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# Ultra-weak photon emission: a nondestructive detection tool for food quality and safety assessment

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**REVIEW ARTICLE**

## Abstract

A new aspect covering interactions between cells and their surroundings via electromagnetic waves was introduced by applying ultra-weak photon emission (UPE). The UPE originates from the relaxation of electronically excited species resulting from oxidative metabolic processes and oxidative stress associated with reactive oxygen species (ROS). The ROS plays a critical role in the quality of foods, and their determination is of extreme importance. The ROS and the intensity of the UPE have significantly correlated. The UPE can be effectively monitored by specific instruments such as photomultiplier tube and charged-coupled devices. The current review is devoted to providing an overview of the quality of food products by the aid of UPE via evaluating the correlations between UPE and food quality indices. In this regard, the UPE can be utilized in food quality as a real-time, noninvasive, and nondestructive technique without complex instruments. However, the implementation of the UPE method for evaluation of food quality needs further investigations.

*Keywords*: defense mechanisms; food quality assessment; oxidative stress; reactive oxygen species; ultra-weak photon emission

## Introduction

All known biological systems possess an active oxidative metabolism or stress that involves oxidation reactions in which reactive oxygen species (ROS) play a critical role. These ROS can efficiently react with biomolecules in organisms, resulting in the synthesis of unstable intermediates. The decomposition of these intermediates mostly leads to the formation of unstable excited electron species. During this formation, a tiny amount of light is generated, and monitoring of this light can give essential information about the organism's oxidative state (Cifra and Pospíšil, 2014; Pospíšil *et al.*, 2014).

Investigations regarding cellular communication through ultra-weak photon emission (UPE) started in the 1910s. At that time, a scientist named Alexander Gurwitsch, after conducting various experiments revealed that two separate series of onion root cell cultures, adjacent to each other, could pose some influences on each other regarding cell division and multiplication rate (Bischof, 2003; Prasad *et al.*, 2014; Scholkmann *et al.*, 2013).

The emission of light by various living organisms was demonstrated by several previous investigations (Burgos *et al.*, 2017; Cifra and Pospíšil, 2014; de Mello Gallep and Robert 2020; Esmaeilpour *et al.*, 2020; Jia *et al.*, 2020;

Prasad *et al.*, 2014; Prasad *et al.*, 2020; Van Wijk *et al.*, 2001). According to literature, the concept of UPE was introduced in a variety of terms such as “biophotons,” “ultra-weak emission,” “self-bioluminescent emission,” “photoluminescence,” “delayed luminescence,” “ultra-weak luminescence,” “spontaneous chemiluminescence,” “endogenous bioluminescence,” and “biochemiluminescence” (Salari *et al.*, 2011; Shanei *et al.*, 2017).

As very active and unstable compounds, free radicals are referred to as atoms, molecules, or ions with unpaired electrons (Mayorga Burrezo *et al.*, 2019). In this regard, the oxygen radicals are classified as free radicals which can be produced continuously in all living organs with destructive effects on cellular proteins, lipids, and, most notably, DNA that may lead to carcinogenesis (Saikolappan *et al.*, 2019). The ROS can be classified into two groups as radical and non-radical species (Gill and Tuteja, 2010; Pospíšil *et al.*, 2019). The ROS can react with biomolecules, such as lipids, nucleic acids, and proteins, to cause a deformity and finally increase their levels of energy. Consequently, this reaction creates electron excitation, with later electron’s transition from a singlet-triplet state to the base state with photon emission, usually called UPE (Pospíšil *et al.*, 2014).

The formation of ROS in the food and agricultural industry must be monitored as it is strongly related to public health and may cause an economic burden at a global level. ROS production can be associated with monitoring plant response to pathogens, drought stress, flooding stress, salt stress, and herbicides among agriculture products. Currently, the evaluation of UPE as a robust, real-time, inexpensive, nondestructive, and noninvasive tool to monitor oxidative reactions among several scientific fields, such as medical, pharmaceutical, biological, environmental, agricultural, and food products, is the point of interest. A probable correlation between UPE and food quality indices can be proposed (Gałązka-Czarnecka *et al.*, 2019; Sun *et al.*, 2019). Therefore, the UPE as a diagnostic tool to monitor agriculture processes can be considered for further developments (Cifra and Pospíšil, 2014; Guo *et al.*, 2017; Inagaki *et al.*, 2008; Moraes *et al.*, 2012; Prasad and Pospíšil, 2011).

Due to the rapid growth of the world population, food security, safety, and quality are important issues that should be considered severe challenges (Cheeseman, 2016; Godfray *et al.*, 2010; McCarthy *et al.*, 2018; Prosekov and Ivanova, 2018). Destructive methods are widely employed to evaluate food quality, but they are usually more labor-intensive and time-consuming, which may harm the material. In contrast, the nondestructive methods allow the measurement of different food quality attributes without affecting physical structure and quality. Therefore, the use of nondestructive methods has attracted many researchers (El-Mesery *et al.*, 2019; Magwaza *et al.*, 2013). Traditional nondestructive techniques, such as machine vision, hyper-spectral imaging, near-infrared (IR) spectroscopy, electronic nose, electronic eye, electronic tongue, ultrasound measurements, and acoustic emission measurements, have been employed to assess the quality of food and agricultural products (El-Mesery *et al.*, 2019; Giovenzana *et al.*, 2017; Kheiralipour *et al.*, 2016; Omar and MatJafri, 2013; Schinabeck *et al.*, 2018; Zhong and Wang, 2019).

Currently, the application of UPE in food quality is a hot topic, and investigations are still ongoing regarding measuring food quality indices. However, to the best of our knowledge, no overview of this subject in the food quality area has been provided. Therefore, this article was undertaken to provide an overview considering the measurement of ROS production by UPE in food quality assessment. In this context, the definition, sources of generation, detection mechanisms, and applications of UPE in agricultural products are pinpointed.

## Ultra-Weak Photon Emission

### UPE definition

In addition to chemical signal transduction pathways, the communication between living beings can be carried out through electromagnetic waves (Van Wijk, 2001). In this regard, they could emit light either spontaneously or coherently, which is different from fluorescence, phosphorescence, and conventional bioluminescence (Cifra and Pospíšil, 2014; Shanei *et al.*, 2017). The spontaneous emission can occur without an external excitation or any pre-illumination. The living organisms have a nonexponential decay of UPE after exposure to external light (Rafii-Tabar and Rafieiolhosseini, 2015). The coherent emission is another aspect of UPE, defined as a state of light in which waves can interfere constructively and form interference patterns (Gu, 1999).

As mentioned earlier, the oxidation of biomolecules during cellular metabolism leads to UPE. It was also reported that an organism’s DNA could act as a source of UPE (Prasad *et al.*, 2014).

Induced UPE can be originated from various oxidative factors, mainly biotic and abiotic stresses. The biotic factors include bacterial (Mansfield, 2005), viral (Kobayashi *et al.*, 2006), fungal (Rastogi and Pospíšil, 2012), and herbivorous stress (Yoshinaga *et al.*, 2006). The abiotic stresses arise from factors such as the surrounding environment (Münzel *et al.*, 2018), mechanical damage

(Liang *et al.*, 2019), undesired temperature (Ahammed *et al.*, 2019), light (Nakashima *et al.*, 2017), and ionizing radiation (Singh *et al.*, 2017). All these factors increase oxidative damages because of excessive production of ROS. The UPE possesses a spectral range varying from 200 to 800 nm with fragile intensity (few to hundreds of photons per cm$^2$) (Yang *et al.*, 2017). It is interesting to note that such intensity of radiation is equivalent to look at candlelight with naked eyes from a distance of nearly 24 km (Bischof, 2005), which elucidates the difficulty of capturing these signals.

### UPE detection

The photographic containers and tubes with a particular sensibility to ultraviolet (UV) rays were the first employed devices for UPE detection, capturing waves in the UV range (Cifra *et al.*, 2011). However, the intensity of these waves was very weak for such detection with available detectors. Therefore, their detection was postponed for many years. After some advancements in technology, several suitable devices were introduced to detect UPE, for example, avalanche photodiodes (APD), photodiode arrays (PDA), charged-coupled devices (CCD), microchannel plate (MCP), visible light photon counters (VLPC), superconducting tunnel junctions (STJ), hybrid photon detector (HPD), photo multiplier-tube (PMT), and channel photomultiplier (CPM). PDAs, CCDs, and MCPs, are used for spatial (2-dimensional [2D]) resolution. Considering the devices introduced for 1D resolution, PMTs deal with a characteristic photon density ranging from a few to up to some hundred photons per square centimeter per second. Therefore, they remain a suitable choice for UPE detection. After PMT development in the 1950s, detection of this light achieved notable improvement, and measurements became accurate (Bischof, 2005; Rahnama *et al.*, 2011). At this stage, scientists discovered that UPE was also emitted in the visible range and UV range. Up to now, PMT and CCD cameras have been used widely for the detection of UPE (Cifra *et al.*, 2011). While the former enhances light radiation up to 100 times, the latter detects this light in two dimensions as a highly sensitive photon detector. The MCP devices are sensitive compared with PDA and CCD (Madl, 2014; Ortega-Ojeda *et al.*, 2018).

## Effect of ROS on Plants

### Oxidative stress

Oxidative stress is defined as "an imbalance between oxidant production by free radicals and the antioxidant capacity of the cell" (Sies *et al.*, 2017), which causes severe adverse effects on the growth and productivity of plants. The biotic, abiotic, and stress conditions (Pitzschke *et al.*, 2006) are demonstrated in Figure 1. ROS are free radicals and play a critical role in oxidative stress in which their accumulation in the plant cell leads to damage to some organelles. Besides, along with ROS, reactive nitrogen and sulfur species play an essential role in the cell's oxidative stress development.

### ROS formation

Reactive oxygen species in all aerobic organisms, as well as plants, are continuously formed as a toxic by-product as a result of aerobic metabolism, while they also can be originated from various enzymatic and nonenzymatic processes as well as two biotic and abiotic factors (Bailey-Serres and Mittler, 2006; Gupta *et al.*, 2015). While the sources of ROS in plant cells are located in chloroplasts, mitochondria, peroxisomes, endoplasmic reticulum, apoplast, plasma membranes, and cell wall (Abouzari and Fakheri, 2015), some ROS can be detoxified by some enzymatic and nonenzymatic mechanisms

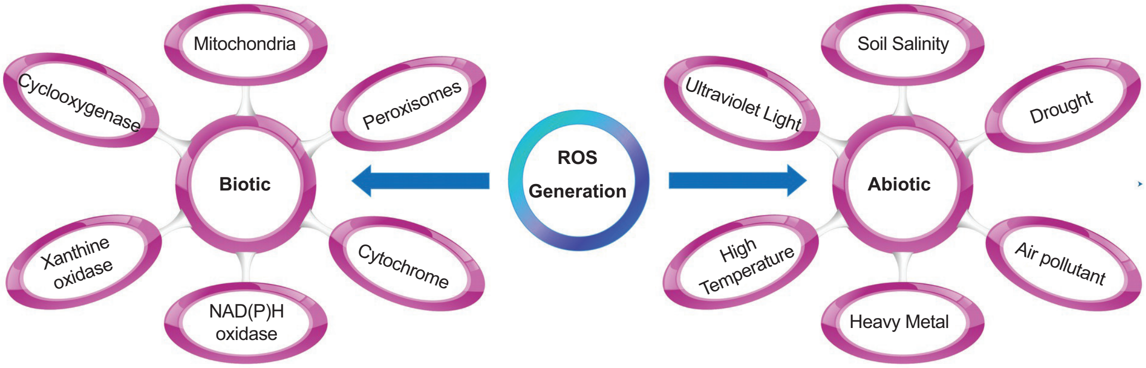

**Figure 1. Sources of ROS generation. ROS, reactive oxygen species.**

(Ahmad, 2013). Figure 2 demonstrates the radical and non-radical forms of ROS.

The reactions for significant ROS generation can be summarized as follows:

$$O_2 + e^- \rightarrow O_2^{\bullet -} \quad (1)$$

$$2O_2^{\bullet -} + 2H^+ \rightarrow H_2O_2 + O_2 \quad (2)$$

$$O_2 + h\nu \rightarrow {}^1O_2 \quad (3)$$

$$Fe^{2+} + H_2O_2 \rightarrow Fe^{3+} + {}^{\bullet}OH + OH^- \quad (4)$$

$$Cu^+ + H_2O_2 \rightarrow Cu^{2+} + {}^{\bullet}OH + OH^- \quad (5)$$

$$O_2^{\bullet -} + H_2O_2 \rightarrow {}^{\bullet}OH + OH^- + O_2 \quad (6)$$

The one-electron reduction of molecular oxygen is responsible for forming high-reactive superoxide radicals (Equation 1). This reduction occurs in mitochondria, chloroplasts, and peroxisomes (Pospíšil *et al.*, 2019). Unlike the superoxide radical, hydrogen peroxide, which is formed through a dismutation reaction by superoxide dismutase (SOD) enzyme, is relatively stable and less reactive (Equation 2) (Battin and Brumaghim, 2009). Hydrogen peroxide can also be produced by different enzymes, such as glycolate oxidase, L-amino acid oxidase, and urate oxidase (Battin and Brumaghim, 2009; Thannickal and Fanburg, 2000). Singlet oxygen, a non-radical, is an excited state of $O_2$, which is not very reactive in its ground state (Equation 3). The chlorophyll and their precursors performed singlet oxygen's primary production (Krieger-Liszkay, 2005; Tripathy and Oelmüller, 2012). In the presence of transition metals (iron [$Fe^{2+}$] or copper [$Cu^{2+}$] ions), the highly reactive hydroxyl radical is formed (Equations 4 and 5) through the Fenton reaction (Battin and Brumaghim, 2009; Janků *et al.*, 2019). Another source of hydroxyl radical is the Haber–Weiss reaction (Equation 6). The Haber–Weiss cycle is a two-step reaction. In the first step, the ferric ($Fe^{3+}$) ion reduction into the ferrous ($Fe^{2+}$) ion occurs via reaction with superoxide radical. The second step is the Fenton reaction (Equations 4 and 5). The first and second steps' net reaction is the Haber–Weiss reaction (Kehrer, 2000).

Under normal conditions, the ROS production rate in cells is low (240 µmol/s and 0.5 µmol $H_2O_2$ at a steady-state level), and the ROS generation is generally in balance with antioxidant capacity. When the oxidative stress exceeds the available antioxidants, the ROS generation's rate increases (240–720 µmol/s and 5–15 µmol $H_2O_2$ in a steady-state level), which consequently, due to further accumulation, causes cell death when some adverse environmental factors perturb the balance between the rate of production and scavenging of ROS, the intracellular levels of ROS may rapidly rise (Pitzschke *et al.*, 2006; Tsugane *et al.*, 1999). Some defense mechanisms involved antioxidant agents that work hand in hand to reduce undesirable phenomenon (Racchi, 2013).

## Antioxidant defense mechanisms

An antioxidant is a substance in low concentration that significantly inhibits oxidation or delays oxidation with different mechanisms (Mousavi Khaneghah, 2016). Among them, oxygen removal or localized oxygen reduction, removal of metal catalytic $Cu^{2+}$ and $Fe^{2+}$, removal of ROS such as $O_2$, $H_2O_2$, and chain reaction interruptions, increase in the rate of ROS scavenging, acceleration of recovery of damaged cell structures, and enhancement of absorbed energy heat dissipation are mentioned in literature. Generally, an antioxidant's capacity to neutralize ROS action and free radicals depends on various factors

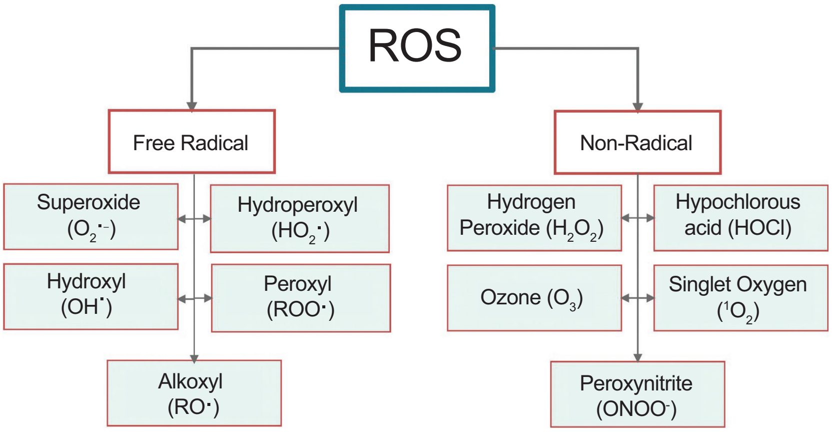

**Figure 2. Radical and non-radical forms of ROS. ROS, reactive oxygen species**

such as activity, interaction with other antioxidants (synergetic), absorption, distribution, and metabolism of antioxidants (Pitzschke *et al*., 2006). Antioxidant systems can be classified into enzymatic and nonenzymatic groups (Table 1) (Caverzan *et al*., 2019; Karuppanapandian *et al*., 2011).

**Table 1. Classification of important enzymatic and nonenzymatic antioxidants.**

| **ROS scavenging by antioxidant enzymes** | |
|---|---|
| **Enzymes** | **Reactions** |
| SOD | $2O_2^{\cdot-} + 2H^+ \rightarrow H_2O_2 + O_2$ |
| CAT | $2H_2O_2 \rightarrow 2H_2O + O_2$ |
| POD | $H_2O_2$ + GSH → $H_2O$ + GSSG |
| APX | $H_2O_2$ + ASCA → $2H_2O$ + DHA |
| MDHAR | 2MDHA + NAD(P)H → 2ASCA + NAD(P) |
| DHAR | DHA + 2GSH → ASCA + GSSG |
| GR | GSSG + NAD(P)H → 2GSH + NAD(P)$^+$ |
| GPX | $H_2O_2$ + 2GSH → $2H_2O$ + GSSG |
| **ROS scavenging by antioxidant nonenzymes** | |
| **Nonenzymes** | **Reactions** |
| AscA | Detoxifies $H_2O_{2,}$ $O_2^{\cdot-}$ and $^*$OH |
| GSH | Substrate for various PODs, GSTs, and GR. Detoxifies $H_2O_{2,}O_2^{\cdot-}$, and $^*$OH |
| TOCs | Protects membrane lipids from peroxidation, detoxifies lipid peroxides, and quenching $^1O_2$ |
| CARs | Quench $^1O_2$ |
| Flavonoids | Can directly scavenge $H_2O_2$ and OH$^{\cdot}$ |

AscA: ascorbic acid; APX: ascorbate peroxidase;
CARs: carotenoids; CAT: catalase; DHA: dehydroascorbate; DHAR: dehydroascorbate reductase; GPX: guaiacol peroxidase; GR: glutathione reductase; GSH: glutathione; GSSG: oxidized glutathione; GSTs: glutathione-S-transferases;
MDHA: monodehydroascorbate; MDHAR: monodehydroascorbate reductase; PODs: peroxidases; SOD: superoxide dismutase; TOCs: tocopherols.

Recently, several studies have been carried out to find the effects of various antioxidants on UPE. The experimental evidence showed that the antioxidants suppressed UPE in various living organisms. For instance, the UPE from human skin was suppressed by three antioxidants (d-δ-tocopherol sodium, L-glutathione, and L-ascorbate) (Tsuchida *et al*., 2019). Different antioxidants (α-tocopherol, glutathione, +6 ascorbate, and coenzyme Q10) notably decreased the UPE from the human skin (Rastogi and Pospísil, 2011). In another research, the results showed that the topical application of oligomeric proanthocyanidins (antioxidants) significantly reduced the UPE from the human skin (Van Wijk *et al*., 2010). Similar research on humans (Egawa *et al*., 1999; Sauermann *et al*., 1999) and mouse skins (Evelson *et al*., 1997) were conducted to find the effect of antioxidants UPE. It has also been shown that the UPE from radish root cells was considerably suppressed by different amounts of sodium ascorbate and cysteine (Rastogi and Pospísil, 2010). The ROS induced in rice cells by *N*-acetylchitooligosaccharide, and consequently UPE, was also highly suppressed by the addition of diphenyl iodonium as a ROS scavenger (Kageyama *et al*., 2006).

## Correlation between ROS and UPE

All living systems are connected to their surroundings through the UPE exchange, while the spontaneous UPE is originated from the transition of electronically excited species to the ground state formed during oxidative metabolic processes (Pospíšil *et al*., 2014). Cyclo-addition of $^1O_2$ or the hydrogen abstraction $^{\cdot}$HO is two mechanisms for oxidation of biomolecules among oxidative metabolic processes. The hydrogen abstraction from proteins, nucleic acids, and lipids by HO$^{\cdot}$ can result in an alkyl radical (R$^{\cdot}$), which could react with $O_2$ and produce peroxy radical (ROO$^{\cdot}$). The cyclization of ROO$^{\cdot}$ and the recombination of two ROO$^{\cdot}$ lead to high-energy intermediates dioxetane (ROOR) and tetroxide (ROOOOR), respectively. The production of dioxetane is also performed by cycloaddition of singlet oxygen. The electronic species, such as triplet-excited carbonyls ($^3$R=O$^*$), singlet ($^1$P$^*$), and triplet pigment ($^3$P$^*$), and $^1O_2$ are formed due to the decomposition of tetroxide and dioxetane (Fedorova *et al*., 2007; Pospíšil *et al*., 2014; Yang *et al*., 2015).

The spectrum of the spectrum associated with photon emission of $^3$R=O$^*$ (350–550 nm) is near UV and blue-green regions of visible light (Fedorova *et al*., 2007). The spectrum range of singlet- and triplet-excited pigments belongs to green-red (550–750 nm) and red–near IR (750–1000 nm), respectively (Pospíšil *et al*., 2014; Sauermann *et al*., 1999). The photon emissions of monomol $^1O_2$ and dimol are close to IR (at 1270 nm) and the visible light (at 634 and 703 nm), respectively (Adam *et al*., 2005; Pospíšil *et al*., 2014).

## UPE Application in Food and Agriculture

As already discussed, UPE is produced and released by ROS and received by biological systems, especially in agriculture. However, how UPE is emitted and received in intercellular and intracellular interactions is still a significant issue. Since the detection and analysis of the UPE spectrum are simple, available, inexpensive, and noninvasive, it can be used in different fields.

As mentioned earlier, most experiments demonstrate the impact of UPE in the field of agriculture, which can be used for the detection of pathogens in plants (Bennett *et al*., 2005; Iyozumi *et al*., 2002; Kageyama *et al*., 2006; Kobayashi *et al*., 2006; Makino *et al*., 1996; Mansfield, 2005; Montillet *et al*., 2005; Rastogi and Pospíšil, 2012), drought stress (Guo and Tan, 2013; Kausar *et al*., 2012; Komatsu *et al*., 2014; Ohya *et al*., 2000), salinity (Ohya *et al*., 2000), flooding stress (Kamal and Komatsu, 2016; Kausar *et al*., 2012; Khatoon *et al*., 2012; Komatsu *et al*., 2014), and herbicides (Inagaki *et al*., 2007, 2008, 2009; Kato *et al*., 2014; Nukui *et al*., 2013).

## Food quality and safety with UPE

As stated above, the studies on UPE in the areas of food quality are limited. The aim is to review the useful, relevant documents to find the relation between food quality and safety with UPE (Table 2).

For better clarity, the extensive description of each study (Table 2) follows.

The UPE method was employed to assess the quality of milk, hen's eggs, and vegetable oils. In the case of milk, to improve its durability, some heating methods were applied, resulting in a further decrease in the light storage capacity of milk and consequently lead to a change in its components and quality, such as protein denaturation dephosphorylation and loss of vitamins. For this purpose, some pasteurized, homogenized, and ultra-high temperature milk samples with different fat percentages were prepared. The samples were exposed to white, red, and blue lights (light illumination). The UPE was mostly increased after light illumination was applied to these samples. It was revealed that the higher the light storage capacity, the lower the intensity of UPE. Based on these findings, a decrease and increase in the milk's light storage with low fat (1.5%) and natural fat content (3.5–3.8%) were noted, respectively. In the case of eggs, the aim was to find the origin of eggs while the egg yolk's desired color attracted the consumers. To identify the origin of eggs, 325 brown hens were divided into four different groups: soil, soil with free-range on vegetation, cage, and sand.

Further chemical analysis showed that no significant differences between the groups were evident. Although the eggs from cages or soil exhibited a lower UPE rate than free-range eggs (on vegetation and sand), it demonstrated that the source of UPE is not a single chemical substance. In edible oil, 24 different types of sunflower oils were subjected to UPE measurement in three groups (without external illumination, after white and red lights illumination). The quality of sunflower oils is characterized by three-factor values, including light storage capacity, decomposition procedures (e.g., low quality of storage and aging), and the order's value in the sense of physiological and nutritional values. A high rate of UPE after red light illumination can be associated with decomposition procedures. The irradiation of food breaks chemical bonds and consequently forms radicals. By illumination with light, the electronically excited radicals fall to their base stats, and due to these different energy levels, the light is emitted. Therefore, food irradiation shows a much higher emission rate (higher by a factor of 50) after light illumination than nonirradiated ones (Lambing, 1992).

Another study aimed to monitor the UPE accompanying autoxidation and water–biopolymer interactions in cereal products using the CCD technique. While the hydration of cellulose, dextran, or starch chains resulted in the hydrogen-bond formation and, consequently, accumulation of the excitation energy, incorporating water into cereal products enhanced the UPE (Slawinska and Slawinski, 1997, 1998).

The quality of tomato fruit was studied using UPE measurement. The fruits were harvested at four maturity stages (green–orange, orange-red, light red, and red) with almost the same size and weight. They were stored at a particular temperature (20 °C) and humidity (80% RH) for 10 days. It was found that the UPE was directly related to harvest maturity. It was mentioned that UPE could be used as a nondestructive method to evaluate tomato quality (Triglia *et al*., 1998).

The UPE was measured for rice (*Oryza sativa* L.) seeds, which were stored during different years (1996, 1998, 1999, and 2001), and the correlation between the degree of aging of rice seeds and the intensity of UPE was noted. It was observed that the rice seeds stored for a shorter period had a stronger intensity of UPE in early imbibition. Moreover, a significant correlation was reported between the germination rates of rice seeds and the intensity of UPE (Chen *et al*., 2003).

The coffee seed viability was studied by the aid of a UPE measurement. For this purpose, six coffee seeds were selected to measure UPE after exposure to white light at a constant temperature (22 °C). The germination rates were recorded on the 15th and 30th day. The proposed method with further investigations can promote advances in storing methods via the UPE technique (Gallep *et al*., 2004).

The quality parameters of differently cultivated carrots from an organic farm and conventional farms in Austria were studied for 5 years (1998–2003) with different quality assessment methods, including sensor tests, food preference tests with laboratory rats, decomposition tests, P-value determination, chemical analysis, and UPE. In this work, the carrot slices were put under a light bulb,

**Table 2. The relation between food quality and UPE.**

| Authors/years | Sample | Aim | Preparation | Conclusion |
|---|---|---|---|---|
| Lambing, 1992 | Pasteurized, homogenized, and ultra-high-temperature milk | Assessing the quality of milk | The samples were exposed to white, red, and blue lights (light illumination) | The UPE was mostly increased after light illumination was applied to samples |
| Lambing, 1992 | Hen's egg | Finding the origin of eggs | Three hundred twenty-five brown hens were divided into four different groups | The eggs from cages or soil exhibit a lower UPE rate than eggs from free-range eggs |
| Lambing, 1992 | Sunflower oils | Assessing the quality of sunflower oils | Sunflower oils were divided into three groups | A high rate of UPE after red light illumination was observed |
| Slawinska and Slawinski, 1997, 1998 | Cereal products | Evaluating the quality of cereal products | Hydration of cereal food products | The incorporation of water into cereal products enhanced the UPE intensity |
| Triglia *et al.*, 1998 | Tomato fruit | Studying the quality of tomato fruit | The tomato fruits were harvested at four maturity stages and stored for 10 days | The tomato fruits with similar colors had significant differences in the UPE intensity |
| Chen *et al.*, 2003 | Rice seeds | Finding the correlation between the degree of aging and the germination rates of rice seeds with the intensity of UPE | Rice seeds are stored in different years | It was revealed that the rice seeds stored for a shorter period had a more vigorous intensity of UPE in early imbibition. |
| Gallep *et al.*, 2004 | Coffee seeds | Finding the correlation between the coffee seeds viability and UPE intensity | Six groups of samples were exposed to white light at a constant temperature | The proposed method with further investigations can be employed to promote advances in storing methods via the UPE technique |
| Velimirov, 2005 | Carrots | For the investigation of the quality parameters of cultivated carrots from organic and conventional farms | The same carrots cultivar grown in the same region were considered for 5 years | A significantly better capacity to store biophotons in organic carrot samples was noted while compared with conventional samples |
| Gallep and Dos Santos, 2007 | Wheat seeds germinating | Investigating the relation between seedling growth and UPE intensity | The samples were placed in three different wastewater sediment solutions | A relation between the seedling growth and the detected light intensity was increased over time |
| Grashorn and Egerer, 2007 | Organic and conventional eggs | To evaluate the quality of the parameters of the eggs | Four different groups of eggs were considered to measure the UPE intensity | The organic eggs showed a higher UPE with a slower decline than conventional ones |
| Wang and Yu, 2009 | Wheat grain | Investigation of the correlation between UPE intensity and vigor of irradiated wheat grain and its irradiation dose | Wheat grain and wheat flour were irritated by 60Co sources. samples were selected and stored for some months for UPE measurement | The UPE analysis cannot be used to detect the irradiation dose but is capable of determining vigor |
| Hossu *et al.*, 2010 | Sweet potato | Correlation between the UPE measurement and the quality of samples | Ag NP solution with different concentrations was added on the surface of the samples. Then UPE measurements were carried out for three cases | UPE was enhanced as much as 15 times by adding Ag NP |
| Kausar *et al.* 2012 | soybean | The correlation between the UPE and seedling growth under flooding and drought stresses | The 3-day-old samples were exposed to flooding or drought stresses for 2, 4, and 6 days | Differential patterns of UPE were detected for considered days, and maximum UPE was evident under flooding stress |
| Khatoon *et al.* 2012 | soybean | The correlation between seedling growth under flooding stress and UPE intensity | The 2-day-old samples were exposed to flooding or drought stresses for 5 days | The UPE was increased in flooded soybean samples compared to untreated samples |

(Continued)

**Table 2. Continued**

| Authors/years | Sample | Aim | Preparation | Conclusion |
|---|---|---|---|---|
| Komatsu *et al.* 2014 | soybean | Correlation between seedling growth under abiotic stresses and UPE intensity | The 2-day-old samples were exposed to abiotic stresses for 5 days | Differential patterns of UPE were detected for considered days, and maximum UPE was evident under flooding stress compared to drought stress; and also, the UPE in the leaves treated with cadmium was higher than untreated soybean |
| Kamal and Komatsu, 2016 | Soybean | Investigating the molecular systems based on flooding stressed sample roots and UPE evaluation | Exposure of the sample roots to flooding stress along with light and dark situations | UPE was considerably increased by flooding stress, then decreased with a continued flooding exposure |
| Cordeiro *et al.*, 2017 | Water samples | To evaluate the contamination of water samples from a river | The UPE of water samples from a river near Curitiba City in Brazil by coliform was assessed | The UPE measurements are an effective way to discriminate between contaminated and noncontaminated samples |
| Grasso *et al.*, 2018 | Seeds of watermelon | Verification of the growth performance of inherently aged or damaged seeds of watermelon | The samples were placed in a controlled dark condition until a 2-mm root length was reached. To the spectral analysis of UPE, the interference filters were employed | The UPE measurements were strictly related to the biological state of the system under analysis |
| Nawara *et al.*, 2018 | Food samples | Designed and manufacture the station to assess the quality of food | The designed device was to measure the degree of UPE of organic matters and processes | The measuring station is a useful way to compare traditional food quality with similar foods produced by industrial methods |
| Sun *et al.*, 2019 | Herbal materials | To identify authentic from counterfeit herbal materials | For this purpose, four category tests were selected | UPE can be utilized as a fast, simple, and inexpensive method, rather than conventional techniques to identify herbal materials |
| Gałązka-Czarnecka *et al.*, 2019 | Eggs | Assessing the quality of eggs | Two different hens, including the caged and free-range, were selected to determine their freshness and quality | It was observed that UPE from free-range eggs had eight times higher intensity than eggs from caged hens. They also found that the eggs from free-range hens had more than three times higher carotenoid than eggs from caged hens |
| Jia *et al.* 2020 | Herbal materials | To study the properties of aged and contemporary Chinese herbal materials | The UPE analysis was performed on some selected groups of aged and contemporary materials of their corresponding species | They found that the UPE technique can be employed to differentiate the aged and contemporary samples |

UPE: ultra-weak photon emission; NP: nanoparticles.

and UPE was measured. A significantly better capacity to store biophotons in organic carrot samples was compared with conventional samples (Velimirov, 2005).

The photon-counting of wheat seeds germinating in three different wastewater sediment solutions was analyzed using a PMT device, and correlation with seedling development was studied. It was indicated that there was an increasing relation between seedling growth and detected light intensity over time (Gallep and Dos Santos, 2007).

The quality of organic and conventional eggs (for 1 year) was investigated using a UPE measurement. In this regard, four different forms of production systems (barn, cage, organic, and free-range) were considered to evaluate the quality of eggs based on conventional (egg mass, shell-breaking strength, albumen height, the proportion of yolk, fatty acid profile, and yellow color) quality criteria and UPE measurements. The results depicted higher UPE with a slower declining trend for organic eggs. It was reported that the measurement of UPE could be a suitable method for evaluating the quality of organic eggs (Grashorn and Egerer, 2007).

Correlation between UPE intensity and vigor of irradiated wheat grain and its irradiation dose was investigated. At first, wheat grain and wheat flour were irritated by 60Co sources with a dose rate of 1 kGy/h, including 0, 0.6, 1.5, 2.4, and 3 kGy. Samples were stored for 0, 6, 12, and 18 months under commercial storage conditions for UPE measurement. In summary, UPE analysis could not detect irradiation dose but was capable of determining vigor (Wang and Yu, 2009).

Hossu *et al*. (2010) tried to find a relation between the UPE and sweet potato samples' quality. They selected eight sweet potato roots with 5-mm thick disk slices and an average of nine samples from each root. The samples were placed in a Petri dish with 8-mL 3% sucrose (media). The samples were incubated for 1 week at a relative humidity of 90–95% and a temperature of 30 °C to increase storage quality. Different concentrations of the 2-mL solution of silver (Ag) nanoparticles (NP) were added on sweet potato samples' surfaces. Then UPE measurements were carried out for three cases (no media, media only, and adding Ag NP). They found that the UPE was enhanced by as much as 15 times by adding Ag NP. They mentioned that the UPE could provide useful information about the quality of biological material.

The relation between the UPE intensity and soybean seedling subjected to abiotic stresses was investigated. For this purpose, Kausar *et al*. (2012) (flooding and drought stresses), Khatoon *et al*. (2012) (flooding stress), and Komatsu *et al*. (2014) (flooding, drought, and cadmium stresses) considered 2 or 3-day-old seedling samples and exposed to stresses above. They measured the activity of the APX and isoflavone reductase, which have related to the UPE measurement. They found that differential patterns of UPE were detected for considered days, and maximum UPE was evident under flooding stress compared to drought stress, and the UPE in the leaves treated with cadmium was higher than untreated soybean samples.

Flooding is abiotic stress that influences plant growth and crop yields. Kamal and Komatsu (2016) investigated the molecular systems based on flooding-stressed roots in soybean and UPE evaluation under light and dark conditions. They found that the UPE was considerably increased with light and dark conditions after flooding stress but decreased with continued flooding exposure. They also showed that increase in the activity of enzyme lysine ketoglutarate reductase/saccharopine dehydrogenase bifunctional was due to flooding stress, which consequently increased ROS rate scavenging and UPE.

The UPE measurement for evaluating microbial contamination (coliform group) of water samples from a river near Curitiba City in Brazil was assessed. It was observed that the UPE measurement is an effective way to discriminate between contaminated and noncontaminated water samples (Cordeiro *et al*., 2017).

Grasso *et al*. (2018) verified the growth performance of inherently aged or damaged watermelon seeds by the UPE technique. For this purpose, they selected two lots of watermelon seeds, with 96 seeds in each lot. All the germination tests were performed using 12 dishes per lot, eight seeds in each dish, and a filter paper. To perform UPE measurements, the samples were placed in a controlled dark condition (at a temperature of 28.3°C) until a 2-mm root length was reached. For the spectral analysis of UPE, the interference filters (Edmund Optics; center wavelength 450, 550, and 650 nm, respectively) were employed. The results showed that the UPE measurements were strictly related to the system's biological state under analysis. They claimed that the proposed method could be used as a noninvasive and nondestructive technique for rapidly analyzing the seeds' viability and enhancing tools for seed-sorting systems.

Nawara *et al*. (2018) designed and manufactured a station to assess food quality. The designed device was to measure the degree of UPE of organic matters and processes. The manufactured instrument included a PC with counting, controlling systems, and measurements, including amplification and counting single photons (ESPC), control card, the light source for automatic recording of test results, and an application software created in the LabView environment. The measuring station was a useful way to compare traditional food quality with similar foods produced by industrial methods. This device can also measure the quality parameters of food products.

Interesting research was conducted by Sun *et al.* (2019) for quality control of herbal materials. They employed the UPE for identifying authentic from counterfeit herbal materials. For this purpose, they used four-category tests, which included (i) authentic versus counterfeit materials; (ii) authentic versus adulterated materials; (iii) authentic versus sulfur-fumigated materials, and (iv) authentic versus dyed materials. The authors found that the UPE could be utilized as a fast, simple, and inexpensive method for identification of herbal materials in comparison to conventional techniques such as morphological and microscopic methods, chromatography and spectrum photometer analyses, molecular biology assays, and biomimetic technologies (Chen *et al*., 2012; Xu *et al*., 2015).

Recently, the traditional and UPE methods were used for determining egg quality. Measured quality parameters were the color at the La Roche point—YCF scale, pH, Haugh unit, and yolk color. Gałązka-Czarnecka *et al.* (2019) selected two different hens, including caged and free-range hens, with 60 eggs, yolk, and white, to determine the freshness and quality. Three yolks of each type of egg were mixed and considered as a sample. It was observed that UPE from eggs of free-range hens had eight times higher intensity than eggs from caged hens. The authors also found that the eggs of free-range hens had more than three times higher carotenoid than caged hens. They stated that further research is needed for using the UPE method as a food quality assessment tool.

Jia *et al.* (2020) studied the aged and contemporary properties of some Chinese herbal materials, including *Glycyrrhiza glabra* L., *Glycyrrhiza inflata* Batalin, *Glycyrrhiza uralensis* Fisch., *Curcuma aromatica* Salisb., *Zingiber officinale* Roscoe, *Acorus calamus* L., and *Alpinia officinarum* Hance. They implemented the UPE technique by PMT devices to differentiate the aged and contemporary samples. They found out that the UPE technique can be able to achieve the desired result. They also suggested that the UPE technique provides useful data on the storage time effect and the herbal medicines' quality assessment.

## Conclusion

This review presents an overall framework on various aspects of UPE. Definition, detection techniques, and different applications of UPE were studied. The UPE results from the relaxation of the electronically excited species, resulting from oxidative metabolic and oxidative stresses. Owing to the growing world population and food security, safety, and quality is imperative issues, the current study focuses on the applications of UPE on the subject of food quality. The proposed method with further investigations could open new horizons on many branches of sciences. This technique is non-invasive and nondestructive and a cheap, rapid, and real-time technique that does not need complex instrumentation.

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