



Microwave Irradiation in Agriculture: Effects on Seed Germination, Growth, Physiological and Biochemical Responses of Horticultural and Agricultural Crops

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ABSTRACT

Microwave irradiation is a novel technique that has gained attention in agricultural and horticultural practices for its potential to enhance seed germination, plant growth, and crop productivity. This review critically evaluates the impact of microwave treatment on various aspects of plant development, including germination rates, vigor, viability, physiological and morphological parameters, biochemical changes, and productivity. Additionally, the review examines the role of microwave irradiation in managing seed-borne and soil-borne diseases. The findings suggest that microwave treatment can lead to improved agricultural outcomes, providing a sustainable approach for enhancing crop performance in diverse fields.

Key words: Microwave irradiation, Gene expression, Seed treatment, Cellular and sub cellular response.

INTRODUCTION

Microwave irradiation has found applications across various fields, including food processing, materials science, and agriculture. In the agricultural sector, the technology is recognized for its ability to improve seed germination, enhance plant growth, and optimize crop yield. Research has demonstrated that microwave treatment can stimulate metabolic processes in seeds, resulting in improved water absorption and quicker germination (Jakubowski, 2015). Furthermore, studies have indicated its effectiveness in enhancing vigor and viability in both vegetable and horticultural crops (Irfan Afzal et al., 2016). The following sections explore the specific impacts of microwave irradiation on seed germination, growth, physiological parameters, morphological

alterations, biochemical parameters, crop productivity, and disease management. The effects of microwave radiation are dependent on the frequency and duration of exposure. Low microwave exposure has been shown to have a good effect on seed germination; However, a protracted exposure reduces plant growth. Several authors recently observed that microwave has a good effect on barley seed germination at short microwave exposure times, but that longer exposure times had a negative effect on seed germination (Abu-Elsaoud & Qari, 2017; Kretova et al., 2018). In addition, studies by Amirnia (2014), Abu-Elsaoud (2015), Jakubowski (2015), and Mohsenkhah et al. (2018) found that MW can be utilized to promote seed germination in pepper, wheat, maize, bean, soybean, and lentil, respectively.

Abu-Elsaoud (2015) found that microwave irradiation has an effect on plant growth, development and seed germination. Low-intensity microwave was shown to have no effect on plant growth and development, whereas higher microwave irradiation doses reduced and retarded seed germination (Oprica, 2008). Ponomarev et al. (1996) investigated the direct effects of microwave on cereal germination, using a wavelength of 1 cm and an irradiation exposure dose of upto 40 minutes on barley, oats, and wheat seeds, with the best results after 20 minutes of microwave exposure (Ponomarev et al., 1996). Crețescu et al. (2013) investigated the effect of microwave radiations of 2.45 GHz on the chlorophyll contents of four barley genotypes after exposure to 0, 10, and 20 seconds. The results revealed a dose-dependent change in chlorophyll contents, ranging from lower chlorophyll in sensitive genotypes to higher chlorophyll in tolerant genotypes (Crețescu et al., 2013).

Radzevicius et al. (2013) found that irradiating vegetable seeds with high-power microwave radiation stimulated many germination and growth rate parameters. Emmanuel et al. (2021) investigated the influence of microwave irradiation in enhancing the productivity of *Abelmoschus esculentus* (L.) Moench (okra). The two okra varieties, viz. Meenaxi-371 and Soniya-1402, were used for the experiment. Their seeds were exposed to 0–14 h (h) of microwave radiation (9.3 GHz). They found that microwave radiation on seeds resulted in an increase in their germination indices and also stimulated the concentration of β -1,3-glucanase enzyme. The results also indicate a remarkable increase in bioactive compounds such as flavonoids, polyphenols, carotenoids, chlorophyll, lutein, protein, and β -carotene in okra seedlings exposed to 8–10 h of radiation. A further dose escalation in the microwave radiation caused a decline in the germination and growth of the okra plant.

Aladjadjiyan, (2002) investigated the influence of microwave irradiation with varying powers on various seed germination consequences of four different ornamental crop species, finding a rise in various germination consequences. Abu-Elsaoud (2015) supported a dose-dependent putative stimulating impact of microwave on growth and germination by comparing the effect of microwave radiations on germination and growth of six distinct Egyptian genotypes of wheat (*Triticum aestivum*) using varied exposure times. Microwave irradiation causes resonance events in biological systems and stimulates living organisms (Aladjadjiyan, 2002).

Olajide et al. (2021) investigated the influence of microwave irradiation to examine the effects of microwave radiation (low and medium) on seed germination of bean and maize. The studies concluded that the length of maize and bean seeds increased during the trials germination days (5,7 and 10) compare to length recorded for control for exposed low and medium microwave radiation at time interval of 1, 2, 3 and 4 minutes respectively.

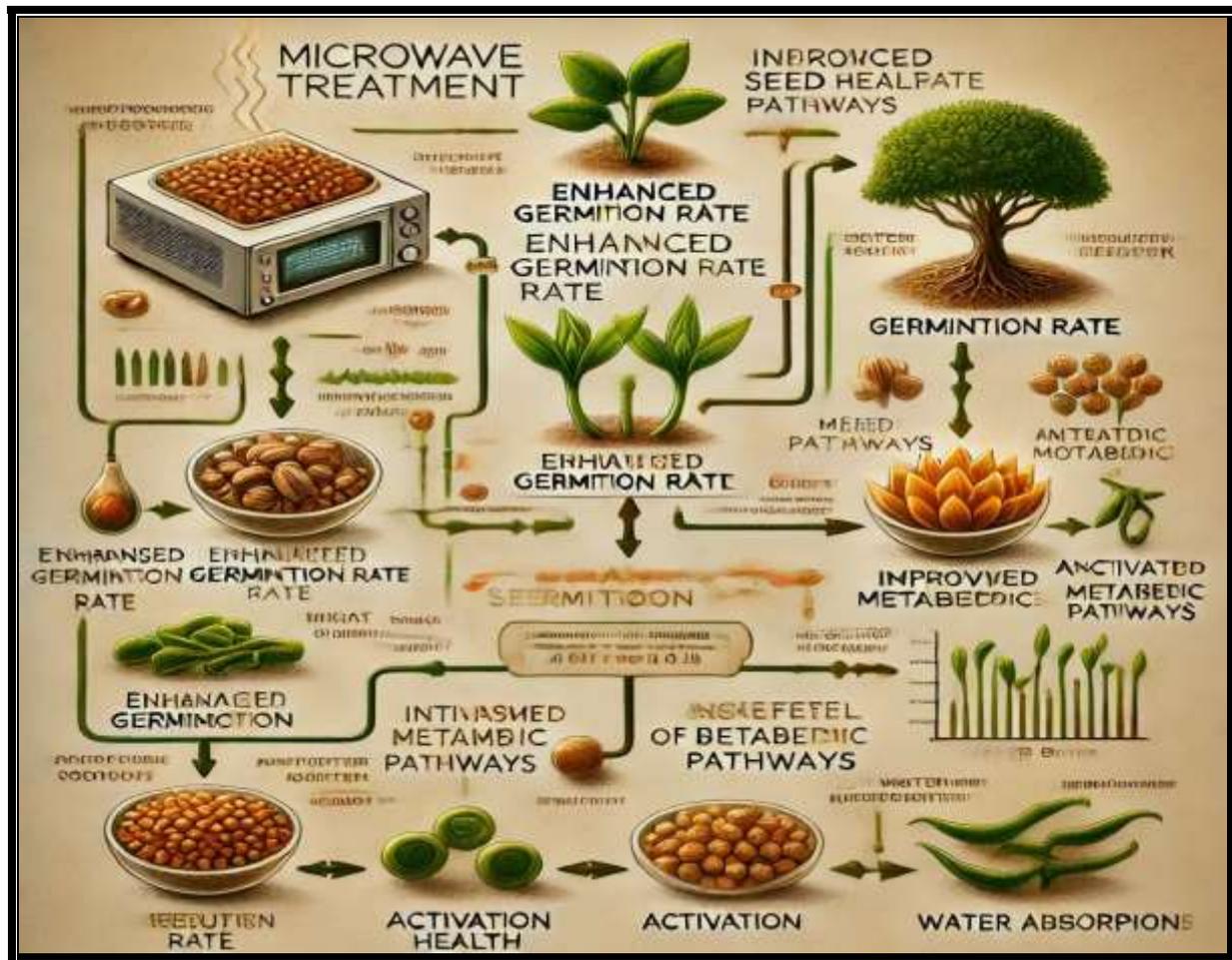


Figure 1. Effects of Microwave Treatment on Seed Germination Indices

The majority of studies on the biological impacts of phone masts (signal towers and radio waves) and microwave radiofrequencies on animal and human health were centered on possible biological effects from phone masts and microwave radio frequencies (Balmori, 2009). The biochemical mechanism by which microwave radiations affect living organisms' biological systems is not entirely understood, and it may vary depending on the amplitude, frequency, and irradiation duty cycle (Aladjadjiyan, 2010; Abu-Elsaoud, 2015; Williams, 2016). Microwaves (300 MHz to 300 GHz) have been shown to cause changes in cell membrane permeability and cell growth rate, as well as interference with ions and organic compounds such as proteins (Eugen Ungureanu et al., 2009). Plants are crucial components of a healthy ecosystem and play an important part in the living world as primary providers of food and oxygen; consequently, it would be helpful to research their interaction with today's enhanced radio and microwave frequency fields. Light, moisture, temperature, and other environmental factors that influence plant growth have been well documented, and research papers based on these investigations are widely available. Plants are acceptable environmental signals, and studies on plants are less emotionally distressing than human or animal studies (Verdus et al., 1997; Vian et al., 1999). Microwave bio-effects research is a new and exciting field of science that involves both biotechnology and microwave engineering.

Microwave bio-effects can be divided into two types: thermal and non-thermal. Microwave fields have been shown to cause harmful biological effects at high power levels. Bio-effects at low power levels, on the other

hand, are yet to be thoroughly understood. Radiation is known to cause physiological and genetic changes, such as the development of numerous epidermal meristems in the hypocotyl, changes in the proteome, and so on (Tafforeau et al., 2004; Tafforeau et al., 2006). Seed germination, shoot development, plant length, fresh weight, fruit yield, and mean fruit weight are all known to be positively influenced by the application of extremely low frequency magnetic fields today (Cakmak et al., 2010). Protein biosynthesis, cell production, photochemical activity, respiration rate, enzyme activity and nucleic acid content have all been demonstrated to benefit from magnetic fields (Stange et al., 2002). Natural aging has been seen in maize and beans, resulting in a reduction in the physiological potential of seeds, which reduces germination capacity, early seedling growth rate, and tolerance to adverse environments (Gutierrez-Hernandez et al., 2007). However, because the action of electromagnetic fields on seeds can affect the course of several physiological processes and drive plant development (Podlenny et al., 2005), it can greatly reverse this phenomenon (Figure 1).

Anna & Carmelo (2002) investigated the impact of microwave on germination and growth of radish (*Raphanus sativus*) seedlings. The studies observed with delayed and reduced growth of radish at low power microwave exposure at 10.5 and 12.5 GHz. To evaluate the effect of microwave treatment on seed germination and health of carrot seeds using two seed lots naturally infected with the pathogens *Alternaria dauci* and *A. radicina*, was carried by Dorota and Hanna (2021). The studies revealed that wet treatment controlled seed-borne fungi more efficiently than dry treatment. However, the exposure duration longer than 60 seconds frequently resulted in deterioration of seed germination. The highest seed germination in cv. Amsterdam was observed after microwave wet treatment at power output levels of 500 W for 75 seconds (81%), 650 W for 45 seconds (85%), and 750 W for 60 seconds (77%), whereas in the case of cv. Berlikumer this occurred when wet seeds were treated at 500 and 650 W for 60 seconds (46% and 43% respectively). Treating seeds soaked in water with microwaves for a period longer than 30 seconds, regardless of the power output, significantly decreased seed infestation with *Alternaria* spp. in both samples.

Few, if any, empirical investigations have been conducted in Nigeria to indicate that microwave radiation has a good influence on seed germination (Hu et al., 1996 and Chen et al. 2005). Regardless of the data on the effect of microwaves on plants that has been gathered, little is known about whether microwave pretreatment of seeds causes a change in the inner energy of seeds, stimulating enzyme activities, improving metabolism, and increasing the intensity of bio-photon emission, which is used as a measure of cell metabolism

Impact of Microwave Irradiation on Germination

Numerous studies have demonstrated the positive effects of microwave treatment on seed germination. Friesen et al. (2014) found that microwave radiation significantly enhanced the germination rates of dry bean seeds infected with *Xanthomonas axonopodis*, suggesting that microwave treatment can improve both germination and seed health. Gaurilcikiene et al. (2013) reported improved germination rates in wheat seeds subjected to microwave irradiation, indicating the method's effectiveness across different crop types. Jakubowski (2015) noted that microwave treatment accelerated germination in bean seeds by enhancing water uptake and activating metabolic pathways (Figure 2). Similarly, Keneni et al. (2011) observed that microwave treatment improved the germination of lentil seeds, demonstrating its broad applicability in agricultural practices. Microwave radiation can significantly enhance seed germination by breaking seed dormancy and improving water absorption. For

instance, microwave exposure at 2450 MHz for varying durations has been shown to increase germination percentages in crops such as pepper and barley (Iuliana et al., 2013; Jakubowski, 2010; Zhao et al., 2012).

In experiments with bean and maize seeds, low-power microwave exposure improved germination percentages and promoted uniform seedling development (Demidchik et al., 2014). However, prolonged exposure can reduce germination, as observed in carrot seeds, where durations exceeding 60 seconds led to decreased germination rates (Fuangfoong et al., 2013; Talei et al. 2011). The underlying mechanisms may involve alterations in seed coat permeability and enzymatic activation (Ellis & Roberts, 1981; Aladjadjian, 2010). Recent advancements also highlight the influence of microwave treatments on the nutritional quality of seeds. For instance, Hernández-Infante et al. (1998) studied the impact of microwave heating on legume seeds, reporting changes in hemagglutinins and protein quality that could affect seed viability. Additionally, Irfan Afzal et al. (2016) discussed recent advances in seed enhancements, including the potential of microwave technology to address challenges in seed biology. Furthermore, studies have explored the specific effects of microwave irradiation on different seed types. For example, Wang et al. (2018) found that microwave irradiation not only enhanced the germination rate of tartary buckwheat but also increased the content of beneficial compounds in its sprouts. These findings underscore the importance of optimizing microwave treatments for various crops to achieve the best outcomes in seed germination and health.

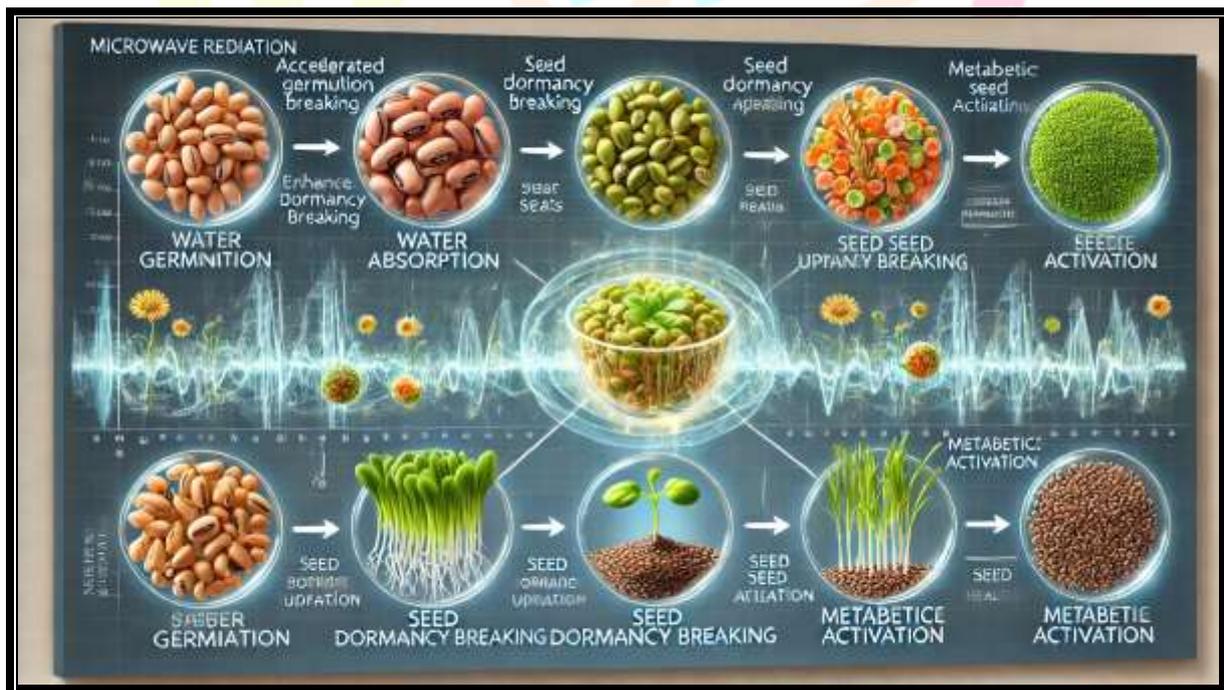


Figure 2. Effects of Microwave Treatment on Enhanced Germination Parameters and Dormancy Breaking in Seeds.

Impact of Microwave Irradiation on Plant Growth and Development

Microwave irradiation has demonstrated a positive impact on plant growth and development, particularly in enhancing seed vigor and viability. Jakubowski (2010) reported significant increases in potato crop yields following microwave treatment of seed potatoes, indicating the potential for this technique to enhance overall plant performance. Similarly, Pande et al. (2012) found that microwave drying could preserve the quality of green gram seeds (*Vigna radiata*) while promoting better growth, further supporting the benefits of microwave treatment. These findings are consistent with research by Irfan Afzal et al. (2016), who observed enhanced seed

vigor and viability due to microwave treatments, suggesting a mechanism that may improve seed germination and subsequent plant development. The influence of microwave radiation on seed quality has been explored in various studies, such as that by Hernandez-Infante et al. (1998), which examined the impact of microwave heating on protein quality in selected legume seeds, demonstrating improvements in seed nutritional profiles. Gupta et al. (2015) discussed the biofortification of maize, highlighting the role of advanced technologies, including microwave treatment, in improving nutritional content and agronomic performance.

Moreover, the effects of microwave treatment extend to insect control and pest management, as demonstrated by studies like that of Silva Fontes et al. (2016), which focused on the control of *Callosobruchus maculatus* larvae in cowpea cultivars through microwave irradiation. This dual benefit of enhancing seed quality while managing pests underscores the versatility of microwave technology in agricultural applications. Additional research supports these findings, with studies like those by Wang et al. (2018), which reported improved germination rates in tartary buckwheat following microwave treatment, and Aladjadjiyan (2002), who noted enhancements in vitality indices of ornamental crops. Furthermore, the use of microwave energy for seed treatment has been shown to reduce the prevalence of fungal contamination in crops (Kretova et al., 2018), further emphasizing its multifaceted advantages in agriculture.

Impact of Microwave Irradiation on Physiological Parameters

Microwave treatment significantly influences various physiological parameters in crops, leading to enhanced seed performance during germination and early growth stages. For instance, González and Pérez (2002) demonstrated that microwave-modified lentil starches exhibited improved physiological responses, which translated to better seed performance. This enhancement can be attributed to the more uniform heating provided by microwaves, allowing for better moisture retention and nutrient absorption (Jethon & Gryzybowski, 2000; Belyaev, 2005). In addition to improving germination rates, Grondeau and Samson (1994) highlighted the thermal effects of microwave radiation in eliminating pathogens. This pathogen reduction contributes to improved physiological health and resilience in treated seeds, enabling them to better withstand environmental stressors (Khalafallah & Sallam, 2009; Fang et al., 2011). The implication of these findings is significant, as healthier seeds can lead to a more robust crop yield (Figure 3).

Microwave irradiation has emerged as a potential technology for agricultural applications, including crop production and preservation. The ability of microwaves to generate heat rapidly and uniformly within the plant tissue has gained attention in recent years. This review focuses on the impact of microwave irradiation on semi-arid crops, which are often exposed to challenging environmental conditions, including limited water availability and high temperatures.

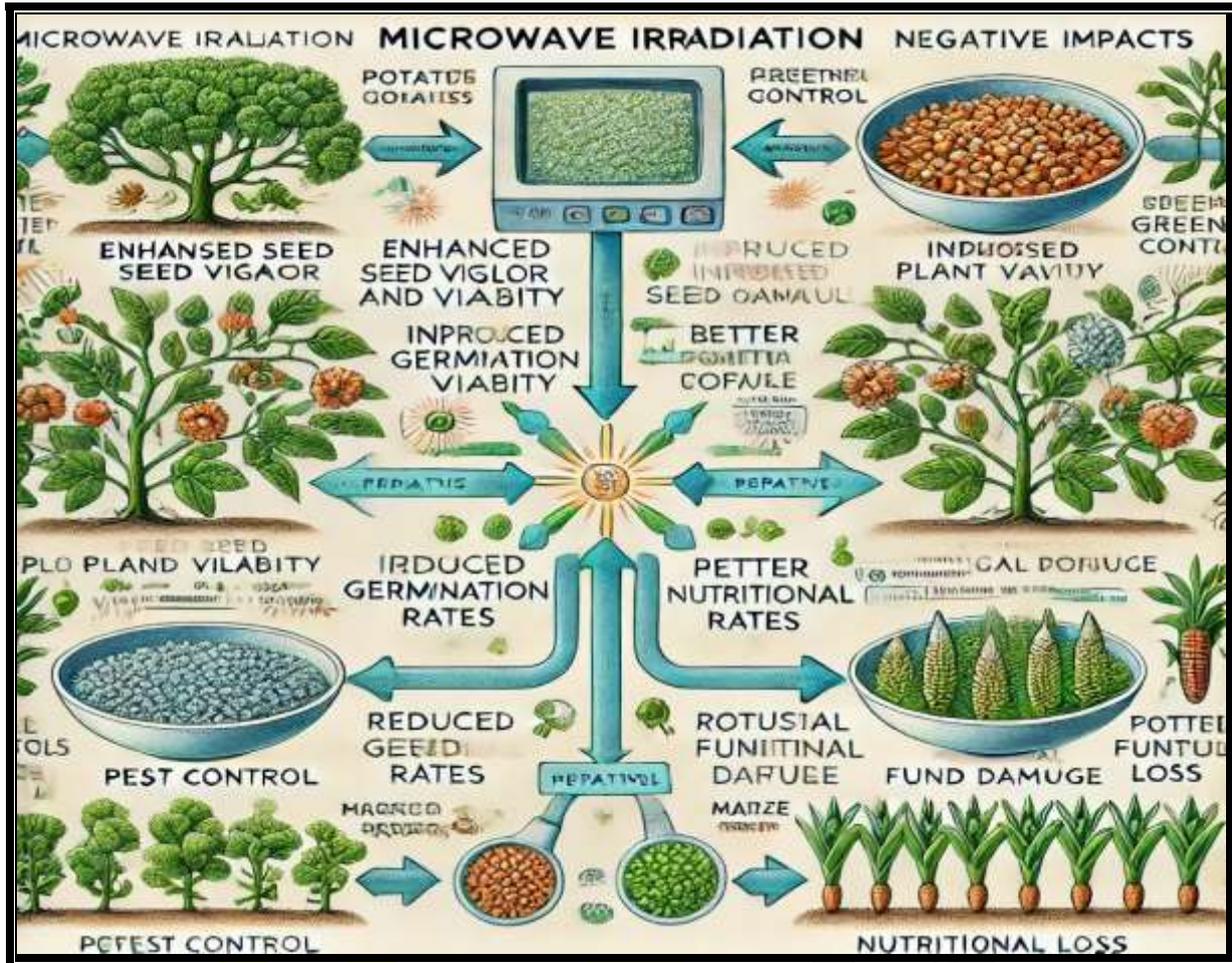


Figure 3. Effects of Microwave Treatment on seed viability, vigor, nutritional loss and pest control.

In order to maintain the food and nutritional security of the expanding population in the face of climate change, the plateau trend in global food production needs to gain velocity, which makes the importance of pulse crops clear. Rajma, a type of pulse crop, plays a significant role in completing the diet of affordable plant protein. In India, 9,466 million hectares are used for common bean agriculture, compared to 29,393 million hectares worldwide. While the world's production is 9,129 million tonnes, it produces 4,117 million tonnes (FAOSTAT, 2016). Sunflower and and Sesame are major semi-arid crops farmed throughout Asia and is a key oil seeds in Asian countries like India, Pakistan, Nepal, China and etc , along with beans. The FAO has identified a gap in production areas in this region, as well as a need that must be addressed: increasing rajma, sunflower and sesame production, which requires significant effort but is one of the few crops with commercial seed production. The growing demand for organic products, combined with an increase in plant materials for food production, has prompted scientists to look for systemic factors to boost output, taking into account not only traditional methods of crop development, such as the use of fertilizers and agrochemicals, which can cause environmental damage to some extent, but also physical methods, such as the use of lasers (Hernandez et al., 1998; Dominguez et al., 2015).

Physical treatment techniques are one of the safest popular methods for improving seed germination and plant growth, thanks to their low environmental impact. Physical elements have also been used to achieve a good biological change in plants without having an impact on the ecosystem (Govindaraj et al., 2017). Electromagnetic waves, including as ultraviolet and microwave radiation, ultrasound, laser and ionizing radiation, are among the physical elements now used for seed treatments. Microwave and UV-radiation, in particular, are thought to be the most essential physical therapies for pre-sowing seed treatments (Araujo et al., 2016).

Microwaves (MWs) are a non-ionizing electromagnetic with a high-frequency range of 300 MHz to GHz and a wavelength range of 1m to 1mm (Wang et al., 2018). Microwaves are a type of electromagnetic radiation with frequencies ranging from 300 MHz to 300 GHz. They work through absorption on a molecular level, resulting in vibration energy or heat, as well as biological impacts (Pakhomov et al., 1998). Microwaves may have long-term health impacts, according to relevant study (Lin, 2004). Because there is no clear mechanism for the impact of microwave radio-frequencies on biological systems, the identification, evaluation and assessment of microwave bio-effects has been difficult and contentious. In biophysical and engineering sciences, there has been a persistent belief that microwave fields are incapable of inducing bio-effects other than through heating (Banik et al., 2003). Microwave radiation effects depend on radiation frequency and exposure period. Generally, low microwave exposure has been successfully used as a positive effect on the accelerating seed germination, while a long exposure usually tends to reduce plant growth. Microwave irradiation could affect plant growth, development and seed germination. Taking this factor into consideration the present proposed study will be carried with various frequencies of microwave irradiation impact on semi-arid crops to find out whether microwave enhances the crop growth or decreases the crop growth upon exposure.

The impact of microwave radiation on germination rates and seedling vigor has been extensively documented, with mixed results. Alexander and Doijode (1995) reported that electromagnetic fields, including microwave exposure, could enhance germination and seedling vigor in onion (*Allium cepa L.*) and rice (*Oryza sativa L.*) seeds with low viability. This enhancement can be attributed to the activation of physiological processes that promote growth and development. Conversely, the study by Hamada (2007) indicated that microwave treatment could adversely affect growth and photosynthetic pigments in wheat. Such findings suggest that the effects of microwave radiation may vary depending on the plant species, treatment duration, and specific exposure conditions. It is essential to optimize these parameters to maximize the benefits of microwave exposure while minimizing potential negative impacts.

Impact of Microwave Irradiation on Morphological Alterations

Research has documented various morphological changes induced by microwave treatment. For example, Gaurilcikiene et al. (2013) observed significant increases in root and shoot length in wheat seeds exposed to microwave radiation. This is crucial for plant establishment, as deeper root systems enhance water and nutrient

uptake (Lee & Zhu, 2010; Ciupak et al., 2007). Furthermore, Friesen et al. (2014) reported alterations in the fresh and dry weight of bean seedlings post-treatment, suggesting that microwave exposure can lead to more robust plant structures. The changes in biomass indicate an overall improvement in plant vigor, which is essential for successful crop production (Reddy et al., 2000; Jakubowski, 2008). Moreover, Kretova et al. (2018) noted alterations in flowering time and leaf morphology in barley treated with microwaves, underscoring the potential for microwave irradiation to influence key developmental stages. These morphological adaptations can result in improved reproductive success, ultimately contributing to higher yields (Kemerov et al., 1999; Iuliana et al., 2013).

Impact of Microwave Irradiation on Biochemical Parameters

Microwave irradiation has also been linked to significant changes in various biochemical parameters, crucial for plant health and productivity. Pande et al. (2012) found that microwave treatment of green gram seeds enhanced chlorophyll pigment content, vital for photosynthesis and overall plant vitality. Increased chlorophyll levels allow for more efficient energy capture during photosynthesis, promoting growth (Tkalec et al., 2007; Chen et al., 2005). Moreover, research indicates that microwave exposure can increase the activity of stress enzymes, such as superoxide dismutase, which play a critical role in mitigating oxidative stress during plant development (Kretova et al., 2018; Demidchik et al., 2014). These enzymes help protect plants from damage caused by reactive oxygen species, enhancing their resilience against environmental stressors (Manickavasagan et al., 2007). Changes in nutrient composition, including carbohydrates, proteins, and lipids, have also been documented. Feng et al. (2012) noted that microwave treatment could enhance nutrient availability, thus supporting better growth and development in treated seeds. Such biochemical enhancements contribute significantly to improved crop performance and overall yield (Radzevičius et al., 2013; Campana et al., 1993).

Impact of Microwave Irradiation on Seed-borne and Soil-borne Diseases

Microwave irradiation has shown promise in managing both seed-borne and soil-borne diseases, which are significant challenges in agriculture. Friesen et al. (2014) highlighted the dual benefits of microwave treatment in enhancing germination while reducing pathogen load in bean seeds. This aspect is crucial for integrated pest management strategies, as healthier seeds result in stronger plants less susceptible to disease (Reddy et al., 2000; Cojocararu et al., 2005). Kretova et al. (2018) also found that microwave treatment effectively reduced fungal contamination in barley, suggesting its utility in promoting crop health. This reduction in pathogen presence can lead to fewer chemical interventions, promoting sustainable farming practices (Mazen et al., 2015; Grundler et al., 1982). Furthermore, Irfan Afzal et al. (2016) noted that the sanitation effects of microwave treatment could play a crucial role in disease management, leading to healthier plants and better crop yields. The potential for microwave irradiation to reduce disease incidence while enhancing plant vigor positions it as a valuable technique in modern agriculture (Bhamra et al., 2020; Boczoń et al., 2009).

The ability of microwave radiation to induce mutations and alter gene expression presents significant opportunities for crop improvement and agricultural biotechnology. By harnessing these effects, researchers can develop crop varieties with enhanced resistance to pests, diseases, and environmental stresses. For instance, microwave-induced mutations may result in the selection of traits that improve yield or nutritional quality. However, the unpredictable nature of induced mutations poses challenges. As indicated by Sparrow (1962, 1965), the relationship between radiation exposure and genetic sensitivity in plants necessitates careful investigation to ensure that desirable traits are promoted without incurring detrimental effects on plant health.

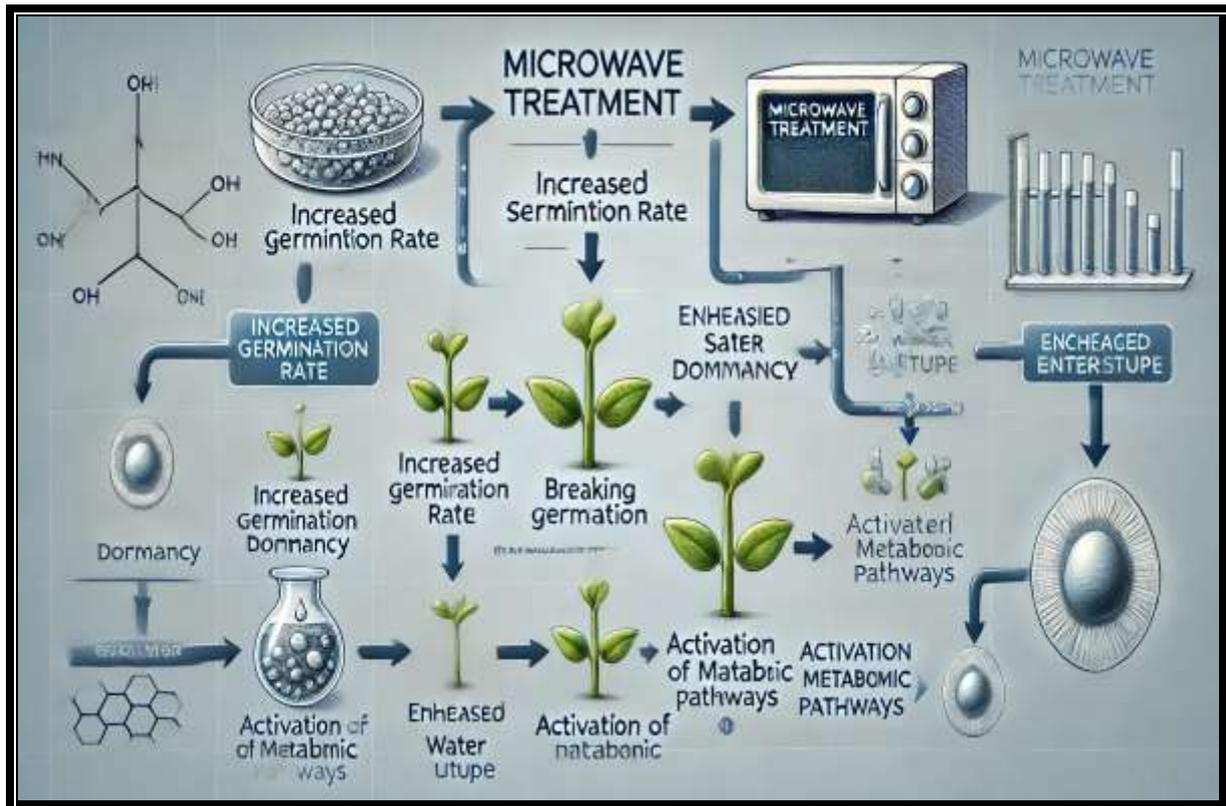


Figure 4. Impact of microwave treatment on physiological and biochemical functions

Impact of microwave on gene expression

Microwave radiation, characterized by its frequency range from 300 MHz to 300 GHz, has emerged as a tool for various agricultural applications, including seed treatment, plant growth enhancement, and crop improvement. The impact of microwaves on gene expression and mutation rates in plants is particularly significant, as these alterations can influence growth, development, and resistance to environmental stresses. This review discusses the detailed effects of microwave radiation on gene expression and mutations across various crops and plants, supported by findings from several key studies. Microwave radiation has been shown to induce changes in gene expression profiles, influencing metabolic pathways and stress responses in plants. For instance, Roux et al. (2006) observed that exposure to 900 MHz electromagnetic fields evoked consistent molecular responses in tomato plants, suggesting that microwave treatment can activate specific genes associated with growth and stress tolerance. Similarly, the research by Jangid et al. (2010) demonstrated that microwave

treatment led to alterations in gene expression in *Vigna aconitifolia*, highlighting the potential for microwave radiation to induce beneficial genetic changes.

Moreover, the induction of heat shock proteins (HSPs) is a well-documented response to microwave exposure. According to Viswanathan and Chopra (1996), HSPs play a critical role in protecting plants from thermal and oxidative stress. The upregulation of HSPs in response to microwave treatment suggests that this form of radiation can enhance a plant's ability to cope with environmental challenges, thereby improving overall resilience. In the context of aromatic plants, Soran et al. (2014) reported that microwave frequency electromagnetic radiation influenced terpene emission and content. Terpenes are crucial secondary metabolites that play roles in plant defense and attraction of pollinators, indicating that microwaves can modify both gene expression and metabolic outputs in these species. Microwave radiation can also induce mutations within plant genomes, which can lead to phenotypic variations that may be advantageous for survival and adaptation. For example, in a study conducted by Pavel et al. (1998), cytogenetic changes were observed in *Triticum aestivum* when exposed to low-intensity microwaves. This research highlights the potential for microwave exposure to cause chromosomal abnormalities that may alter plant characteristics (Figure 4).

Similarly, Aladjadjiyan (2002) investigated the effects of microwave irradiation on the vitality indices of ornamental perennial crops. The findings suggested that while microwave treatment could enhance some growth parameters, it might also induce mutations that affect overall plant vigor. This dual effect underscores the need for careful consideration of microwave exposure conditions in agricultural practices. In another significant study, Yoshida and Kajimoto (1988) examined the effects of microwave treatment on soybeans, noting changes in the molecular species of triglycerides and trypsin inhibitors. Such changes can have profound implications for the nutritional quality of crops, suggesting that microwaves not only induce mutations but also alter metabolic pathways related to food composition. Recent studies have highlighted the mutagenic effects of various forms of radiation, including ion beams and gamma rays, on plant genomes, further enriching our understanding of the impact of electromagnetic radiation on plant gene expression and mutations. Zheng et al. (2020) investigated the mutagenic effects of three ion beams on rice, employing whole-genome sequencing to identify heritable mutations. This approach underscores the power of advanced genomic techniques in characterizing radiation-induced changes, which can complement traditional methods like microwave treatments.

In a related study, Yang et al. (2019) performed a genome-wide comparison of mutations induced by carbon-ion beams and gamma-ray irradiation in rice. Their findings revealed distinct mutation profiles between the two radiation types, suggesting that the mechanisms by which microwaves and other radiation types induce mutations may differ. Understanding these differences is crucial for optimizing radiation treatments in crop improvement. Zhao et al. (2018) focused on the effects of carbon-ion radiation on DNA methylation in rice seeds, demonstrating that different doses of radiation can lead to significant alterations in methylation patterns. DNA methylation is a vital epigenetic modification influencing gene expression, and changes in methylation can

result in heritable phenotypic variations. This research emphasizes the potential of radiation treatments, including microwaves, to induce epigenetic changes that affect crop traits. Volkova et al. (2018) examined the long-term ecological effects of chronic radiation exposure on Scots pine populations, reporting hypermethylation and genetic differentiation. Such findings provide insights into how sustained exposure to radiation, including microwaves, could lead to cumulative genetic and epigenetic effects in plants over time. This is particularly relevant for understanding the impact of environmental stressors on crop resilience (Figure 5).

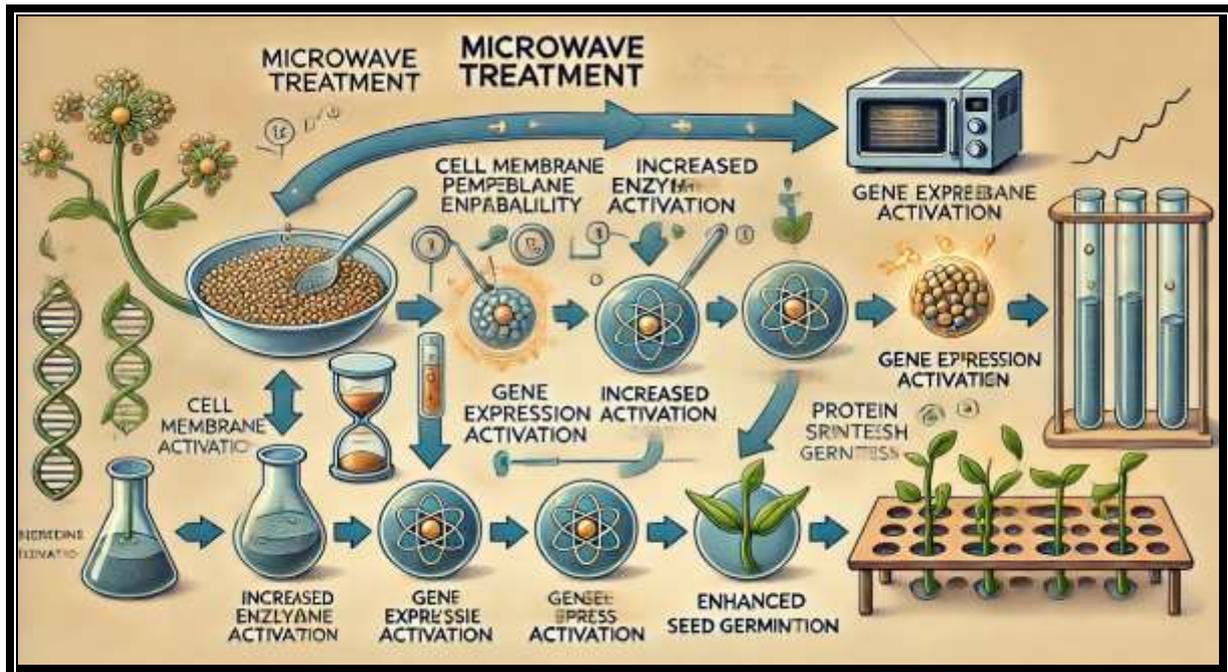


Figure 5. Impact of microwave treatment on plant/seed DNA integrity

The study by Volkova et al. (2019) on barley embryos exposed to gamma irradiation highlighted that both low- and high-dose radiation triggers changes in the transcriptional profile and an increase in hydrogen peroxide content in seedlings. This increase in oxidative stress can lead to further mutations and altered gene expression, compounding the effects of initial radiation exposure. The relationship between oxidative stress and gene expression modifications suggests that microwave treatments may similarly induce stress responses that can enhance or impair plant growth. In a study by van de Walle et al. (2016), *Arabidopsis* plants exposed to gamma radiation exhibited varied oxidative stress responses across successive generations. These findings imply that the effects of radiation, including microwaves, can have long-term repercussions on plant health and resilience, affecting not just immediate offspring but also subsequent generations. Tan et al. (2019) utilized RNA-Seq to characterize genome-wide variations induced by gamma-ray radiation in barley. This modern approach allows for a comprehensive understanding of the genetic alterations resulting from radiation exposure. Such techniques could also be applied to study the effects of microwave radiation, offering insights into how electromagnetic

treatments influence gene expression and contribute to phenotypic variation. Additionally, Shi et al. (2014) compared the genomic and epigenomic mutations induced by space flight and heavy ion radiation in rice, revealing a complex interplay between environmental factors and genetic changes. While this study focused on different radiation sources, it reinforces the importance of exploring how various forms of radiation, including microwaves, can interact with genetic material in plants.

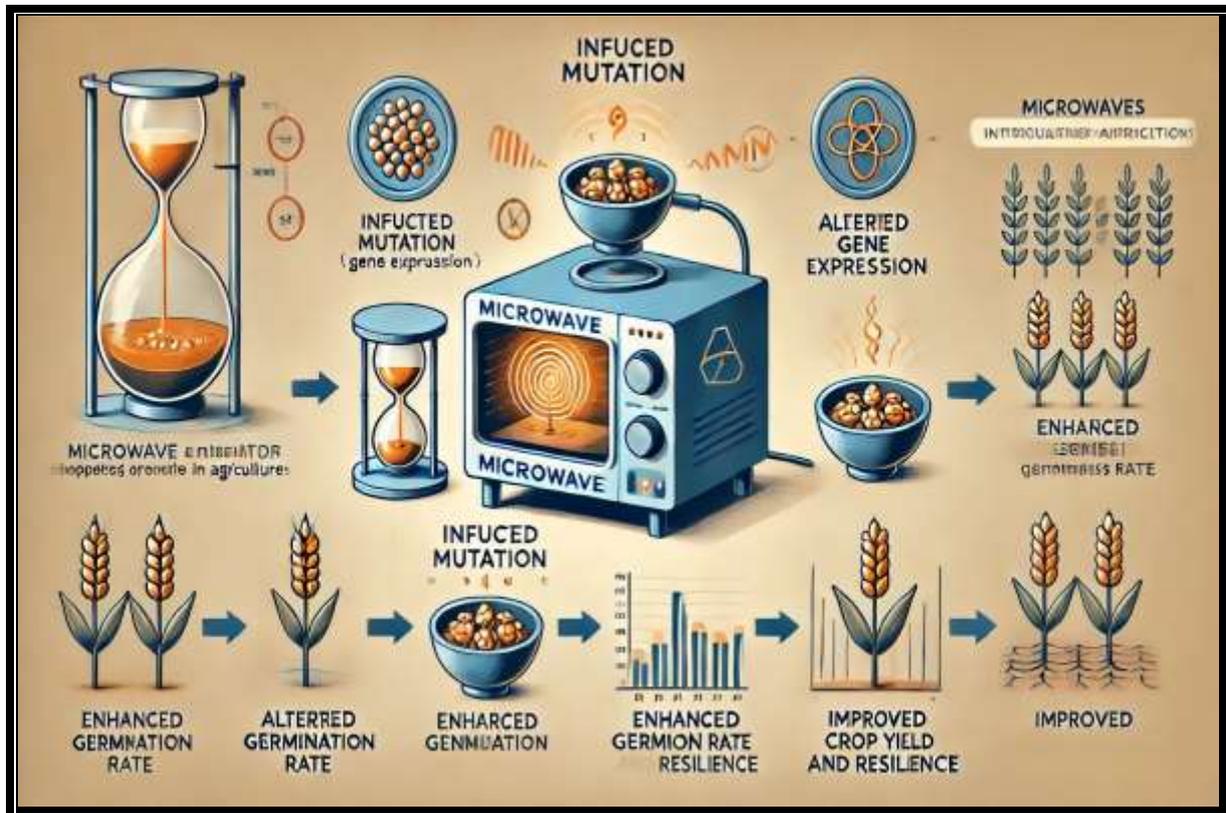


Figure 6. Impact of microwave treatment on cellular and sub cellular mechanisms

Conclusion

Microwave irradiation is emerging as a versatile tool in agriculture and horticulture, with multiple applications that can benefit crop development and productivity. This review underscores its efficacy in enhancing seed germination by promoting water absorption, breaking dormancy, and stimulating metabolic activities, which are crucial for faster and more uniform sprouting. The treatment has also shown potential in improving plant growth parameters by accelerating cellular processes that contribute to increased plant vigor and resistance under diverse environmental conditions. Furthermore, microwave irradiation induces notable biochemical responses, including enhanced enzyme activity and antioxidant levels, which contribute to plant resilience against abiotic stresses.

Beyond growth benefits, microwave treatment offers a novel approach to managing seed-borne and soil-borne pathogens, reducing reliance on chemical treatments and supporting sustainable agricultural practices. Studies indicate that tailored microwave exposure can mitigate diseases, thus improving seed and soil health, which is fundamental for sustainable crop productivity. The combined effects on germination, growth, biochemical

response, and disease management position microwave irradiation as a promising tool for a wide array of agricultural and horticultural applications. However, while the findings suggest numerous advantages, the impact of exposure duration, power settings, and crop type must be optimized to maximize benefits and mitigate any potential adverse effects. Future research should continue exploring the molecular and genetic mechanisms underlying these responses to establish comprehensive guidelines for safe, effective, and scalable applications of microwave irradiation across different crops and agricultural systems.

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