www.gsjpublications.com
Journal of Global Scientific Research (ISSN: 2523-9376)
6 (6) 2021/ 1412-1424

Journal of Global Scientific Research
www.gsjpublications.com/jgsr

Plant Chemiluminescence as a Physical Phenomenon and its Agriculture Applications on Plant Seedlings: A Comprehensive Review

Samir K. Lazim

Department of Agricultural Machines and Equipment, College of Agriculture, University of Basrah, Iraq.

Email Address:
samir.lazim60@gmail.com

Received: 5 May 2021, Revised: 11 May 2021, Accepted: 20 May 2021, Online: 2 June 2021

Abstract

This paper provides a general review of the findings published in research papers from 1955 to the present on the history of plant chemiluminescence (CL) studies and their agriculture applications on plant seedlings. The CL technique has become a very duty tool in agricultural application fields due to its high sensitivity, simplicity, and low cost. As a result, CL's study of plants and their applications in agriculture has carried out great progress. There is a possibility that an easy new way to check environmental changes and oxidative stress and to determine a plant's overall health may be to measure the CL emitted from a plant. I have selected and summarized some interesting CL application techniques in this review, such as the degree of accelerated aging seeds under stress and storage conditions and also the study of mechanical injury to plant tissue. Besides, I found several dedicated reports in this review that include the CL method for detecting or monitoring the plant's capacity to produce reactive oxygen species (ROS) or to detect compounds that present scavenger effects over these radicals.

Keywords: chemiluminescence, ageing, imbibition, reactive oxygen species, radical scavengers

1. Introduction

Luminescence is the most convenient term for light-producing processes. Luminescence could be classified into three types as fluorescence, bioluminescence, and chemiluminescence (CL), according to the source of excitation. In all cases mentioned above, light is produced when molecules in an electronically excited state decay into a stable ground state. Light is the energy source for fluorescence, and chemical reactions such as oxidation are the energy source of bioluminescence and chemiluminescence (Fereja *et al*., 2013; Jimenez &Navas, 2002; Abeles, 1986). Some of the other terms used in the literature to describe the same phenomenon are ultraweak photon emission (UPE) and ultraweak chemiluminescence (UCL). UBE in the

visible region is low-level chemiluminescence from biological systems such as microorganisms, plants, and animals, in originates from the relaxation of electronically excited species during the oxidative metabolic and stress processes (Prasad *et al*., 2020; Pospisil *et al*., 2014; Kato *et al*., 2014; Bertonha *et al*., 2010). Due to its very significant activity, UPE researchers have a wide range of potential applications in agriculture. It is well known those plant seedlings, as they grow emit a very low amount of light, the so-called ultraweak photon emission (UPE). From the first discovery of ultra-weak photon emission (UPE) in seeds measurements by Coli in 1955, there has been a lot of evidence that plants change the intensity of UPE depending on changes in their condition and circumstances (Kato *et al*., 2014). Those authors have been researching and developing techniques using UPE to non-invasively test plant states in response to stress since the 1990s. The study of UCL from plants is a new technique for plant micro-analysis that has been in place since the 1980s. The term chemiluminescence (CL) is identified as the light emission, of ultraviolet, visible, or infra-red radiation from a molecule or atom as a result of the transition to an electronically excited state decay to a stable ground state, as a consequence of a chemical reaction, (Jimenez & Navas, 2002). It is possible to split studies on CL into three parts. The first is oxidative chemistry, which is the driving force behind CL; the second is plant endogenous CL and the factors affecting its production; and finally, experiments using CL probes, which are light-producing compounds when exposed to H2O2 or superoxide anion. Via two mechanisms, plants generate light: fluorescence and chemiluminescence. Fluorescence energy comes from light, while CL energy comes from superoxide radical oxidative reactions and H2O2 (Moraes *et al*., 2010).The best chemiluminescent probes that have been used extensively in plant and animal research are luminol (5-amino-2,3-dihydrophthalazine-1,4-dione) or its derivatives and lucigenin (bis-N-methylacridinium nitrate) (Al-Hashimi *et al*., 1997; Jimenez & Navas, 2002). The electronically excited state in these compounds returns to their ground state with the emission of energy as light (CL), which can be detected by the photomultiplier tube detectors (Moraes *et al*., 2010). It is well known that photon emission intensity measurement is useful for detecting physiological changes and determining the of these changes before harm takes place on plants (Lida *et al*., 2000). In plants, CL has been emitted in response to environmental changes and stress, such as wounding plants mechanically (Lida *et al*., 2000; Salin & Briges, 1981); oxidative stress (Beals & Byl, 2014); drought damage (Ohya *et al*., 2002), and temperature and humidity changes (Footitt *et al*., 2016; Chen *et al*., 2006a; Boveris *et al*., 1984). Several reports on the early studies of CL in plants have been published. In the early 1950s, for the first time, Colli and collaborators discovered that plants produce CL (Colli et al., 1954; Colli *et a*l., 1955). These authors discussed some properties of chemiluminescence from wheat, bean, lentil, and corn seedlings, giving a quantitative comparison of the intensity of chemiluminescence for different plants including some plant parts, and at various stages during germination. In the 1960s, several Russian groups managed by Vladimirov (1966) and Agaverdiyev &Tarusov (1965) studied the visible region luminescence from many plants. Then, from the early 1970s to the present, several reports of chemiluminescence from different parts of plant tissues began to appear. For example, CL has observed with seeds (Gallep & Robert, 2020; Saeidfirozeh *et al*., 2018; Lida *et al*., 2000; Saeki *et al*., 1989; Boveris *et al*.,1984); with roots (Wany *et al*., 2016; Chen *et al*., 2010; Zielinska *et al*., 2008; Rogovin *et*

al., 2001; Salin & Briges, 1981; Abeles, 1978; Vartapetian *et al*., 1974; and Colli *et al.*, 1955); with stems (Lida *et al*., 2000; Salin & Briges, 1981; Abeles *et al*., 1978; Agaverdiyev & Tarusov, 1965; Colli *et a*l., 1955), and with leaves (Wany *et al*., 2016; Miladinovic *et al*., 2013; Chen *et al*., 2010; Sakharov, 2001; Lida *et al*., 2000; Skotnica *et al.*, 1999; Butt & Bestwick,1997; Roschger *et al.*, 1993). It has well known that all stressed and unhealthy cells emit more photons than healthy cells (Moraes *et al*., 2010; Salin & Briges, 1981). Many research groups have studied the CL emission from plants and seeds, indicated a correlation with metabolic changes and oxidative stress (Albert *et al*. 2015; Miladinovic *et al*., 2013; Jantan *et al*., 2011). Other studies were found that light levels rise when organisms are injured (Yoshinaga & Kato, 2006; Chen *et al*., 2006 b; Chen *et al*., 2003b; and Abeles *et al*., 1978); or when the early imbibition of seeds (Chen *et al*., 2010; Chen *et al*., 2006a; Chen *et al*., 2003a; Saeki *et al*., 1989; Boveris *et al*., 1984). Because of its variety of practical applications in industries, agriculture, and medicine, the chemiluminescence phenomenon in transforming chemical energy into light emission has been an attractive subject of intensive research over the years (Yeh & Ai, 2019; Liu *et al*., 2010; Roda *et al*., 2004; Lida *et al*., 2000; Chen *et al*., 2003a; Duong *et al*., 2020; Khan *et al*., 2014). In plants, the study of CL and their agriculture applications has gained significant progress due to their simplicity, low cost, and high sensitivity (Pandey *et al*., 2017; Amarowicz & Raab, 1997; Perez & Rubio, 2005; Pulgarin *et al*., 2012). Agriculture is affected by many problems of environmental and oxidative stress. The photon emission intensity of CL from damaged plants may be to hints as to some physiological and biochemical response to external stress. It's possible that measuring the chemiluminescence emitted from a plant could be a practical application and maybe an easy way to measuring the overall health of a plant. Therefore, this review article focused on CL emission as a significant signal from plants undergoing physiological changes.

2. Chemiluminescence Under Wounded Plant Tissue

It is well known that when an animal or plant materials are stimulated by external injuries, they will instinctively protect themselves against damage (Sitprija & Sitprija, 2012; Chen *et al*., 2006b; and Salin & Briges, 1981). All plant species are vulnerable to mechanical damages during their life by injury, which may lead to cause both losses of nutrients and entry of microbes (Piesik *et al*., 2006). Plant tissue responds to environmental changes and stress factors, such as other mechanically injured, results in increased CL as a defense mechanism against wounding (Winkler *et al*. 2009; Piesik *et al*., 2006; Chen *et al*., 2006b; Salin & Briges, 1981). Many studies have found more photons emission near an injury from stress and damaged plant parts than from unstressed (Winkler *et al*., 2009; Kokubo & Yamamoto, 2008; Yoshinaga & Kato, 2006; Suzuki *et al*., 1991). These authors found that spectral characteristics and decay of the photon emission from wound plants depend on the state of health of the tissue. Furthermore, the authors suggested that time-dependent variations in emission intensity suggest that some physiological and biochemical changes, maybe have taken place in the wounded tissues. Thus, the photon emission intensity measurement is beneficial for detecting physiological and biochemical changes in the wounded tissue. Plants respond to self-defense mechanisms in response to injury, either to repair damaged tissues or defense against pathogens and herbivores (Pandey *et al*., 2017; Yoshinaga & Kato, 2006). Consequently, the phenomenon of enhanced light emission upon wounding may be part of an over-all defensive response by plants to seal off the wound

and generate new tissue (Creath, 2008). Several previous reports had shown that stress resulting from wounding (mechanical injury) increases CL or ultraweak photon emission from various parts of plants. Abeles (1978) has recorded a light production from the root and stems tissue of peas (Pisum sativum), beans (Phaseolus Vulgaris), and corn (Zea mays) by measuring chemiluminescence in a scintillation spectrophotometer. Salin & Bridges (1981) observed an enhanced CL upon mechanical injury stem and root segments from soybean seedling. Suzuki *et al*. (1991) applied a photon counting system to detect ultraweak light originating from physically injured adzuki bean and soybean seedlings. As well as, the authors found that possible to determine accurately the wounded regions of the seedlings which exhibit strong emission. Also, Lazim (2005) observed the light emission by measuring CL from roots of corn (Zea mays L.) after mechanical injury and was found that emission increased by the addition of luminol or lucigenin. Chen *et al*. (2006b) used a sensitive single-photon counter system to identify ultraweak bio-chemiluminescence (UBC) from germinating soybean cotyledon under mechanical wounding. Yoshinaga & Kato (2006) reported ultraweak photon emissions from herbivore-damaged maize plants, concluding that caterpillar regurgitation is a significant behavior for releasing photon emissions from cut corn leaves. Kokubo & Yamamoto (2008) used the cucumber plant's ability to emit biophotons to investigate the effects of non-contact healing known as laying-on-of-hand. Also, Winkler *et al*. (2009) measured the ultraweak and induced photon emission from wounded Cucurbita pepo seedling using single-photon counting devices. As well as, the authors observed an increase in the ultraweak photon emission depends on the kind of wounding and its localization on the plant. A recent study showed that Arabidopsis subjected to mechanical injury showed enhanced photon emission, which led to changes in the spectral distribution of the emitted photons (Prasad *et al*., 2020). Some hypotheses were proposed from earlier chemiluminescence studies of seedlings, focusing on chemiluminescence wounded tissue, which produces higher photon emission than normal tissue. It is known that, whether animal or plant matter that when their bodies are stimulated by external stress or injuries, they will respond instinctively to defend. For example, polymorphonuclear leukocytes emit photons during the process of phagocytosis (Prilutsky *et al*., 2011; Lilius & Marnila, 1992). The peroxidase system in the animal cells may be responsible for light production by actively phagocytizing leukocytes (Bedouhene *et al*., 2017; Schadelin *et al*., 1980). Peroxidase is one of the main wound-inducible proteins in different plants upon mechanical wounding (Pandey *et al*., 2017). It seemed appropriate to examine whether plant CL is affected by a mechanism similar to that of animal cells. The similarities between emission from plant and root tissue and emission from leukocytes in animal cells have described by Salin & Bridges (1981); Abeles (1978). Moreover, the author suggested that a peroxidase enzyme system upon mechanical injury has contributed to the production of chemiluminescent-excited species. This system is known to be responsible for chemiluminescence in leukocytes, and it appears that plants have a similar system. According to Saeki *et al*. (1989), mechanical injury enhanced the chemiluminescence of root and stem segments of soybeans. And also, they suggested that peroxidases, found abundantly in roots predominantly, contribute to light emission in wounded plant tissue. On the other hand, Chen *et al*. (2003b) suggested that ROS reaction induced by chloroplast and mitochondria damage due to wounding could be the primary step that initiates a stimulating burst of lipid peroxidation. Which leads to

$^1O_2$ generation, and when singlet oxygen and ROS decay from excited states, photon emission has generated. While Salin and Bridges (1981) suggested that increased CL in wounded root tissue is associated with increasing peroxidase activity, hydrogen peroxide generation, and singlet oxygen production. Additionally, oxidative injury in response to a wound involves the initial formation of activated oxygen species and the consequent interaction with macromolecules such as proteins, fats, sugars, and nucleic acids, leading to its damage (Thompson *et al*., 1987). Finally, the wound-healing response, involving peroxidative reactions, and the enhanced light emission response to wounding may be part of a wider protective response by plants to close the wound and regenerate new tissue.

3. A Chemiluminescence Technique to Determine the Degree of Ageing Seeds

The crop quality study is one of the most critical parts of seed science. Preservation of viability of seeds without losing their standard vigour is a problem in agriculture and horticulture. Abiotic stress conditions, such as high temperature and relative humidity or, storage conditions cause seeds to lose vigour and their viability of germinability (Sharma *et al.*, 2021 & Chen et al., 2003a). Seeds usually lose viability after a few days or weeks under such storage conditions (Murthy *et al*., 2003). Accelerated ageing is an actual test sign of seed vigor and storability, where it helps to understand the seed degradation processes that occur during ageing (Patil *et al*., 2019; Barreto & Garcia, 2017). The spontaneous CL technique has known as a possible way of developing a fast, quantitative, and noninvasive method for the rapid measurement of the degree of ageing seed (Chen *et al*., 2003a). The chemiluminescence method may be provided new information on biochemical and physical changes in seeds during germination and help estimate the seed age (Saeki *et al*., 1990). It is well known that the interactions between water and cereal have a significant impact on cereal crop, storage, and quality (Sharma *et al*., 2020; Chen *et al*., 2002a). Several studies have been observed low-level chemiluminescence with sharply increases upon imbibition on different seeds, such as macaw palm (Barreto &Garcia, 2017); mung bean (Rafieiolhosseini *et al*., 2016); rice (Chen *et al*., 2006 a); soya (Triglia *et al*., 1993); and soybean (Boveris *et al*., 1984, 1983).There are several reports and reviews on seed ageing that showed seeds with a longer storage time had a lower intensity of CL during early imbibition. For example, some studies in storage rice seeds have confirmed that chemiluminescence emission had an attachment with the degree of seed aging during early imbibition (Chen *et al*., 2003a; Chen *et al*., 2002 a, b). Likewise, the same results were recorded in rice by Chen *et al*. (2000) when they note storage time of rice seeds was related to the ultra-weak biophoton emission characters during the early imbibition period. As well, they mentioned that emission might be a way to examine new and aged seeds. On the other hand, the connection between chemiluminescence intensity and water content of soybean seeds after the storage has been established through Saeki *et al*. (1990). While, Puntarulo & Boveris (1990) shown that the spontaneous and imbibition chemiluminescence upon accelerated aging of soybean embryonic axes was similar to those measured after natural aging. The CL studies contributed significantly to the knowledge of seed ageing mechanisms during early seed imbibition. Several mechanisms to understood seed ageing during early imbibition have been suggested by some authors. Chen *et al*. (2002 a) suggested that CL in rice seeds during early imbibition has mainly linked to single oxygen ($^1O_2$), also it depended upon the aging of degree seeds. Chen *et al*. (2006 a) also suggested that CL of rice seed during

early imbibition arises partially from enzyme-catalyzed reactions. Whereas Wang *et al*. (1990) suggested that enzymic lipid peroxidation may play a remarkable role in CL of Lipoxygenase-lacking soybean seeds during an accelerated aging process. A number of other studies have shown that aging in seeds during early imbibition has closely linked with reactive oxygen species (ROS), which is also responsible for CL (Liu *et al*., 2007; *Chen et al.*, 2003a; Chen *et al*., 2002 a; Boveris *et al*., 1984). Chemiluminescence in all biological tissues reflects the production of free radicals accompanied by lipid peroxidation. On the other side, the lipid peroxidation reaction involved in seed aging is considered a factor in plant seed CL (Saeki *et al*., 1990). Seed ageing during storage under accelerated ageing conditions has primarily been caused by lipid peroxidation and the accumulation of free radicals, which is the most common cause of accelerated damage seed. As well as, oxidative during aging involves the initial formation of activated oxygen species and the consequent interaction with macromolecules (Thompson *et al*., 1987), and it can then cause damage to proteins, fats, sugars, and nucleic acids. There are many studies and reviews that have confirmed that seed aging and germination capability loss are due to the accumulation of free-radical lipid peroxidation products (Puntarulo & Boveris, 1990; Murthy *et al*., 2003; Veselova *et al*., 2015; Patil *et al*., 2019).

4. Monitoring ROS formation and Antioxidant Defense Machinery in Plants using Chemiluminescence Method

There are many sources of reactive oxygen species (ROS) and antioxidative defense in plants, including various environmental and biological factors, such as drought, high salinity, external injuries, and aging of plant organs. It is well known, chloroplasts, mitochondria, cell walls, endoplasmic reticulum, and plasma membrane all contain ROS in plant cells (Pandey *et al*., 2017). Also, ROS arises during the fundamental metabolic process such as mitochondrial aerobic respiration and photosynthesis (Ohya *et al*., 2002).The reactive oxygen species (ROS) involves both non-radical forms (hydrogen peroxide, H_2O_2; and singlet oxygen, $^1O_2$), and free radicals such as superoxide radicals (O^{*-2}); hydroxyl radical (OH); perhydroxy radical (HO_2); and alkoxy radical (RO) (Gill & Tuteja, 2010). These reduced species of oxygen are linked with membrane lipid peroxidation, protein oxidation, and enzyme inhibition leading to Cell Death (Pandey *et al*., 2017). When plants are exposed to biotic and abiotic stress factors, oxidative bursts of ROS are generated either during the response to a typical cellular stress reaction or during metabolic processes linked to life-sustaining enzyme-catalyzing reactions (Albert *et al*., 2015; Pospisil *et al.*, 2014). Excessive concentrations of ROS can be toxic by the damage of the chloroplasts and mitochondria through oxidative destruction to lipids, proteins, and nucleic acid. Oxidative injury during aging or in response to a wound involves the initial formation of activated oxygen species and the consequent interaction with macromolecules (Thompson *et al*., 1987), and it can then cause damage to proteins, fats, sugars, and nucleic acids. Antioxidant protection systems, both enzymatic and non-enzymatic, can prevent stress-induced ROS accumulation. They include a variety of scavengers, such as superoxide dismutase, SOD; ascorbate peroxidase, APX; glutathione peroxidase GPX; and catalase, CAT; and non-enzymatic low molecular metabolites, such as ascorbic acid, ASH; glutathione, GSH; and flavonoids (Gill & Tuteja, 2010). Thus, the degree of physiological damage to the stressed plant depends on the ROS concentration. As a result, knowing the ROS concentration in a stressed plant aids in determining the extent of harm caused

by environmental stress (Ohya *et al*., 2003). CL is widely used to measure ROS in a noninvasive, direct manner (Kim *et al*. 2019; Haklar *et al*. 1998). Moreover, it is a sensitive, simple, and rapid method for monitoring these radicals, or compounds that have scavenging properties over them (Jimenez & Navas 2002). When ROS interacts with biomolecules, they produce unstable bimolecular intermediates, which decompose into exciting electron species. Consequently, excited states decay radiatively by the emission of photons (Saeidfirozeh *et al*., 2018). Depending on the ROS reacts to a biomolecule, a part of the reaction energy is used to emit photons whose wavelengths range from far infrared to ultraviolet (Ohya *et al*., 2003). Ultra-weak photons (CL from biological systems) are released automatically by the relaxation of electronically excited species when ROS are produced via oxidative metabolic processes and oxidative stress reactions (Cifra & Pospisil, 2014; Pospisil *et al*., 2014). Moreover, ROS is one of the most toxic factors in the emission of ultra-weak photons in plant systems. According to this factor, biophoton emission occurs as a result of ROS formation during plant damage caused by various environmental stresses (Ohya *et al*., 2003). Several studies showed a growing interest in the possible association of oxidative free radicals in some plant processes like wound healing (Pandey *et al*., 2017; Bryan *et al*., 2012; Lazim, 2005) and seed aging (Kurek *et al*., 2019; Wiebach *et al*., 2019). Several authors studied the ROS involvement in the CL emission. For example the involvement of free radical traps and lipoxygenase inhibitors was noted in CL emission for soybean embryonic axes by Boveris *et al*. (1984). Albert *et al*. (2015) used a luminol-enhanced chemiluminescence assay to demonstrate the ROS-burst in plant leaf pieces of Arabidopsis plant. Yoshioka *et al*. (1990) studied the CL emission and formation of radicals from tea treatment leaves in various methods. They suggested that the chemiluminescence becomes more stimulating as the quantity of the free radical increases. They also suggested that the radical generated by enzymatic oxidation of polyphenols is the source of CL in the tea leaf. The Ultra-weak CL from germinating soybean cotyledon under mechanical wounding has been documented by Chen *et al*. (2002c). They suggested that the main process was probably that chloroplast and mitochondria damage at the wounded place and led to ROS generation. The chemiluminescence of extracts from leguminous seedlings of adzuki bean and soybean has been investigated by Lida *et al*. (2000). And as described by these authors, the defense against reactive oxygen metabolites can lead to the formation of chemiluminescence substances such as flavonoids, phenolic acid, and peroxidase during germination. Using the flow injection—CL system, Choi *et al*. (2000) demonstrated the high radical scavenging effect of Chinese herbal components and the structures of flavonoids. On other hand, Veselova *et al.* (2004) have observed an increase in ROS generated from embryonic axes of dry pea seeds by chemiluminescence. They suggested that post-hypoxic oxidative stress was the cause for the damage of cell division. While, Ohya *et al*. (2003) have recorded the correlation between the physiological damage of ROS to adzuki bean seedlings and biophoton emission from the root. They have found that photon measurement has very useful for estimating physiological damage to plants due to environmental stress. On the other hand, the interaction of luminol with ROS was investigated by Papuc *et al*. (2012) to see whether celandine polyphenol extracts could remove any reactive oxygen species formed. They found that celandine leaf extract had the best ability to clean out the hydrogen peroxide. Rastogi & Pospisil (2010) also found that ROS, especially singlet oxygen, plays a role in biophoton emission in radish root plants. Lastly, CL

may serve as a simple, fast, sensitive, and non-destructive way to monitor the amount of ROS capable of interacting with peroxidase in plant tissue.

5. Conclusions

In conclusion, this paper present a general review of the history of chemiluminescence (CL) in plant studies and their applications in agriculture. Chemiluminescence methods have become a valuable tool due to their numerous advantages, such as low cost, high sensitivity, and simplicity. In addition, their use of easy and inexpensive instrumentation for monitoring emission. All these advantages have been allowed the method that has conveniently used in the agricultural application fields. There are many possible applications of CL based on the relationship between photon emission and environmental changes and oxidative stress indicators in plants. Lastly, new information about the mechanism of physiological changes and damage can be acquired through CL measurements.

6. Acknowledgments

The author gratefully acknowledges the comfort of the College of Agriculture, the University of Basrah-Iraq, for their scientific research encouragement.

Conflict of interest: Authors declare that there is no conflict of interests.

Samir K. Lazim: Orcid: https://orcid.org/0000-0002-8650-4829

7. References

[1]. Abeles, F. B. (1986). Plant chemiluminescence. Annual review of plant physiology 37, 49–72. DOI: 10.1146/annurev.pp. 37. 060186.000405

[2]. Abeles, B. F. (1978). Plant chemiluminescence. *Plant Physiol*, 62, 696–698. DOI: 10.1104/pp.62.5.696

[3]. Al-Hashimi, A. M., Mohammed, F. H., & Lazim, S.K. (1997). Comparative study of haemoglobin estimated by traditional WHO technique and cheminescence method. *Dirasat*, 24, 161-77. https://www.researchgate.net/publication/310425971

[4]. Albert, M., Butenko, M., Aalen, R., Felix, G., & Wildhagen, M. (2015). Chemiluminescence detection of the oxidative burst in plant leaf pieces. *Bioprotocolorg*, l5, 6:1-5. http://www.bio-protocol.org/e1423

[5]. Amarowicz, R. & Raab, B. (1997). Antioxidative activity of leguminous seed extracts evaluated by chemiluminescence methods. *Z. Naturforsch C*, 52, 709–712. https://doi.org/10.1515/znc-1997-9-1022

[6]. Agaverdiyev , A. S. H, & Tarusov, B. N. (1965). Ultraweak chemiluminescence of wheat stems in dependence on temperature. *Biofizika*, 10 (2), 351. https://www.researchgate.net/publication/294411857

[7]. Barreto, L.C., Garcia, Q.S. (2017). Accelerated ageing and subsequent imbibition affect seed viability and the efficiency of antioxidant system in macaw palm seeds. *Acta Physiol. Plant*, 39, 72. DOI 10.1007/s11738-017-2367-z

[8]. Beals, C., Byl, T. (2014). Chemiluminescent examination of abiotic oxidative stress of watercress. *Environ Toxicol Chem*, 33,798–803. DOI: 10.1002/etc.2484

[9]. Bedouhene, S., Moulti-Mati, F., Hurtado-Nedelec, M., May-Chan, D., & El-Benna, J. (2017). Luminol-amplified chemiluminescence detects mainly superoxide anion produced by human neutrophils. *Am J Blood Res*, 7 (4), 41-48. Doi:10.1088/1742-6596/1818/1/012060

[10]. Bertonha, E., Moraes, T. A., Conforti, E., & Gallep, C. M. (2010). Periodic Time Components in Spontaneous Ultra-Weak Photon Emission of Wheat Seedlings in Stressing Solutions. The Latin America Optics and Photonics Conference, OSA 2010;MB08. DOI: 10.1002/bio.2658

[11]. Boveris, A., Puntarulo, A. S., Roy, H. A., & Sanchez, A. R. (1984). Spontaneous chemiluminescence of soybean embryonic axes during imbibition. *Plant Physiol*, 76, 447–51. DOI: 10.1104/pp.76.2.447

[12]. Boveris, A., Varsavsky, A. I., Da Silva, S. G., & Sanchez, R. A. (1983). Chemiluminescence of soybean seeds: Spectral analysis, temperature dependence and effect of inhibitors. *Photochemistry and Photobiology, 38*, 99–104. DOI: 10.1111/j.1751-1097.1983.tb08372.x

[13]. Bryan, N., Ahswin, H., Smart, N., Bayon, Y., Wohlert, S., & Hunt, J. A. (2012). Reactive oxygen species (ROS) —a family by fate deciding molecules pivotal in constructive inflammation and wound healing, *European Cells and Materials*, 24, 249–265. https://doi.org/10.22203/ecm.v024a18

[14]. Butt, A. D., Bestwick, C. S. (1997). Generation of chemiluminescence during enzymatic isolation of protoplasts from leaves of *Oryza sativa*. *J Plant Physiol*, 150:729–733. DOI: 10.1016/s0176-1617 (97)80290-8

[15]. Chen, J., Xiao, Q., Wu, F., Pei, Z., Wang, J., Wu, Y., & Zheng, H. (2010). Nitric oxide emission from barley seedlings and detached leaves and roots treated with nitrate and nitrite. *Plant Soil Environ*. *56*, 2010 (5), 201–208. DOI: 10.17221/231/2009-pse

[16]. Chen, W. L., Xing, D., & Van Wijk, R. (2006a). Chemiluminescence during rice seed imbibition at different temperatures. *Luminescence*, 21, 31–35. DOI: 10.1002/bio.879

[17]. Chen, W. L., Zhou, Q., Li, L., Xing, D., Van Wijk, R. & Tang, Y. H. (2006b). Comparing ultraweak bio-chemiluminescence emission in wounded green and etiolated soybean cotyledons. Proc. SPIE, 6088, 60881G1-60881G10

[18]. Chen, W. L., Xing, D., Wang, J., & He, Y. (2003a). Rapid determination of rice seed vigour by spontaneous chemiluminescence and singlet oxygen generation during early imbibition. *Luminescence*, 18, 19–24. DOI: 10.1002/bio.695

[19]. Chen, W., L., Xing, D., Tan, S., Tang, Y., & He, Y. (2003b). Imaging of ultra-weak biochemiluminescence and singlet oxygen generation in germinating soybean in response to wounding, Luminescence, 18, 37–41. https://doi.org/10.1002/bio.703

[20]. Chen, W., Xing, D., & Yonghong, H. (2002a).Ultraweak chemiluminescence of rice seeds during accelerated agin. Proc. SPIE 4536, International Workshop on Photonics and Imaging in Biology and Medicine, https://doi.org/10.1117/12.462545

[21]. Chen, W. L., Xing, D., & Yonghong, H. (2002b). Determination the vigor of Rice seed with different degrees of aging with ultraweak chemiluminescence during early imbibtion. *Acta Botanica Sinica*, 44, 1376-1379. https://www.researchgate.net/publication/289337017

[22]. Chen, W., Xing, D., & Wang, J. (2002c). Changes of ultraweak biochemiluminescence from germinating soybean in the wounding defense response, Proc. SPIE 4920, Advanced

[23]. Sensor Systems and Applications, (9 September 2002); https://doi.org/10.1117/12.481946

[24]. Chen,W., Xing,D., & Yonghong H., (2000). Ultraweak biophoton emission of new and aged rice seeds during early imbibition," Proc. SPIE 4224, Biomedical Photonics and Optoelectronic Imaging, (11 October 2000); doi:10.1117/12.403976

[25]. Choi, H. Y., Jhun, E. J., Lim, B. O., Chung, I. M., Kyung, S. H., & Park, D. K. (2000). Application of flow injection-chemiluminescence to the study of radical scavenging activity in plants. *Phytotherapy Research*, 14, 250–253. DOI: 10.1002/1099-1573(200006)14:4<250::aid-ptr587>3.0.co;2-

[26]. Cifra, M. & Pospisil, P. (2014). Ultra-weak photon emission from biological samples: Definition, mechanisms, properties, detection and applications. *Journal of Photochemistry and Photobiology B: Biology* 139, 2–10. https://doi.org/10.1016/j.jphotobiol.2014.02.009

[27]. Colli, L., Facchini, U., Guidotti, G.,& Sommariva, O. (1955). Further measurements on the bioluminescence of the seedlings. *Experimentia*,11,479–81. DOI: 10.1007/bf02166829

[28]. Colli, L., Facchini, U., & Rossi, A. (1954). Light emission by germinating plants. *Nuovo Cimento*, 11, 255. DOI: 10.1007/bf02820374

[29]. Creath, K. (2008). A look at some systemic properties of self-bioluminescent emission. In: *Proceedings of SPIE*, 7057, 705–708. https://doi.org/10.1117/12.800667

[30]. Duong, Le., Dhamecha, D., Gonsalves, A., & Menon, J. U. (2020). Ultrasound-Enhanced Chemiluminescence for Bioimaging. *Frontiers in Bioengineering and Biotechnology*,**8,25.** https://doi.org/10.3389/fbioe.2020.00025

[31]. Fereja, T. H., Hymete, A. , & Gunasekaram, T. (2013). A recent review on chemiluminescence reaction, principle and application on pharmaceutical analysis. *Isrn Spectroscopy*, 9, 1–12. https://doi.org/10.1155/2013/230858

[32]. Footitt, S., Palleschi, S., Fazio, E., Palomba, R., Finch-Savage, W. E., & Silvestroni, L. (2016). Ultraweak photon emission from the seed coat in response to temperature and humidity-a potential mechanism for environmental signal transduction in the soil seed bank. *Photochem Photobiol*, 92(5),678–687. DOI: 10.1111/php.12616

[33]. Gallep, C. M., & Robert, D. (2020). Time-resolved ultra-weak photon emission as germination performance indicator in single seedlings. *Journal of photochemistry and photobiology* 1: 100001. https://doi.org/10.1016/j.jpap.2020.100001

[34]. Gill, S.S., & Tuteja, N. (2010). Reactive oxygen species and antioxidant machinery in abiotic stress tolerance in crop plants. Plant Physiol Biochem, 48, 909–930. DOI: 10.1016/j.plaphy.2010.08.016

[35]. Haklar, G., Yuksel, M., & Yalcin, A. S. (1998). Chemiluminescence in the measurement of free radicals: theory and application on a tissue injury model. *Marmara Med J*, 11,56–60. https://dergipark.org.tr/en/pub/marumj/issue/25310/267348

[36]. Jantan, I., Harun, N. H., Septama, A. W., Murad, S., & Mesaik, M. A. (2011). Inhibition of chemiluminescence and chemotactic activity of phagocytes in vitro by the extracts of selected medicinal plants. *J Nat Med*, 65(2), 400–405. DOI: 10.1007/s11418-010-0492-8

[37]. Jimenez, A. M., & Navas, M. J. (2002). Chemiluminescence Methods (Present and Future). *Grasas y Aceites*, 53, 64-75. https://doi.org/10.3989/gya.2002.v53.i1.290

[38]. Kato, K., Iyozumi, H., Kageyama, C., Inagaki, H., Yamaguchi, A., & Nukui, H. (2014). Application of ultra-weak photon emission measurements in agriculture. *Journal of Photochemistry and Photobiology B: Biology* **139**, 54–62. DOI: 10.1016/ j.jphotobiol.2014.06.010

[39]. Khan, P., Idrees, D., & Moxley, M. A.(2014). Luminol-based chemiluminescent signals: Clinical and non-clinical application and future uses. Appl Biochem Biotechnol, 173, 333–355. DOI 10.1007/s12010-014-0850-1

[40]. Kim, J. S., Jeong, K., Murphy, J. M. (2019). A Quantitative Method to Measure Low Levels of ROS in Nonphagocytic Cells by Using a Chemiluminescent Imaging System. *Oxid. Med. Cell. Longev*. 2019, 1-11. https://doi.org/10.1155/2019/1754593

[41]. Kokubo, H. & Yamamoto, M. (2008). Research on emission mechanisms of biophotons from cucumber. Journal of International Society of Life Information Science, 26(1), 53-58. https://doi.org/10.18936/islis.26.1_53

[42]. Kurek, K., Plitta-Michalak, B. & Ratajczak, E. (2019). Reactive oxygen species as potential drivers of the seed aging process. *Plants (Basel)*, 8, 174. https://doi.org/10.3390/plants8060174

[43]. Lazim, S. K. (2005). Lucigenin and Luminol-Enhanced Chemiluminecence in Mechanical Injured Roots of Corn (Zea mays L). Basrah J. Agric. Sci. 18 (1), 25-34. https://www.researchgate.net/publication/310426058

[44]. Lida, L., Masaki, K., Kazuhide, A.,Yumiko,Y., & Kazuyoshi, O. (2000). Chemiluminescence of adzuki bean and soybean seedlings. *Luminescence*, 15, 9-13. DOI: 10.1002/(SICI)1522-7243

(200001/02)15:1<9:: AID-BIO569>3.0.CO;2-X

[45]. Liu, M., Lin, Z., & Lin, J. M. (2010). A review on applications of chemiluminescence detection in food analysis. *Analytica Chimica Acta*, 670, 1–10. DOI: 10.1016/j.aca.2010.04.039

[46]. Liu, X., Xing, D., Li, L., & Zhang, L. (2007). Rapid determination of seed vigor based on the level of superoxide generation during early imbibition. Photoc*hem Photobiol Sci*, 6, 767–774. DOI: 10.1039/b704337f

[47]. Lilius, E. M., & Marnila, P. (1992). Photon emission of phagocytes in relation to stress and disease. *Experientia*, 48,1082–1091. DOI: 10.1007/bf01947995

[48]. Miladinovic, D.L. , Ilic, B.S. , Najman, S.J. , Cvetkovic, O.G. , Sajnovic, A.M. , Miladinovic, M.D. , & Nikolic, N.D. (2013). Antioxidative responses to seasonal changes and chemiluminescence assay of *Astragalus onobrychis* leaves extract. *Central European Journal of Chemistry*, 11, 123–132. DOI: 10.2478/s11532-012-0163-6

[49]. Moraes, T. A., Martins, L. C., Ramos, S. R., Garofalo, R. T., & Gallep, C. M. (2010). Spontaneous light emission of wheat seedlings with K2Cr2O7. *The Latin America Optics and Photonics Conference, OSA.*

[50]. Murthy, U.M.N., Kumar, P.P., & Sun, W.Q. (2003). Mechanisms of seed ageing under different storage conditions for Vigna radiata (L.) Wilczek: lipid peroxidation, sugar hydrolysis, Maillard reactions. *Journal of Experimental Botany*, 54, 1057-1067. DOI: 10.1093/jxb/erg092

[51]. Ohya, T., Yoshida, S., Kawabata, R., Okabe, H., & Kai, S. (2002). Biophoton emission due to drought injury in red beans: possibility of early detection of drought injury. *Jpn. J. Appl. Phys.* 41, 7625–7628. DOI: 10.1143/JJAP.41.4766

[52]. Pandey, V.P., Awasthi, M., Singh, S., Tiwari, S., & Dwivedi, U.N. (2017). A Comprehensive Review on Function and Application of Plant Peroxidases. *Biochem. Anal. Biochem*, 6, 1–16. DOI: 10.4172/2161-1009.1000308

[53]. Papuc, C., Crivineanu, M., Nicorescu, V., Predescu, C., & Rusu (Mircea), E. (2012). Scavenging activity of reactive oxygen species by polyphenols extracted from different vegetal parts of celandine (Chelidonium majus). Chemiluminescence screening. *Revista de Chimie*, 63(2), 193-197. https://www.researchgate.net/publication/286757316

[54]. Patil, K.G, Karjule, A., Patel, D.A., & Sasidharan, N. (2019). Effect of accelerated ageing on viability and longevity of wheat (*Triticum aestivum*) seed. *Indian J Agric Sci*, 89, 920–928, https://www.researchgate.net/publication/333894192

[55]. Perez, F., & Rubio, S. (2005). An improved chemiluminescence method for hydrogen peroxide determination in plant tissues. *Plant Growth Regul*. 48: 89–95. DOI 10.1007/s10725-005-5089-y

[56]. Piesik, D. , Weaver, D.K. , Peck, G.E. & Morrill, W.L. (2006). Mechanically injured wheat plants release greater amounts of linalool and linalool oxide. *Journal of Plant Protection Research*, 46 , 29 – 39.

[57]. Prasad, A. , Gouripeddi, P., Devireddy, H. R. N., Ovsii, A., Rachakonda, D. P., Wijk, R. V. & Pospisil, P. (2020). Spectral distribution of ultra-weak photon emission as a response to wounding in plants: An in vivo study. *Biology (Basel)* **9**, 139. doi:10.3390/biology9060139

[58]. Prilutsky, D., Rogachev, B., Marks, R. S., Lobel, L., & M. Last. (2011). Classification of infectious diseases based on chemiluminescent signatures of phagocytes in whole blood, *Artif. Intell. Med.*, 52, pp. 153–163. https://doi.org/10.1016/j.artmed.2011.04.001

[59]. Pospisil, P., Prasad, A., & Rac, M. (2014). Role of reactive oxygen species in ultra-weak photon emission in biological systems. *J. Photochem. Photobiol. B*, 139, 11–23. http://dx.doi.org/10.1016/j.jphotobiol.2014.02.008

[60]. Pulgarin, J. A. M. & Bermejo, L. F. G. & Duran, A. C. (2012). Use of the

Attenuation of Luminol-Perborate Chemiluminescence with Flow Injection Analysis for the Total Antioxidant Activity in Tea Infusions, Wines, and Grape Seeds. *Food Anal. Methods*, 5:366–372. DOI 10.1007/s12161-011-9246-9

[61]. Puntarulo, S., & Boveris, A. (1990). Effect of natural and accelerated aging on the hydroperoxide metabolism of soybean embryonic axes. *Plant Science*, 68, 27-32

[62]. Rafieiolhosseini, N., Poplova, M., Sasanpour, P., Rafii-Tabar, H., Alhossaini, M.R., & Cifra, M. (2016). Photocount statistics of ultra-weak photon emission from germinating mung bean. *J Photochem Photobiol B* 162, 50-55. DOI: 10.1016/j.jphotobiol.2016.06.001

[63]. Rastogi, A. & Pospisil, P. (2010). Effect of exogenous hydrogen peroxide on biophoton emission from radish root cells. *Plant Physiology and Biochemistry*, 48, 117-123. DOI: 10.1016/j.plaphy.2009.12.011

[64]. Roda, A., Pasini, P., Mirasoli, M., Michelini, E., & Guardigli, M. (2004). Biotechnological applications of bioluminescence and chemiluminescence. *Trends Biotechnol*, 22, 295–303. DOI: 10.1016/j.tibtech.2004.03.011

[65]. Rogovin, V. V., Mushtakova, V. M., & Fomina, V. A. (2001).The Inhibition of Chemiluminescence in Pisum Sativum L. Roots by Certain Metal Ions. *Biology Bulletin*, 28, 110–112. DOI: 10.1023/a:1026627208979

[66]. Roschger, P., Scott, R. Q., Devaraj, B., & Inaba, H. (1993). Observation of phase transition in intact leaves by intrinsic low level chemiluminescence, Photochem. Photobiol. 57, 580-583. DOI: 10.1111/j.1751-1097.1993.tb02337.x

[67]. Saeki, R., Miyazawa,T., Masashi, U., & Inaba, H. (1990). Relationship between low-level chemiluminescence and germination of soybean seeds. *Agric. Biol. Chem*. 54, 1603-1605. https://doi.org/10.1271/bbb1961.54.1603

[68]. Saeki, R., Kobayashi, M., Usa, M., Yoda, B., Miyazawa, T., & Inaba, H. (1989). Low-level chemiluminescence of water-imbibed soybean seeds. *Agric. Biol. Chem*. 53, 3311–3312. DOI: 10.1271/bbb1961.53.3311

[69]. Saeidfirozeh, H., Shafiekhani, A., Cifra, M., & Masoudi, A. (2018). Endogenous Chemiluminescence from Germinating Arabidopsis Thaliana Seeds. *Sci. Reports*, 8, (1) 16231. https://doi.org/10.1038/s41598-018-34485-6.

[70]. Sakharov, I. Yu. (2001). Long-term chemiluminescent signal is produced in the course of luminol oxidation catalyzed by peroxidase isolated from leaves of African oil palm tree. *Biochemistry(Moscow)*, 66, 515-519. DOI: 10.1023/a:1010254801513

[71]. Salin, M. L. *&* S. M. Bridges, S. M. (1981). Chemiluminescence in wounded root tissue. Evidence for peroxidase involvement. *Plant Physiol*. 67, 43–46. DOI: 10.1104/pp.67.1.43

[72]. Schadelin, J., Schadelin, R., & Mandell, G. L.(1980). Chemiluminescence of phagocytic cells. *CRC Crit Rev Clin Lab Sci*, 13: 1-19. DOI: 10.3109/10408368009106443

[73]. Sharma, A. , Pandey, S.T., & Verma, O. (2021). Response to pre- sowing seed treatment on germination indices, seedling growth and enzymatic activities of chickpea (*Cicer arietinum* L.) seed. *International Journal of Ecology and Environmental Sciences*. 3, (1), 405-410. https://www.researchgate.net/publication/350048437

[74]. Sitprija, V., Sitprija, S. (2012). Renal effects and injury induced by animal toxins. *Toxicon*, 60, 943–953. ; doi:10.3390/toxins9050163

[75]. Skotnica, J., Fiala, J., Ilik, P., & Dvorak, L. (1999). Thermally induced chemiluminescence of barley leaves. *Photochem Photobiol*, 69, 211–217. DOI: 10.1111/j.1751-1097.1999.tb03275.x

[76]. Suzuki, S., Usa, M., Nagoshi, T., Kobayashi, M., Watanabe, H. & Inaba, H. (1991). Two-dimensional imaging and counting of ultraweak emission patterns from injured plant seedlings. *J. Photochem. Photobiol. B Biol.* **9**, 211–217. https://doi.org/10.1016/1011-1344(91)80153-9

[77]. Thompson, J. E, Ledge, R. L., & Barber, R. F. (1987). The role of free radicals in senescence and wounding. *New Phytol*,105, 317-344. DOI: 10.1111/j.1469-8137.1987.tb00871.x

[78]. Triglia, A., Grasso, F., Musumeci, F., Scordino, A., Luciani, F., Battiato, A., Allegra, A. & Rajfur, Z. (1993). Temperature dependence of the ultraweak spontaneous photon emission from soya seeds. *Nuovo Cimento D*, 15, 1361-1370. DOI: 10.1007/bf02451682

[79]. Vartapetian, B. B. , Agapova, L. P. , Averyanov, A. A. , & Veselovskii, V. A. (1974). New approach to study of oxygen transport in plants using chemiluminescent method. *Nature*, 249, 69. DOI: 10.1038/249269a0

[80]. Veselova, T.V., Veselovsky, V.A., Obroucheva, N.V. (2015). Deterioration mechanisms in air-dry pea seeds during early aging. *Plant Physiol Biochem*, 87,133–139. https://doi.org/10.1016/j.plaphy.2014.12.019

[81]. Veselova, T.V., Veselovsky, V.A., Turovetsky, V.B., Galchuk, S.V., Vanyushin, B.F., Aleksandrushkina, N.I., & Rubin, A.B. (2004). Post-Hypoxic Oxidative Stress after Radicle Protrusion as a Possible Cause for the Production of Abnormal Seedlings in Pea. *Seed Sci. Technol*. 32, 283–296. **DOI:** https://doi.org/10.15258/sst.2004.32.2.02

[82]. Vladimirov, Y. A. (1966). Ultraweak Luminescence Accompanying Biochemical Reactions. *Springfield, Vermont: NASA*.

[83]. Wang, J., Fujimoto, K., Miazawa, T., Endo, Y., & Kitamura, K. (1990). Sensitivities of lipoxygenase-lacking soybean seeds to accelerated aging and their chemiluminescence levels. *Phytochemistry*, 29, 3739–3742. https://doi.org/10.1016/0031-9422(90)85323-8

[84]. Wany, A., Gupta, A.K., Kumari, A., Gupta, S., Mishra, S., Jaintu, R , Pathak, P.K. & Gupta, K.J. (2016). Chemiluminescence detection of nitric oxide from roots, leaves and root mitochondria. In: Kapuganti Jagadis Gupta (ed.), Plant Nitric Oxide: Methods and Protocols, Methods in Molecular Biology, Springer Science+Business Media New York, 1424, 15-29. DOI: 10.1007/978-1-4939-3600-7_2

[85]. Wiebach, J., Nagel, M., Borner, A., Altmann, T.,& Riewe, D. (2019). Agedependent loss of seed viability is associated with increased lipid oxidation and hydrolisis. *Plant Cell Environ*, 43, 303–314. https://doi.org/10.1111/pce.13651

[86]. Winkler, R., Guttenberger, H., & Klima, H. (2009). Ultraweak and induced photon emission after wounding of plants. *Photochem Photobiol*, 85, 962–965. https://doi.org/10.1111/j.1751-1097.2009.00537.x PMID: 19254235

[87]. Yeh, H. W., & Ai, H. W. (2019). Development and applications of bioluminescent and chemiluminescent reporters and biosensors. *Annual Review of Analytical Chemistry*, 12,129–150. DOI: https://doi.org/10.1146/annurev-anchem061318-115027, PMID: 30786216

[88]. Yoshinaga, N., Kato, K., Kageyama, C., Fujisaki, K., Nishida, R., & Mori, N. (2006). Ultraweak photon emission from herbivory-injured maize plants, *Naturwissenschaften*, 93 38–41. DOI: 10.1007/s00114-005-0059-9

[89]. Yoshioka, H., Rin, K., Tsuyuma, S. (1990). Light emission and formation of radicals after grinding tea leaves. *Agric. Biol. Chem*. 54, 3105-3110. https://doi.org/10.1080/00021369.1990.10870481

[90]. Zielinska, D., Wiczkowski, W., Piskuła, M. K. (2008). Evaluation of photochemiluminescent, spectrophotometric and cyclic voltammetry methods for the measurement of the antioxidant capacity: the case of roots separated from buckwheat sprouts. Polish J Food Nutr Sci, 58, 65-72. https://www.researchgate.net/publication/280992340