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Review

Laser in agriculture

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A b s t r a c t. The present review has been timed to coincide with the 50th anniversary of the LASER invention and this coincides with the current worldwide problems: climate change, energy, water supply, poverty, inequalities, and the population need for food. For example, one of the problems worldwide is the quantity and quality of agricultural seeds and foods. In developing countries this is more apparent, causing various diseases and malnutrition. In this review the utility of the laser technique when applied to agriculture has been addressed. The review has shown its applicability to one of the plant's phenological stages so that it can contribute to improve agricultural productivity and quality. Moreover, its application may be regarded as a sustainable method existing today, one invention from the past to the future.

K e y w o r d s: laser, biostimulation, seeds, photoreceptors, agriculture

INTRODUCTION

The laser (Light Amplification by Stimulated Emission of Radiation) was discovered by Th.H. Maiman, 50 years ago, using a flash lamp pumped ruby crystal as the medium (Maiman, 1960). The concept of 'stimulated emission of radiation', was first conceived by Einstein (1917). But it was in 1951 that its use for practical amplification of electromagnetic waves was recognised, and in 1954 the first such device, the maser (microwave amplification by stimulated emission), was constructed. Schawlow and Townes (1958) pointed out how the same process could be made to work for visible electromagnetic waves, which then set off a flurry of work in many places to build such a device (Townes, 2007). The laser discovery in the past century has been of great impact and applied in the society from its conception until today. Among its applications is its use in agriculture as a biostimulator device. The laser light of low intensity produces biostimulation when used on seeds, seedlings and plants (Aladjadjiyan, 2007a; Chen *et al.*, 2005a,b; Dziwulska, 2006; Govil *et al*., 1985; Hernandez *et al*., 2001, 2004, 2005, 2006, 2007a,b, 2008a,b; Humetskyi and Skvarko, 2002; Inyushin, 1991; Inyushin *et al*., 1981; Li and Feng, 1996; Mikos-Bielak and Koper, 2003; Muszyński and Gładyszewska, 2008; Perveen *et al*., 2010; Pietruszewski *et al.,* 2007; Podleśny *et al*., 2001; Romaniuk, 2001; Saghafi *et al*., 2005; Skvarko and Pochynok, 2010; Vasilevsky, 2003; Vasilevsky *et al*., 2001; Voronkov and Tsepenyuk, 1988).

The basis of the stimulation mechanism in any plant physiological stage is the synergism between the polarized monochromatic laser beam and the photoreceptors (Bielozierskich and Zolotariewa, 1981; Koper *et al*., 1996) that, when triggered, activate numerous biological reactions (Karu, 1989). There are many facts that indicate the biostimulating action of laser radiation on various organs and tissues in animals and plants (Anisimov *et al*., 1997). The plants absorb light *via* their photoreceptors (Spalding and Folta, 2005). They control all stages of plant development (Casal and Yanosvsky, 2005; Chen *et al*., 2004; Golovatskaya, 2005; Kneissl *et al*., 2008; Shimizu *et al*., 2002; Smith, 2000). Laser activation of plants results in an increase of their bioenergetic potential, leading to higher activation at fitochrome, fitohormone and fermentative systems, as a stimulation of their biochemical and physiological processes

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(Vasilevski *et al.*, 2001). Speaking about of incidence of light on the phenological stages of the plants, during their evolution, three major classes of photoreceptors are important to mention in plants at the molecular level: the phytochromes, that were the first family of plant photoreceptors to be discovered; they are most sensitive to the red and far-red region of the visible spectrum, the blue/UV-A-absorbing cryptochromes, and the phototropins (Lariguet and Dunand, 2005; Quail, 2002; Schäfer and Bowler, 2002; Torres *et al.*, 2006). The phytochromes are ubiquitous in plants, but also identified in many prokaryotic species and fungi (Lamparter, 2004; Levskaya *et al.*, 2005, Li Xu *et al.*, 2009; Mathews, 2006).

Phytochromes, meaning 'plant colour', are photoreceptive signaling proteins responsible for mediating many light-sensitive processes in plants, including seed germination, seedling de-etiolation and shade avoidance. They detect red and near-infrared light (600-750 nm) through the photoisomerization of a covalently bound tetrapyrrole chromophore such as phycocyanobilin (Levskaya *et al.*, 2009). The cryptochromes (from the Greek chroma meaning color and crypto- as in 'cryptic' or 'cryptogam') are flavin-type blue light photoreceptors found in many organisms including bacteria, plants, animals, and humans (Banerjee and Batschauer, 2005). They mediate a variety of blue light (320 to 500 nm) dependent responses including photomorphogenesis and growth responses in plants (Bouly *et al.*, 2007). The phototropins, on the other hand, are composed of an amino-terminal photosensory domain and a carboxy-terminal Ser/Thr protein kinase domain. A flavin mononucleotide molecule tightly bound to the so-called LOV (Light, Oxygen, Voltage) domains allows light sensing. LOV domains are encountered in plants, fungi, and bacteria (Chen *et al.*, 2004; Han *et al.*, 2007).

In this way, light is life for plants (Quail, 2002). A plant ability to maximise its photosynthetic productivity depends on its capacity to sense, evaluate, and respond to light quality, quantity, and direction (Briggs and Olney, 2001). The growth of plants in artificial light has been of interest because it offers the possibility of controlling the quality and intensity of the light, and the time of exposure. Thus, several sources of light in different phenological stages of plants, seeds, seedling, plants *etc.* have served to improve their establishment in a wide range of field conditions, from flash lamps to lasers, those latter being the source of irradiation which constitutes the focus of the present article. Such processes can occur under the effect of light emitted from incoherent sources, as the use of incandescent lamp for seed treatment before sowing (Kuznetsova *et al.*, 1976), but the use of laser light at specific wavelengths increases the ratio at which the molecules are excited (Letokhov, 1985). Illumination of biological tissue by coherent laser light leads to strong intensity gradients of the radiation in the tissue due to speckle formation, which causes inter- and intracellular gradient forces whose action may significantly influence the paths and speeds of biological processes (Ruvinov, 2003), that is also one of the important factors in the consideration of laser light as a pre-sowing seed treatment. Laser applications in agriculture have had beneficial effects on germination, vigour, growth, stress resistance, health quality, yield, crop quality, *etc*. This review has as objective to make a revision of the scientific literature about the application of laser in agriculture and its potential to contribute in improving the quantity and quality of food production.

BACKGROUND

Pre-laser age applied in agriculture

Since 1948 Borthwick, Hendricks and colleagues conducted experiments to establish the central hypothesis of phytochrome action, proposed by them: the photoreceptors exist in two photoconvertible forms, Pr and Pfr Pr is biologically inactive and upon absorption of red photons is converted to Pfr, the active form. Pfr is converted back to Pr by far-red photons (Borthwick *et al.*, 1948; 1951; 1952a; 1952b). The photoconversions involve a number of intermediate forms in both directions, and the establishment of an equilibrium between Pr and Pfr takes several minutes even at daylight irradiance levels. Hendricks and Borthwick (1966) performed lettuce seed germination experiments, demonstrating that a reversible photoreaction controlled this process. They purifyed the pigment responsible for this effect, which they named phytochrome, and also described its role in seed germination, seedling development, and flowering. Also, they studied the phototransformation time to go from one state to the other in the phytochromes. Hendricks calculated the irradiation times on phytochromes to change its state by applying red light from a fluorescent lamp emitting at 700 nm wavelenghth (Butler, 1963; 1982). Meanwhile, as those experiments were performed in this area of knowledge, the discovery of the laser and its incursion in biology occurred.

The incursion of laser in biology was made by Bessis *et al.* (1962), with the application of a ruby laser on cellular organelles. Rounds *et al.* (1965) demonstrated that destruction of pigmented and non-pigmented tissues from laser radiation is dependent upon the ability of the cell to absorb the imposed energy. Johnson *et al.* (1965) suggested that the respiratory activity of amniotic tissue was temporarily inhibited by laser irradiation. Rounds *et al.* (1968) reported inhibition of the rate of oxygen consumption by brain cells, following green laser radiation, implicating this biochemical pathway as one mode of cellular injury; their experiments led to indicate that injury of the brain cells was mediated through damage to the respiratory enzymes. One of the major areas of biology in which laser applications were focused was the micro-irradiation. The laser biostimulation phenomenon was first noted and published by Mester *et al.* (1967) who conducted experiments with mice. He shaved the hair off their backs, divided them into two groups and irradiated one group with a low powered ruby laser. The treatment group to his surprise, grew the hair back more quickly than the untreated group. He called this 'Laser Biostimulation'. The laser light as biostimulator has been applied in the agriculture, where some scientific reports evidence its usefulness.

LASER APPLIED IN AGRICULTURE

Wilde *et al*. (1969) and Paleg and Aspinall (1970) pioneered the use of a ruby laser and He Ne, respectively, in the agriculture. Wilde *et al*. (1969) showed that exposure of certain seeds to laser radiation appeared to speed up the germination and growth of their plants. He indicated: 'if these preliminary results are borne out, the technique could increase per-acre yields and reduce requirements for troublesome pesticides'. Paleg and Aspinall (1970) demonstrated that laser emission of 632.8 nm activates the phytochrome system, and it was possible to produce phytochrome response at large distance. Since these first reports until nowadays there have been numerous studies applying laser in agriculture and these have shown the potentiality of its application in this field. The number of studies has increased in this century, due to the need that exists to stop the destructive processes of the soil, the environment, and thus to ensure the protection of the food that affects the human health.

From the initial laser application in agriculture until now, different laser light types have been used, from ultraviolet to far infrared, including UV (200-400 nm), visible light (400-700 nm), near infrared radiation (750-2 500 nm) and far infrared (5000-10^6 nm). Solid, gaseous and semiconductor lasers have been applied in agriculture, for example: ruby laser (694 nm), He-Ne (632.8 nm), nitrogen laser (337.1 nm), argon (514.5 nm), YAG: Nd laser (532 nm), diode laser (510, 632, 650, 670, 810, 940 and 980 nm), AsAlGa semiconductor laser (650, 660 and 850) and CO_2 (10 600 nm) (Fig. 1). These lasers have been used alone or in combined forms; with simple or several irradiation regimes. The laser light wavelength most frequently used in the biostimulation process is the red, where the phytochrome absorbing occurs. Phytochrome is localized at the plasmalemma, mitochondrial and chloroplast membranes, endoplasmic reticulum, possibly in the cell nuclei (Samuilov and Garifullina, 2007), and in the embryo of the seeds (Pons, 2000). Apart from photoreceptors responsible for light absorption, a system of interconnected membrane structures is operating within the cell and accounts for utilisation and transformation of absorbed light energy (Shakhov, 1993). The energy from the laser light absorbed in the seed triggers physiological and biochemical processes, due to the transformation of light energy to chemical energy.

The laser treatment is one of the physical methods that also include electromagnetic treatment (Domiguez *et al*., 2010a; Hernandez *et al*., 2007a; 2009b; Pietruszewski, 1993; 1999; Zepeda *et al*., 2010) and/or electric treatment (Pozeliene and Lynikiene, 2009) that can improve the sowing quality (Klimont, 2001a; Laszkiewicz, 2001) and food, help achieve higher productivity, and at the same time reduce the risk of contamination from soil and water (Aladjadjiyan, 2007b). According to our review of literature on the application of laser in Agriculture for the treatment of seed, it has been found that the important parameters are the seed characteristics, the position of the seed during the laser irradiation, and the laser irradiation parameters. Regarding the seed characteristics, the:

- optical (β: optical absorption coefficient, $1/\beta$: optical penetration length);
- thermal (α: thermal difussivity);
- photothermal (non radiactive-relaxation time);
- phenotypic (quality physical, physiological and health);
- genotypic (genetic quality) are important to consider. The moisture of seeds, their photosensitivity, damage status, low physiological state *etc*. must be taken into account, because any change in the seeds properties can alter the absorption spectra in these (Braga *et al*., 2003; Cruz *et al*., 2006; Domiguez *et al*., 2009, 2010c, 2010b; Hernandez *et al*., 2005, 2008a, 2009a, 2010; Rezende *et al*., 2009; Susuki *et al*., 2005), as well as the biostimulation process.

Regarding the position of the seed during the laser irradiation, the following have been considered:

- free fall,
- fixed (irradiating on the side of the embryo),
- turning (in order to irradiate the seeds as uniform as possible).

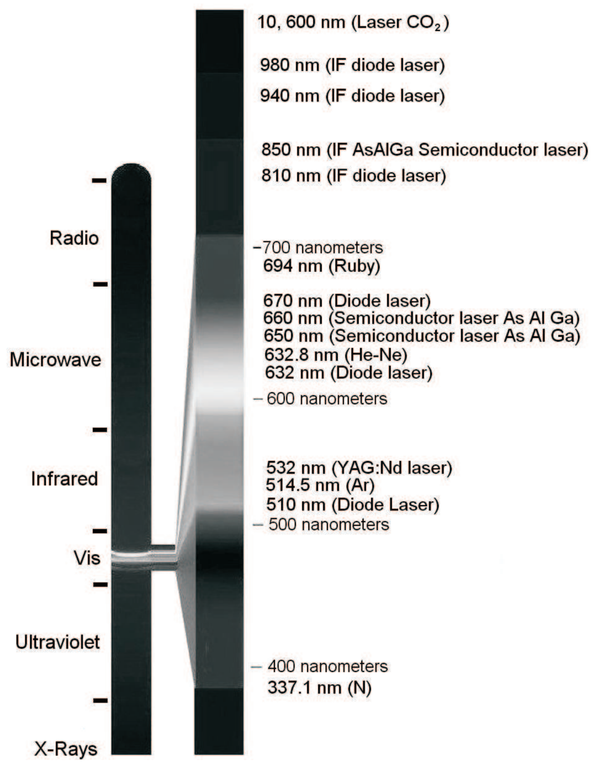

Fig. 1. Electromagnetic spectrum of the application of laser light in agriculture.

Also, the laser irradiation parameters are important to take into an account at the biostimulation process:

- λ – wave-length,
- t – exposure time,
- I – intensity,
- D – dosage,
- RI – irradiation regime number and light type (pulsed or continuous).

There are numerous studies that show the effects of presowing laser irradiation, both in cereals, among them the basic seeds as rice, maize, and in vegetables, such as: tomato, radish, peas, cucumber, lettuce, onion, etc. On the other hand, several studies indicated that the seeds of vegetables are more sensitive and susceptible to laser stimulation than cereals (Drozd and Szasjener, 1999; Gładyszewska, 2006). Also, experimental tests in laboratory and field have been performed which have been reported in the scientific literature, showing the effects on different seeds, seedlings, plants and irrigation water (Aladjadjiyan and Kakanakova, 2008; Inyushin, 1991; Klimont, 2001b; Vasilevsky, 2003).

Other researches on laser irradiation in agriculture show that it could have a potential application as an insecticide (Yao *et al*., 2009), herbicide (Mathiassen *et al*., 2006), fungicide (Bel'skii and Mazulenko, 1984; Dobrowolski *et al*., 1997; Hernández *et al*., 2005; Ouf and Abdel-Hady, 1999; Wilczek *et al*., 2005a; 2005b) and in pollination process (Li and Yu, 2006).

Laser light effects

The synergy of events that happen to interact with laser light leads to a series of obvious effects, which have been studied in different parts of the world, providing evidence of the potencial possibility of its use in agriculture. The scientific reports have demonstrated the following findings: increases of the energy potential of seeds; accelerated maturity makes plants precocious; increasing resistance to diseases; influence on alpha-amylase activity and the concentration of free radicals in the seeds of several plants that could deactivate seed dormancy; improved germination rate; germination percentage; germinating energy and uniformity of germination; increased seed vigor; impact on the respiration process, photosynthetic activity, and chlorophyll content and carotenoid content of seedlings from irradiated seeds (Aladjadjiyan and Kakanakova, 2008; Durkova, 1993; Gładyszewska, 2006; Hernandez *et al*., 2005, 2006, 2007a, 2008a; Jun Lin *et al*., 2007; Starzycki *et al*., 2005). Soliman and Harith (2010) showed that irradiation with He-Ne laser light at 1.70 W cm^{-2} for 9 min affected the germination indices of *A. farnesiana* seeds. In an experimental work conducted by González *et al*. (2008) the authors reported that lasers of 1, 5, 10 and 15 mW affected the germination, showing an increase or a decrease dependent of the parameters of radiation. Hernandez *et al.* (2008b) evaluated the effect of light from laser diode of 650 nm and power of 27.4 mW on photosensitized wheat seeds. Photosensitized seed increased the germination with respect to the non-coloured. Szajsner and Drozd (2003) evaluated the influence of a pre-sowing He Ne laser treatment on the sowing value and early phases of four spring barley cultivars; an increase in the germination capacity was reported. Other results confirm the favourable effects the He Ne laser has on germination, for example in the following cases: on natural medicinal plant material using pre sowing He Ne laser (Gao *et al*., 2008), on red clover seeds and seed of Chinese pine (Jun Lin *et al*., 2006; Wilczek and Ćwintal, 2009, on red clover seeds and seed of Chinese pine, also showing an influence on the respiration and photosynthesis processes (Anghel *et al*. 2001), on photosynthetic intensity of red clover seeds (Wilczek and Fordoński, 2007), on morphological characters and diastatic power of winter wheat genotypes (Szajsner, 2009), on the activity of amylolytic enzymes of maize hybrids seeds (Podleśny and Stochmal, 2005), on androgenesis in some chosen varieties of winter triticale in experiments *in vitro* (Katańska *et al*. 2003), on the course of the individual phases of the development of white lupine and faba bean plants (Podleśny and Podleśna, 2004). In irradiation of tissue culture of wheat, reporting considerable changes in the structure of the lipid matrix (Salyaev *et al*., 2007). The application of a semiconductor laser on wheat and cucumber affected their germination and growth (Hernandez *et al*., 2001; Mitchenko *et al*., 2008). The 532 nm laser affected the photosynthesis efficiency of soybean seedlings and could increase the isoflavone content (Tian *et al*., 2009).

In addition to the effects of seed treatment before sowing observable in early stages of growth, there is also evidence reported by some authors that the quality and quantity of production is affected at later stages. Vasilevski and Bosev (1997a), studying He-Ne laser treated potato tubers prior to planting, found a 17.8% of increase in the number of tubers per plant, and a 21.4% increase in the weight of the tuber. In vegetable production, increased yielding, early maturity, and better quality of the products has been demonstrated on the example of tomatoes, pepers, cucumbers, onions and beans (Vasilevsky and Bosev, 1997b). Pre-sowing seed laser biostimulation enhanced the production of some crop plants such as maize (from 10 to 15%), spring wheat (from 20 to 30%), spring barley (from 20 to 25%), sugar beets (from 10 to 30%), rape seeds (from 10 to 15%) Gładyszewska *et al*. (1998). Pre-sowing laser seed treatment influenced yields of roots and leaves of sugar beet, depending on the regime of irradiation and reduced the content of N, P, K, Ca and N in the roots (Koper *et al*., 1996). Triticale seed irradiation with red light caused an increase of mineral element contents, notably that of sodium, zinc and iron, but to a lesser extent of potassium and calcium; magnesium level decreased (Truchliński *et al*., 2002b). Influence of pre-sowing red light irradiation and nitragine dressing of chickling vetch seeds on the chemical composition of their yield also have been reported (Truchliński *et al*., 2002a).

Beet, maize, spring barley and wheat seeds exposed to irradiation by divergent laser beams during their free falling down from the vibratory conveyor modified their germination and sprouting duration of vegetation period, resistance to frost and diseases, and crop yielding (Koper *et al*., 1997). In white lupine seeds, laser irradiation affected some mechanical properties of yielded lupine seeds, and irradiation of tomato seeds produced an effect on the physicochemical properties of the fruits (Koper and Rybak, 2000; Koper *et al*., 1999). Yamazaki *et al*. (2002) investigated the effect of red laser-diode light supplemented with blue light on plant growth of rice; their results showed 36% decrease in number of tiller spikes and 60% decrease in seed yield at final harvest, and the authors suggest the necessity of an optimization process when laser is applied as a pre-sowing treatment. On the other hand, the pre-sowing irradiation of seeds has had a favourable effect for the yield on faba bean seeds, alfalfa, wheat, maize and barley, for specific parameters of irradiation (Dziwulska *et al*.,2006; Podleśny 2007; Szajsner and Drozd, 2003, 2007; Szajsner *et al*., 2007; Wesołowski and Cierpiała, 2006). Podleśny (2007) indicated the efficiency of laser treatment in the function of weather conditions. Truchliński *et al*. (2002b) showed an influence of pre-sowing red light radiation and nitragine dressing of chickling vetch seeds on the chemical composition of their yield, mainly affecting the increase in total protein, crude fibre and mineral element (Na and K) levels. Pre-sowing clover seed stimulation with laser radiation with several irradiation regimes affected dry matter yield (Wilczek *et al*., 2006).

Others studies have pointed to the role of lasers in stress resistance modification. For example, the embryos in bean (*Vicia faba* L.) seeds were exposed to He-Ne or CO_2 laser radiation, and afterwards the epicotyls were exposed to UV-B radiation; the results showed that laser pretreatment of embryos enhanced UV-B stress resistance in the epicotyls of broad bean (Qi *et al*., 2000). The use of laser light can be regarded also as a stress agent damaging cells and tissues. Salyaev *et al*. (2001b) found that low-intensity laser radiation stimulates morphogenetic processes in tissue cultures of wheat and wild grasses, such as rhizogenesis and the formation of morphogenic calli and regenerated plants. Salyaev *et al*. (2007) suggest that a general cell response induced by laser-light irradiation can be divided into two specific responses: the first one consists in a rapid stress effect resulting in an increase in the amount of lipid peroxidation products, and the second and longer one are the secondary reactions related to the adaptive metabolic changes and apparently accompanied by the stimulation of morphogenetic processes. Chen

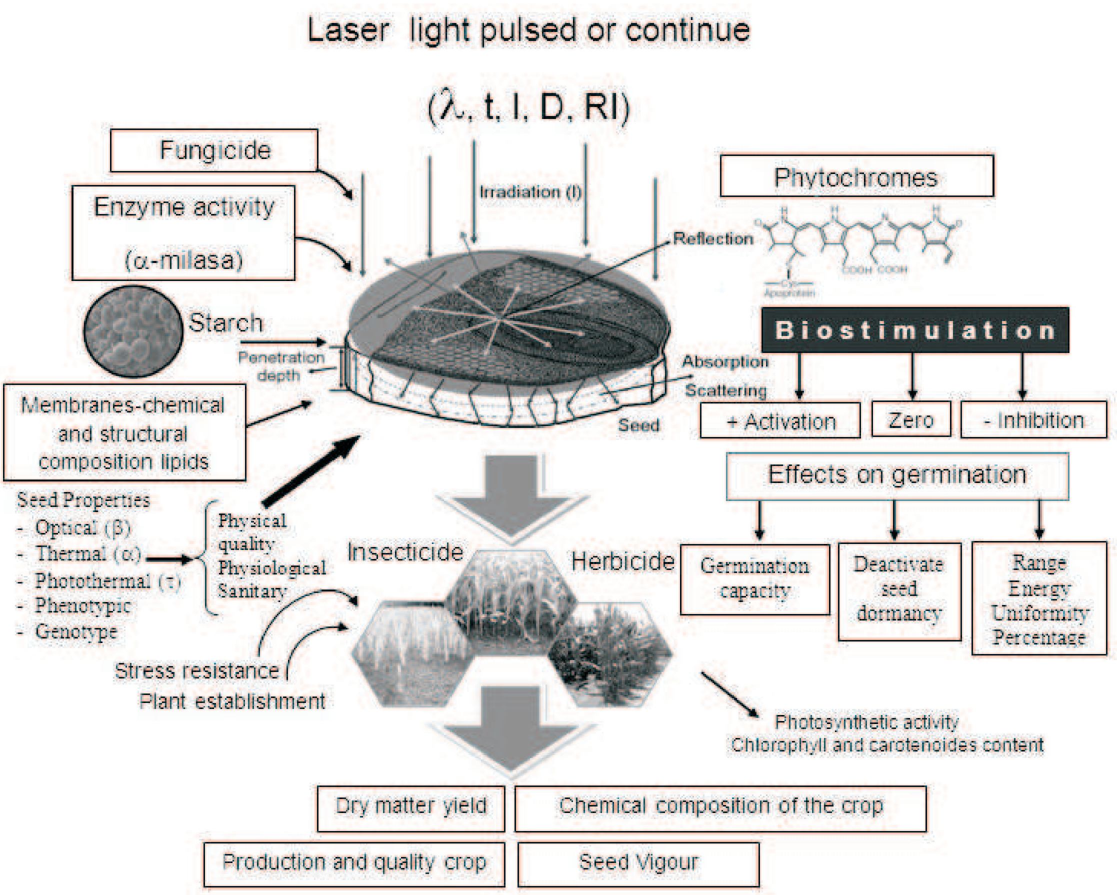

Fig. 2. Potential applications of laser light in the agricultural sector according to the literature review (λ – wave-length, t – exposure time, I – intensity, D – dosage, RI – irradiation regime).

T a b l e 1. Summary of the effect of laser biostimulation on plant

Seed type	Laser type	Wavelength λ (nm)	Exposition time (min)	Power density	Response
Phaseolus Rhaphanus Medicago Cucurbita	ruby	694	2.5-3 ms 0.7 ms	1 to 125 and 25 J cm^{-2}	Germinated and grow faster. This effect could increase yields and a reduction in pesticide (Wilde *et al*., 1969)
Lettuce	He Ne	632.8	10 s 30 min	3	Cause a stimulation of germination resulted in a decreased germination (%) (Paleg and Aspinall, 1970)
Chrysanthemum	He Ne	632.8	–	50	Reduced the rate of floral development (Paleg and Aspinall, 1977)
Pinus banksiana	He Ne	632.8	100, 1000 ms	5	Laser activation of phytochrome-controlled germination in *Pinus banksiana* (Campbell and Donald, 1979)
Vigna radiata	Ar	514.5	0,1,2,5,10,20,40	1 W	Increased in fresh and dry weights and the RNA, DNA and protein contents (Govil *et al*., 1983)
Cucumber	He-Ne	632.8	–	24	Stimulated embryonic root growth, photosynthesis rate and peroxidase activity and reduced leaf plastid pigment content (Shaban *et al*., 1988)
Hibiscus cannabinus L.	He-Ne	632.8	–	–	Increased seed production and reduced the growth period (Son, 1990)
Vigna radiate L.	N, Ar	337.1 514.5	30 5	200 KW 1 W	Produced an increase in seed protein content of *Vigna radiata* L. (Govil *et al*., 1991)
Zea mays L.	N Dye He Ne	337.1 510 632.8	4, 40 210 18, 80 s	2.5 mJ 0.232 mJ 5.6 mW	Caused changes in the carbohydrate metabolism of the germinating maize seed (Toth *et al*., 1993)
Maize, wheat, spring barley, sugar beets	He Ne	632.8	–	–	Better plant seedlings, higher resistance to cold and earlier plant maduration (Koper, 1994)
Sugar beets	He Ne	632.8	–	40	Influenced yields of roots and leaves of the sugar beet (Koper *et al*., 1996)
Cucumber	He Ne	632.8	–	20	The irradiation of cucumber seeds increased the quantity of the photosynthetic product and the content of plastid pigments in leaves (Cholakov *et al*., 1997)
Leucaena leucocephala cv. Cunningham	He Ne	632.8	5 s to 60 min	1	Stimulating and the inhibitory were observed in the seeds (Cepero *et al*., 1997)
Lupinus albus L.	He Ne	632.8	–	30	Positive effects on germination under optimal as well as under chilling stress conditions (Podleśny *et al*., 1997)
Tomatoes, peppers, cucumbers, onions and beans	He Ne	632.8	–	–	Increased yields, early maturity, a better quality of the products (Vasilevsky and Bosev, 1997a)

T a b l e 1. Continuation

Seed type	Laser type	Wavelength λ (nm)	Exposition time (min)	Power density	Response
Wheat	He Ne	632.8	–	$4x10^{-3}$ mJ cm^{-2}	Effect on morphological characters determining the cereal yield: length and density of ear (Drozd *et al*., 1999)
Soybean (*Glycine max* L. Merrill)	He-Ne	632.8	1,3,6 and 10	7.3	Reductied the number of seed-borne fungi and germination was increased (Ouf and Abdel-Hady, 1999)
Spring barley	He-Ne	632.8	30,60,90	1 mW cm^{-2}	Induced biostimulation effect on the yield parameters (Rybiński, 2000)
Synechococcus cedrorum	YAG:Nd	532	Pulse 10 ns Time: 2,5,15	15 kW	Changes in the fluorescence spectra of phytoplankton (Tsipenyu and Dimitry, 2000)
Cucumber	As Al Ga	660	30 s	30	Increased growth (Hernandez *et al*., 2001)
Wild grasses	He-Ne	632.8	5,30	10	Positive effect on the callus producing capacity of tissues of wild grasses (Salyaev *et al*., 2001a)
Wheat Callus Culture	He–Ne	632.8	5	12	Affected morphogenetic processes in cultured tissues of higher plants (Salyaev *et al*., 2001b)
Triticale seeds of Gabo and Migo cv.					Caused the increase of mineral element contents, notably that of Na, Zn and Fe, but to a lesser extent of K and Ca; Mg level decreased (Truchliński *et al*., 2002b)
Bean *Vicia faba* L.	He-Ne	632.8	5	5.43 mW cm^{-2}	Positive physiological effect on the growth of UV-B-damaged plants (Qi *et al*., 2002)
Triticum aestivum	He-Ne	632.8	2	5 mW mm^{-2}	The results indicated that the content of endonuclease sensitive sites was reduced (Rong *et al*., 2002)
Winter triticale	He Ne	632	1,15	24	The number of callus obtained per 100 plated anthers indicated a biostimulating activity (Katańska e*t al*., 2003)
Wheat	AsAlGa	650	60 sec	30	Stomatal density was diminished as consequence of seed laser irradiation. The seedling growth and morphology were modified as result of seed irradiation (Benavides-Mendoza *et al*, 2003)
Barley *Hordeum vulgare L.*	He-Ne	632	60, 180	–	Influenced the area of two uppermost leaves as well as theirs photosynthetic activity expressed by the photosynthetic rate, transpiration rate and coefficient of water use (Rybiński and Garczyński, 2004)
Wheat (Rysa, Mobela)	He-Ne	632.8	0.1 s	4mW cm^{-2}	Increased the strength and energy of germination, and in the intensity of germinating seeds respiration (Makarska *et al*., 2004)
Oat		670	1, 4 min	200	increased germination capacity (Drozd *et al*., 2004)
Wheat and maize	diode	630		20	Decreased photosynthesis intensity (Dinoev *et al*., 2004)

T a b l e 1. Continuation

Seed type	Laser type	Wavelength λ (nm)	Exposition time (min)	Power density	Response
Trifolium pratense L.	He-Ne	632	0.1 s	0,3 and 6 mW cm^{-2}	Fungi of the Alternaria (Alternaria alternata) type had the highest share in the seed inhabitation. The Phoma and Penicillium strains were eliminated by laser irradiation (Wilczek *et al*., 2004)
Isatis indigotica Fort seeds	He-Ne	632.8	5	5.23 mW cm^{-2}	Can improve the inner energy of seeds, lead to an enhancement of cotyledon enzymes, and speed up the metabolism of the cell, resulting in significantly increased biophoton emission (Chen *et al*., 2005b)
B. napus	He-Ne	632	30,60,90, 120	24	Can be used in breeding and high quality seed production of winter rapeseed (Starzycki *et al*., 2005)
Medicago sativa L.	He-Ne	632	0.1s	3 and 6 mW cm^{-2}	Laser treatment significantly decreased the percentage of those seeds infected with fungi (Wilczek, 2005b)
Carrot, radish , cress	–	532, 526	–	8	Activated seeds in such a way that the total biomass (Sommer and Franke, 2006)
Medicago sativa L.	He Ne	632.8	0.1 s 1-, 3- and 5-times	40	Laser stimulation resulted in growth of the number of shoots per 1 m^2 and the yields of green and dry matter (Dziwulska *et al*., 2006)
Wheat (Jantar)	semicon-ductor	–	–	50 mW cm^{-2}	Showed positive changes in the germination energy at the 7th day (Dinoev, 2006)
Cotton	He-Ne		1x 10^{-3} s	20	Not influence the proceeding of plant development stages. A stimulation effect has been found on the rate of growth of high stem of plants and flowering dynamic of testing cultivars (Delibaltova and Ivanova, 2006)
Zea mays L.	As Al Ga	660	30,60,120,180,300,600	30	The laser seed irradiation significantly increased the seed vigour (Hernandez *et al*., 2006)
Medicago sativa L.	He Ne	632.8	20 ^{s}	40	The number of seeds germinating normally increased and hard seeds decreased upon laser stimulation (Dziwulska, 2006)
Weed species	diode	532,810	250,500,1000, 2000,3000 ms 160,320.640, 1260,2500 ms	5W, 90W	Method of physical weed control (Mathiassen *et al*., 2006)
Wheat	He Ne	632.8	–	40	Only small growth in the winter wheat grain yield (Wesołowski and Cierpiała, 2006)
Bare-grained oat	semicon-ductor	–	–	200	Induced significant stimulation of coleoptiles length (Drozd and Szajsner, 2007)
Trifolium pratense L.	He Ne	632.4	0.1 s	40	Increased lignin concentration in fibre along with potassium; mineral ash in fibre and content of crude fibre in plants were decreased (Ćwintal and Wilczek, 2007)

T a b l e 1. Continuation

Seed type	Laser type	Wavelength λ (nm)	Exposition time (min)	Power density	Response
Zea mays L.	Lvov-1	632.8	25 ms	50	Decreases the microviscosity of aqueous medium and accelerates the motions of water and spin probe molecules (Samuilov and Garifullina, 2007)
Medicago sativa L.	He Ne	632.8	0.1	–	Not were significant differentiate in the alfalfa dry matter yield (Ćwintal and Olszewski, 2007)
Miscanthus x giganteus plants	He-Ne		30, 45, 60, 90	24	Not observed any clear laser effect on the number of regenerated calli (Głowacka *et al*., 2007)
Wheat	SC	650	–	3.97 mW cm^{-2}	Had the capability to protect plants from UV-B-induced DNA damage (Qiu *et al*., 2007)
Suchi	AsAlGa	650	30 s	30	The seedling growth and morphology were modified as result of seed irradiation (Benavides *et al*., 2003)
Chinese pine seeds (*Shaanxi*)	He-Ne	632.8	40, 60 and 100 s	10.8	Enhancement of seed vigor (germination rapidness, root system expansion, and of fresh seedling mass (Jun Lin, 2007)
Triticum aestivum L.	He-Ne	632.8	5	10	Changed the structure of the lipid matrix (Salyaev *et al*., 2008)
Triticum aestivum L.	He-Ne	632.8	0, 3 10, 30, 60, 180, 600, 1200, 1800 s	5.23 mW cm^{-2}	The biochemistry and physiology metabolisms of the plants pretreated with laser were accelerated (Abu-Elsaoud *et al*., 2008)
Perennial ryegrass seeds, Solen c.v.	red, green	532, 660	30 s	5mW 21.9mW	Some macroelements: phosphorus, potassium, magnesium or sodium were larger (Grygierzec, 2008)
Isatis indigotica (*Brassicacae*)	He-Ne	633	5	5.23 mW cm^{-2}	Can raise the enzymes activities, acceleration plant physiological mechanism and increased plant growth exposed to UV-B (Chen, 2008)
Pueraria phaseoloides	red	–	1, 5, 10 and 15	1, 5, 10 and 15	Increased the numeric value of the seed germination percentage (Gonzalez *et al*., 2008)
Echinochloa crusgalli	CO_2	10, 600, 940	1 s	–	Effective weed control was found to be possible by irradiating the meristems (Wöltjen *et al*., 2008)
Nicotiana tabacum	diode		2 s		
Raphanus dativus L.	He Ne	632.8	1s	4, 2 mW cm^{-2}	Accelerated the germination (Muszyński and Gładyszewska, 2008)
Triticum aestivum L.	AsAlGa	850	15, 30, 60, 120 s	12.5, 25, 50, 100 mW cm^{-2}	Biostimulated growth (Hernández *et al*., 2008b)

T a b l e 1. Continuation

Seed type	Laser type	Wavelength λ (nm)	Exposition time (min)	Power density	Response
Fennel *Feoniculum vulgare* Mill.	He-Ne	632.8	5,10,20	10	Increased the nitrogen content which led to increase in protein which needs to cover the increase of plant organs (Osman *et al*., 2009)
Zea mays L.	diode	650	20 s	27.4	Negative biostimulation for seedling emergence percentage, seedling emergence rate and chlorophyll a content was observed (Hernandez *et al*., 2009)
Pimpinella anisum and *Cuminum cyminum*	He Ne	632.8	5, 10, 20	95 mW cm^{-2}	Effect by enhancement the growth of the anise and cumin plants which already affect the growth and the essential oil in cumin and anise plants (Tobgy *et al*., 2009)
Isatis indigotica (Brassicacae)	He-Ne	633	5	5.23 mW mm^{-2}	These results suggest that laser radiation has an active function in repairing UV-B-induced lesions in seedlings (Chen, 2009)
Trifolium pratense L.	He Ne	632.4	0.1 s	40	Increased the germination energy of red clover and the share of normally germinating seeds, while decreasing the % of hard seeds. It had no significant influence on germinating ability (Ćwintal *et al*., 2010)
Brassica napus L.	Nd:YAG, diode, IF diode	532, 632 and 980	3	75, 110 and 250	Showed positive changes in the proline content. Can be useful for improving rapeseed yield in the field conditions, especially in those regions where salinity occurs (Ashrafijou *et al*., 2010)
Vicia faba L.	He-Ne, D	632.2, 650	5	30 30	A combination of g-irradiation and He-Ne or diode laser, a marked increase in glutathione content was found and was more pronounced than that of gamma irradiation alone (Aly and Hossam, 2010)
Acacia farnesiana L.	He Ne		1, 3, 5, 7 and 9	0.03, 0.20, 0.61, 1.14, and 1.70 W cm^{-2}	Significantly affected germination indices when compared with control seeds (Soliman and Harith, 2010)
Helianthus annuus L.	He Ne	632.8	–	100, 300, 500 mJ	Incremented internal energy due to laser pre-sowing seed treatment increased the activities of amylases and proteases, which ultimately increased seed germination (Perveen *et al*., 2010)
Triticumaestivum L.	CO_2	10600	300 s	20 mW mm^{-2}	Enhances physiological tolerance of wheat seedlings improving the physiological metabolism of signal systems as well as enzymatic and non enzymatic defense systems (Chen *et al*., 2010)

et al. (2010) showed the effect of CO_2 laser pretreatment of wheat seeds on the physiological tolerance of seedlings to chilling stress. The experiment of Starzycki *et al*. (2005) pointed to the laser light as a physical factor enhancing rapeseed resistance to blackleg disease.

On the other hand, treatment with laser light has been reported in the literature also in combination with other treatments such as gamma rays or electromagnetic field. Such combinations influence photosynthesis, dry matter and crude protein (Cholakov and Petkova, 2002; Sujak *et al*., 2009). Figure 2 illustrates the potential applications of laser light in the agricultural sector according to the literature review.

Table 1 presents a list of several effects that can be found in the literature, product of various scientific activities in the world.

CONCLUSIONS

1. Although the mechanisms of laser biostimulation have not been understood entirely, the application of this phenomenon in the agricultural sector could have a wide range of practical applications for farmers and seed industry.
2. The type of laser used will depend on the technical characteristics and cost.
3. The effects of laser irradiation for biostimulation can be positive, negative, or none.
4. It is necessary to investigate the parameters of laser light irradiation to produce favourable effects of biostimulation conditions according to the seed itself and environmental conditions.

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