and color change	[108]
	UV-C	3.6 kJ m^{-2}	Delayed senescence	[216]
			Delayed fruit softening	[171]

4. Conclusions

The application of MF accelerates seed germination and vegetative as well as reproductive growth in plants due to an increase in energy and its distribution to biomolecules in the cell. Electromagnetic fields can affect the driving of ions, the polarization of electric dipoles, water absorption, storage, and ionization. It also changes the selective permeability of the cell membranes, the position of protein and lipid domains in the membrane, and the molecular position of charge.

Most studies noted changes in the primary/secondary metabolites and enzyme activities, even upon weak MF induction. Also, the enhancement of water and nutrient uptake, photosynthesis, carbohydrates, protein, and enzyme metabolisms would impact the promotion of vegetative and generative growth. MFs alleviate plants' tolerance to adverse environments by reducing oxidative stresses.

MF treatment can enhance plants' drought tolerance by stimulating water and Ca^{2+} uptake, cell membrane permeability, and reducing stomatal conductance. In addition, MF-exposed plants are more resilient to heat stress (increase in heat stress proteins) and cool stress (polar lipids and erucic acids regulation). Moreover, MFs mitigate the stress effects thanks to increasing antioxidant levels and thus reducing oxidative stress in plants. This makes magneto-primed plants more resilient, bearing better-quality fruits.

The application of UV-C light has many desirable features in comparison to traditional chemical methods of combating pathogens causing food spoilage and fruit storage diseases. The mechanism of action of UV-C light includes direct elimination of microorganisms and induction of the plant's defense reaction. The most important advantages of using UV-C for fresh fruit or vegetables include the fact that it is a non-toxic method that does not generate any residues of harmful chemicals in the UV-treated fruit or vegetables, and there is no problem with the waste generated (Table 8). In addition, when used in appropriate doses, UV-C treatment is a non-invasive method, with a minimal effect on the nutritional quality and organoleptic parameters of food. Moreover, another advantage of applying UV-C radiation in extending the shelf life of fruit is that the method is fast, low energy consumption, and environmentally friendly.

Table 8. Comparison of advantages and limitations of magnetic field (MF) and UV-C radiation methods.

	Criterion	MF	UV-C
Advantages	Effectiveness of microbial inactivation	Considerable for pulsed MF or at high MF induction level	Considerable on fruit surface
	Toxicity/Risk of formation of toxic by-products	None	Non-toxic/no residues
	Cost	Low	Low
	Effect on the nutritional quality and organoleptic parameters	Minimal (sugar changes)	Minimal
	Invasiveness of the method	Non-invasive	Non-invasive
	Energy consumption	Low to medium	Low
Limitations	Penetration capacity	Excellent	Low
	Irregularities or wounds on the fruit surface	None	Low effectiveness

On the other hand, the application of UV-C alone to eliminate microorganisms on fresh produce is not common because the method has significant limitations due to its low penetration capacity. Most materials absorb UV-C radiation, which cannot penetrate deeper layers and may inactivate microorganisms only on the surface of a solid product. It is estimated that UV-C radiation penetrates plant tissue to a depth of 50–300 nm [206]. Therefore, the use of UV radiation in the food industry is somewhat limited. It can be used for surface solid food disinfection or packaging [206]. Because UV-C radiation only inactivates microorganisms located on the fruit surface, the problem of latent infections (e.g., in apple fruit) is not eliminated [217]. Moreover, the presence of irregularities or wounds on the fruit surface does not allow full control of microorganisms responsible for fruit storage diseases. Although hormetic treatment of fruit with UV-C radiation induces resistance to postharvest diseases and brings some effects, they are relatively low. Considering the limitations of this method, the synergistic effect of two different technologies is combined. In addition to UV-C light treatment, chemicals [218–220], gamma irradiation [221], modified atmosphere storage [222], heat treatment [155,156,223], ultrasound [224,225], or edible nano-coating [226] are also used.

MFs alone or synergistic with UV-C radiation could be a very promising method for reducing fruit pathogens without any detrimental residuals. However, further experimental effort is needed to elaborate on the most precise, effective, and important repeatable methods designated for the food industry.

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