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An Overview of the Impact of Seed Priming on Tomato (*Solanum lycopersicum*) L.) Under Normal and Salt Conditions: From Seed Germination to Harvest

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Abstract: Tomato (*Solanum lycopersicum* L.) is one of the most important vegetable crops worldwide and in Saudi Arabia, due to its high nutritional value and suitability for cultivation under a wide range of environmental conditions. Tomato is one of the cash vegetable crops that generate good and continuous income for farmers for two to three months. Globally, tomato is considered a major source of income and a major contributor to food security. Due to the small genome of the tomato, it is considered as a model for physiological, genetic, molecular and breeding studies to improve the morphological, yield and yield attributes and its tolerance to biotic and abiotic stresses. However, tomato production and expanding cultivation face many challenges, especially with the global environmental changes regarding climate changes, freshwater availability and quality, pests and diseases and soil quality. There were many studies conducted to find effective and applicable solutions to overcome the environmental problems facing the expansion of tomato cultivation and increase productivity, including following good agricultural practices (GAP), improving and breeding new varieties of high yield and quality under harsh environmental conditions and the use of growth biostimulants that help plants grow and produce under difficult conditions. Seed priming is one of the recommended solutions to help tomatoes germination, growth and productivity under biotic and abiotic stresses. The presented review study aims to present the recent studies that have been carried out on the use of seed priming to improve tomatoes germination, growth and productivity under environmental stress conditions. The review is divided into three sections focusing on: (1) seed priming to improve tomato seeds germination; (2) seed priming to improve the growth and yield of tomatoes; and 3) seed priming to improve tomato tolerance salt stress.
Keywords: *Solanum lycopersicum*, salt stress, seed Priming, halo Priming, Salinity, Induced resistance

INTRODUCTION:

Globally, the total area cultivated with tomatoes is 5167388 hectares, while the total production of fresh and processed tomatoes is 189133955.04 tons (FAO, 2021). Tomato is the second crop after potato and the fourth after rice regarding the cultivated area, total production and consumption worldwide (Hamoh et al., 2020; Sattar et. al., 2021). It was reported that the tomato market represents 0.059% of total world trade. The top tomato exporter countries in the world were Mexico ($2.62B), Netherlands ($1.82B), Spain ($1.11B), Morocco ($852M), and Canada ($448M) (FAO, 2020). China is the leading country in production with 61,631,581 tones followed by India with 19,377,000 tones, the USA (12,612,139 tones), Turki (12,150,000 tones), and Egypt with 6,624,733 tones (FAO, 2021). Regarding the nutritional values of tomatoes, it was reported that tomato fruits contain 95% water, 4% carbohydrates, and contains less than 1% of proteins and fats. Tomato is rich in many nutrients, a major dietary source of the antioxidant lycopene, which has been linked to many health benefits, including reduced risk of heart disease and cancer. In Saudi Arabia, the total cultivated area with tomatoes was 15030 hectares and the total production quantity was 620866 tones (FAO, 2021). The soil quality, freshwater limitation, and arid climates were the most important challenges to expanding tomato production in Saudi Arabia. There were reported that tomato cultivation challenges many problems worldwide and in Saud Arabia. These problems include climate change, abiotic stresses (salinity, drought and heat stresses), biotic stresses (pests and diseases problems) and soil quality (soil nutrition, saline-affected soils, and desertification (Alam et al., 2021; Yutecia González-Grande, et al., 2020). Abiotic stresses including salinity and drought are regarded as of the most deadly external constraints for successful and sustainable agricultural production in arid or semi-arid regions of the world (Khan et al., 2016; Rengasamy, 2010). Salt stress enhances the deposition of harmful salt ions in the soil surface as well as at the crop root zone, which gradually converts arable regions to fallow or barren (Fig 1). Globally, at this moment,

Fig 1. Effects of salt stress on plant growth, yield and quality.

more than considerable areas of arable lands (>6.0 %) and zones under irrigation (20 %) are severely suffering from salinization (Alam et al., 2021; Ashraf and Harris, 2013; Bacha et al., 2017). Soils become saline when electrical conductivity (EC) of more than 4 dS/m with NaCl (approximately 40 mM) and osmotic pressure (0.2 MPa). Salt stress decreases the water potential resulting in osmotic stress, ionic disparity, and disturbance of essential plant nutrient dynamics. Moreover, Salt stress negatively affects the chloroplast functions and renders a deleterious impact on the photosynthetic performance in crops (Munns, 2002; Munns & Tester, 2008). Seed priming (Fig 2) is considered one of the most promising methods for alleviating salt stress's negative effects on plant crops. Seeds priming is the treatment of seeds with different methods include hydropriming, osmopriming, Chemopriming, and hormonal priming (Jisha et al. 2013; Paparella et al. 2015). Priming of seeds helps the plants by stimulating the pregerminated metabolic process and activating of many enzymes that confer the metabolism of proteins, carbohydrates and lipids involved in the mobilization of stored reserves in seed and play role in the breakdown of the macromolecules for embryo growth and development that exerts a positive influence on early and better seedling emergence (Jisha et al. 2013; Paparella et al. 2015). The present review aims to summarize the recently published studies that focused on the use of seed priming to improve tomatoes germination, growth and productivity under environmental stress conditions.

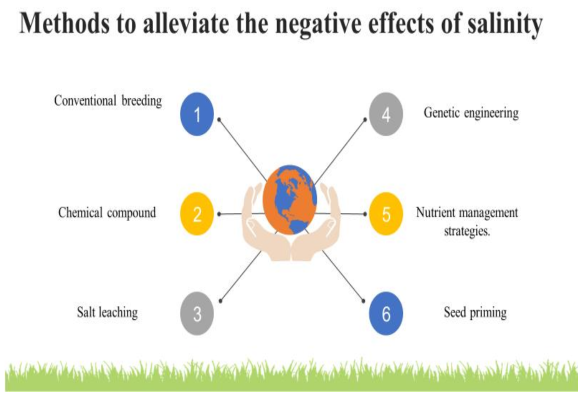

Figure 2. Alleviating negative effects of salt stress on plant growth and productivity

1. Seed priming for the improved seeds germination and seedlings vigor of tomato

1.1. Seeds Germination

The successful life cycle of any plant starts with seed germination and establishment/development vigor seedlings which require several physiological changes in the metabolites and secondary metabolites levels leading to healthy reproductive plants (Bewley et al., 2015; Weitbrecht et al., 2011; Ogbaji et al. 2013). The rapid and uniform germination of plant seeds is one of the most important factors that affect plant performance in the vegetative, flowering and reproductive stages of the life cycle. Rapid and uniform germination can help the plant to alleviate environmental constraints and enhance growth and yield and overcome abiotic and biotic stresses (Zhang et al. 2012, Mousa et al., 2013; Alam et al., 2021). Treating the seeds with some substances improves seeds germination (germination speed and uniformity), seedling growth and development (fasten radical and shoot emergency and development) and plant performance during vegetative, flowering, and productive stages. Seed germination comprises all morphological, physiological and biochemical changes inside the seeds at the imbibition phase (soaking the seeds with enough water) that result in the radicle emergence from the seed coat and then shoot sprouting (López-Vargas, et al.2020). During the past 20 years, researchers have directed their attention to studying the effect of different seed priming substances (Hydropriming, chemo-priming, biopriming, natural substances, …etc) on the speed and uniformity of germination, seedlings' vigor and development for a large number of crops, including tomatoes (Biswas, et al. 2019; Galviz-Fajardo, et al., 2020; López-Vargas, et al.2020). It is agreed that having fast and uniform germination and strong seedlings are the major premise of plant growth, yield and quality. The seeds germination processes is evaluated by measuring physiological (antioxidant activity, chemical and biochemical indicators …etc) and morphological (seeds imbibition, radical emergency, shoot sprouting …etc) indicators that can be used to explain the obtained results. Seed germination requires the critical germination factor of water of good quality and in limited cases light and temperatures and specific pretreatments for hard/dormant seeds. In hydropriming, the seeds will be germinated at imbibition range from 35%-100%, however, the seed will be faster germinated at imbibition for a range of 35% followed by incubation for 1 hour (Badek et al. 2006). Seeds of cherry tomato were treated using static magnetic (magneto-priming method) at a dosage of 50–150 milli Tesla (mT) for 30 min and 1 hour, the results showed that maximum germination is ensured by using 100 mT for 30 min (Gupta et al., 2015). Treating the seeds of tomato with potassium nitrate (KNO3) (50 mM), as a chemo-priming method, lead to a significant increase in germination speed % and germination rate compared to other chemo-priming treatments (i.e. polyethylene glycol (PEG 6000) -1.1MPa and PEG+KNO3) (Lara et al., 2014). The authors explained the increased germination time and rate to activation of the nitrate reductase enzyme pathway, because of the absorbance of nitrate, which enhance seed embryo metabolism and promoted seed germination without any negative effects on germination percentages and seedlings uniformity. Seed priming with KNO3 at 0.75 mM led to significantly improved seeds viability of tomatoes which was reflected in the increase of final emergence (%), mean emergence time, and physiological attributes (Ali et al., 2020). The tomato germination rates and time were also promoted by treating the seeds with natrium chloride (NaCl) and gibberellic acid (GA) (Nakaune et al., 2012). According to the Authors, the rate of germination was higher by 4.9 and 4.6 times at 36 hours after sowing for treated seeds as compared to hydro-primed seeds (treated with water), while the levels of endogenous abscisic acid was similar for both chemo-primed (seeds treated with NaCl and GA4) and hydro-primed (seeds treated with only water) seeds. Osmopriming is the treatment of seeds in aerated osmotic solutions containing KNO_3, K_3PO_4 or KCl salts or polyethylene glycol (PEG), which help to enhance seed germination through the activation of many pre-germination metabolites processes and enhance the antioxidant enzymes system. Osmopriming of tomato seeds with PEG at 10% (w/v) (PEG) solution for 48 hours in the dark at 20±1°C in the dark improved germination percentages under normal and saline water (100 mM NaCl) treatments (Zhang et al., 2012).

1.2. Seedlings vigor of tomato

Recent work focused on seed priming using melatonin, which is known as a molecule with many benefits for human health. Also, melatonin in plants works as one of the important components for defense systems in plant, and melatonin works as an internal sensor for oxidative stress in the plant (Tan et al., 2012). It was reported that treating the tom,ato seeds with melatonin at 0.1 mM improved the seedling health index of tomatoes by 44.11% and root dry weight by 24.6% as compared to the control (Liu et al., 2015). Soaking the tomato seeds in salicylic acid (SA) at 250, 500 and 1000 µM enhanced germination rate, germination time and seedlings' growth and development as compared to control (seeds soaked in water) and lower concentrations of SA (5, 50 and 100 µM) (Galviz-Fajardo, et al., 2020). The effects of chemo-priming using $Mg(NO_3)_2$ at 5, 7.5 and 10 mM on tomato seeds germination and seedlings' vigor under different temperatures (10, 25 and 40°C) was investigated (Nafees et al., 2019). The authors found that soaking the tomato seed in 7.5 mM of $Mg(NO_3)_2$ recorded the highest germination rate at all tested temperature degrees (10, 25 and 40°C). Moreover, they reported that seed priming with 7.5 mM of $Mg(NO_3)_2$ increased plant height, number of branches and green leaves, leaf area/plant, plant fresh and dry weights, root number/plant, root length, root fresh and dry weight, superoxide dismutase activity (SOD) and protein content at all tested temperature degrees (10, 25 and 40°C). Yogesh and Prashant (2018) studied the effects of treated tomato seeds of two varieties (Navodya and S-22) with NaCl and KNO3 at 1% on germination and seedlings growth after 12, 24 and 24 hours. They found that the primed seed of the variety 'S-22' recorded the highest germination percentage (91.75%), Vigour index length (1957.52), Vigour index mass (9.083), Seed metabolic efficiency (0.188), Electrical conductivity of seed leachates (dSm^{-1})(91.59) as compared to the control (hydro-primed seeds of the variety S-22). Seed priming using nano-size titanium dioxide (N-TiO2) at 0, 100, 200, and 400 mg L^{-1} to improve germination and seedlings vigor of tomato (*Lycopersicum esculentum* L.), onion (*Allium cepa* L.), and radish (*Raphanus sativus* L.) seeds were investigated (Haghighi Maryam and da Silva, 2014). The highest germination percentage of tomato (100%) and onion (30%) was observed at 100 mg L^{-1} of N-TiO2, while a 100% germination of radish seeds was observed at 400 mg L^{-1} N-TiO2. Regarding seedlings growth, the tallest seedlings of tomato, onion and radish were observed with 400, 200 and 100 mg L^{-1} N-TiO2, which indicated that N-TiO2 can be used as a seed-priming agent for horticultural crops (Haghighi Maryam and da Silva, 2014). Priming with low levels (2 and 4%) of ethanol improved seed germination, seedling vigor and enhanced antioxidative activity that results in better performance of tomato seeds in both tomato cultivars. Priming the tomato seeds with ethanol at 2 and 4% for 24 hours improved seed germination percentage and the seedlings vigor and antioxidant capacity system of the plants (Irfan, et al., 2013). Gupta et al., (2015) investigated the responses of cherry tomato seedlings to seed priming with the pulsed magnetic field (PMF) and fish protein hydrolysate (FHP). They obtained an increased seedling vigor of 23% for the treated seeds as compared to the control. According to Horri et al., (2007) the seed priming using fish proline hydrolysate (FPH) at 2.5 mL/L significantly increased plant height as compared to the control. Osmopriming with PEG caused a remarkable increase in the radicle length, shoot length and total fresh weight of tomato seedlings under saline conditions (Zhang et al., 2012).

2. Impact of seed priming on growth and yield of tomato plants

An important question is frequently asked, how is seed priming still effective during the plant life cycle and can help the plants at their late growth stages (i.e. vegetative, fruit, and seed setting and maturity) to perform well under biotic and abiotic stresses?. And we can easily answer, as a result of seed priming, physiological and metabolic operations that caused the DNA repair pathway will be activated, the pathway for synthesis of de novo protein, inhibit or reduce cell metabolite leakage, gene expression for defense pathway and synthesis of an antioxidant enzyme system (Ibrahim, 2016). This prevents oxidative damage in the plant cells, and lipid peroxidation, and helps the plant grow and yield under different biotic and abiotic stresses (Rahman et al., 2020). Halopriming of tomato and chili seeds in 3% KNO_3 significantly enhanced seedlings' vigor at the laboratory level and plant growth and yield at the field as compared to hydropriming and nonprime seeds of both crops (Maiti et al., 2013). According to the author's findings, soaking the seeds in 3% of KNO3 for 30 hours (tomato) and 40 hours (chili) enhanced early flowering, plant height and total fruit yield as compared to non-primed and hydro-primed seeds at the field level. Under Saudi conditions, Al-Amri (2013) conducted a field experiment to investigate the response of tomato varieties to seed priming with shikimic acid at 30, 60 and 120 ppm. The author observed a significant increase in plant biomass, fresh fruits number and weight per plant, and total yield of fresh and dry fruits as compared to nonprime and hydro-primed seeds (Al-Amri,2013). Moreover, soaking the tomato seeds in shikimic acid improved fruit quality by enhancing vitamin C, lycopene, carotenoid contents, total acidity and fruit total soluble sugars (TSS%). The impact of halopriming using 60 ppm of shikimic acid and biopriming using *Streptomyces griseus* (MT210913) (*S.*

griseus) for seeds of two tomato rootstocks (*Solanum cheesmaniae* L. (line LA 524) and GS hybrid) on growth and yield of the tomato scion 'Peto 86' under cold stress in the field were investigated (Sayed et al., 2022). The results revealed that biopriming the seed of tomato rootstock 'GS-hybrid' with *S. griseus* helped the tomato scion 'Peto-86' mitigate the negative effects of cold stress as compared to the primed seeds with shikimic acid, non-primed and hydro-primed seeds. The yield of fresh fruits was increased by 10.5% and 5.7% in the first and second seasons when the tomato scion 'Peto-86' was grafted on seedlings of GS hybrid produced using bio-primed seeds with *S. griseus* (Sayed et al., 2022). The leaves of bio-primed grafted combination Pet0-86/GS hybrid contained higher concentrations of GA3 and macro- and micro-elements. salicylic acid was used as seed priming at concentrations of 0.25mM, 0.5mM and 0.75mM to enhance the growth and yield of tomatoes under heat stress (Singh et al., 2016). The authors' findings indicated that seeds germination, plant vegetative growth and yield were significantly reduced under high temperatures. However, soaking the seeds in 0.5mM salicylic acid extremely improved the percentage of germinated seeds and germination time under heat stress. but also reduced germination time under stress conditions. Also, the quality of the fruit including TSS, TA, vitamin C and lycopene content was significantly improved by priming using Salicylic acid. They recorded a significant increase in the fruit yield of tomatoes as compared to no-primed seeds (Singh et al., 2016). In recent research, many researchers directed their attention to the radiation priming of crops seed using Infrared Radiation (IR), Ultraviolet radiation (UV), Ultraviolet C-band radiation (UV-C) and Cold Atmospheric Plasma (CAP) to improve crop growth and productivity under different environments. Al-Amir and Attia, (2022) tested the efficiency of seed priming using UV-C at a dosage of 0.85 and 3.42 $kJ.m^{-2}$, on growth and yield under water salinity (NaCl, 100 mM). A significant increase in the growth parameters of tomato plants was observed due to the priming treatment with UV-C. The authors attributed the positive impact of UV-C treatments, as a seed priming approach, on tomato plant growth, to the possible increase in essential micronutrients and the stimulation of the plant defense system due to the radiation treatment of the seeds (Al-Amir and Attia, 2022). Cold plasma is usually used in medicinal fields, it is an environmentally safe/friendly technique/procedure, and it has a great impact on the generation of various reactive oxygen/nitrogen species, however, it is rarely used in agriculture. The reactive oxygen/nitrogen species are essential for the regulation of plants' physiological, biochemical, and cellular processes (Sivachandiran and Khacef, 2017; Ling et.al, 2016). Recently, experiments were conducted to test the efficiency of treating the crops seed with Cold Atmospheric Plasma (CAP) for 1 min, 5 min and 10 min, on the seed germination and plants growth and yield (Adhikari et al., 2020). According to the authors, tomato seeds that were treated with Cold plasma seed priming (CAP) showed the highest germination percentage and germination time and germination uniformity as compared to untreated seeds. In Addition, CAP seed priming enhanced the plant's growth, antioxidants capacity system, phytohormone, and expression of defend genes under drought stress. The authors attributed the positive impact of CAP on tomato plants' growth and development to the generation of reactive oxygen/nitrogen species, which control many of the biochemistry and physiological parameters of plants.

3. Impact of seed priming on tomato tolerance to Salinity stresses

Seeds pretreatment not only improved seed germination time, percentage and rates, but the effects of seed pretreatments can help the plants' performance at vegetative, flowering and fruit/seeds setting and maturity stages. The explanation for the long-term efficient effects of seed priming during the plant life cycle may be attributed to the positive impact of priming materials on different metabolites and secondary metabolic processes including, 1) activating the physiological and metabolic operations that caused the DNA repair pathway, 2) activating the pathway for synthesis of de novo protein, 3) inhibiting or reducing cell metabolite leakage, 4) enhancing gene expression for defense pathway and 4) enhancing the synthesis of an antioxidant enzyme system (Ibrahim, 2016; Rahman et al., 2020). During the past decades, several research reports demonstrated the positive impact of pretreatments of crops seed (seed priming) on the enhancement of plant growth and yield under soil and/or water salinity (Taïbi et al., 2021; El-Beltagi et al., 2022; Xie et al., 2022). Most of the researchers focused on the study of the effect of seed preparation on the development of plants' tolerance to salinity at early growth stages (seed germination and seedlings stage). There is limited information available about the impact of seed priming treatments/agents on enhancing the salt tolerance of tomatoes at late growth stages (vegetative, flowering and maturity) based on physiological, biochemical and genetic aspects. It was reported that seed priming with NaCl enhanced seed germination and seedlings vigor of tomatoes under salt conditions by alleviating the adverse effects of salt (Elouaer and Hannachi 2012; Ibrahim 2016; Gebreegziabher and Qufa 2017). In a recent research, González-Grande et al., (2020) demonstrated the positive impact of seed priming using NaCl on the growth and yield of the tomato variety 'Río Grande'. The seeds were treated with NaCl at concentrations of 0, 85, 171 and 257 mM until germination, then transferred to a hydroponic system, where the salt concentration in the system was 85 mM NaCl. The water salinity reduced the leaf water potential, photosynthetic pigments, stomatal conductance and photothensitic rate. Seed priming with NaCl improved salt tolerance in tomato plants by enhancing the antioxidant enzyme system, osmotic adjustment and water use efficiency. Priming with 0.5 and 1.0 M NaCl mitigated the adverse effects of salt stress of two tomato varieties and enhanced the growth and yield as compared to non-primed seeds (Cano et al., 1991). The authors observed a significant decrease in shoot contents of Cl and Na, while the K/Na ratio was significantly increased, which may explain the yield increase of the tomato variety 'GC-72'. Soaking the tomato seeds in Ascorbic acid (AsA) at 100mM alleviated the negative effects of salt stress during different growth stages (Alex et al., 2021). According to the authors, AsA treatment increased water potential and water use efficiency, leaf photosynthetic pigments, and antioxidant enzymes SOD, CAT, POX, GAX, GA, and GSH. Contrarily, the authors observed a significant decrease in Na, lipid peroxidation, and H2O2. Finally, the authors attributed the improved yield of tomatoes under salt stress to the positive effects of AsA as a promising seed-priming agent.

4. Conclusion

Pre-treatments of tomato seeds using different seed priming materials/techniques significantly improved seed germination, seedling vigor, plant growth, and yield under normal conditions and or diverse environmental stresses. Seed priming, physiological and metabolic operations that caused the DNA repair pathway will be activated, the pathway for synthesis of de novo protein, inhibit or reduce cell metabolite leakage, gene expression for defense pathway and synthesis of an antioxidant enzyme system. This prevents oxidative damage in the plant cells, and lipid peroxidation, and helps the plant grow and yield under different diverse conditions. Most of the research during the past decades was directed to study the impact of seed priming on tomato seed germination and seedling vigor under normal and stressful conditions. Additional physiological, biochemical and molecular studies are required, especially with the great progress in analytical technologies, protocols and types of equipment, to illuminate the positive impact of seed priming on metabolism and secondary metabolite, antioxidant enzyme system and molecular processes. Also, additional research is required to study the impact of seed priming of tomato seeds and or/seedlings on the growth and yield of tomato plants at the greenhouse and field levels, to achieve the sustainable production of tomatoes.

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نظرة عامة عن تأثير تحضير بذور في الطماطم تحت تأثير الظروف الطبيعية والملوحة: من انبات البذور إلى الحصاد

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مستخلص. تعتبر الطماطم أحد أهم محاصيل الخضار في جميع أنحاء العالم وفي المملكة العربية السعودية، نظرًا لقيمتها الغذائية العالية وكفاءتها للزراعة في ظل مجموعة واسعة من الظروف البيئية. الطماطم هي واحدة من محاصيل الخضار النقدية التي تولد دخلاً جيدًا ومستمرًا للمزارعين لمدة شهرين إلى ثلاثة أشهر. على الصعيد العالمي، تعتبر الطماطم المصدر الرئيسي للدخل والمساهم الرئيسي في الأمن الغذائي لصغر حجم المجين في الطماطم، فإنه يعتبر نموذجًا للدراسات الفسيولوجية والوراثية والجزيئية والتربية لتحسين الصفات والمحصول وتحمله للضغوط الأحيائية وغير الأحيائية. إن إنتاج الطماطم وتوسيع نطاق زراعتها يواجهان تحديات كثيرة، لا سيما مع التغيرات البيئية العالمية فيما يتعلق بالتغيرات المناخية، وتوافر المياه العذبة وجودتها، والآفات والأمراض، وجودة التربة. تم إجراء العديد من الدراسات لإيجاد حلول فعالة وقابلة للتطبيق للتغلب على المشاكل البيئية التي تواجه التوسع في زراعة الطماطم وزيادة الإنتاجية، بما في ذلك اتباع الممارسات الزراعية الجيدة، وتحسين وتربية أصناف جديدة ذات إنتاجية وجودة عالية في ظل ظروف بيئية قاسية واستخدام المحفزات الحيوية للنمو التي تساعد النباتات على النمو والإنتاج في ظل ظروف صعبة. يعد تحضير البذور أحد الحلول الموصى بها للمساعدة في إنبات الطماطم ونموها وإنتاجيتها في ظل الضغوط الأحيائية وغير الأحيائية. وتهدف دراسة المراجعة المقدمة إلى تقديم الدراسات الحديثة التي تم إجراؤها حول استخدام تحضير البذور لتحسين إنبات الطماطم ونموها وإنتاجيتها في ظل ظروف الإجهاد البيئي. تنقسم المراجعة المقدمة إلى ثلاثة أقسام: (١) تحضير البذور لتحسين إنبات بذور الطماطم؛ (٢) تحضير البذور لتحسين نمو الطماطم وإنتاجها؛ (٣) تحضير البذور لتحسين قدرة الطماطم على تحمل الإجهاد الملحي.

الكلمات الرئيسية: الطماطم، الاجهاد الملحي، تحضير البذور، تحضير الهالة، الملوحة، المقاومة المستحثة.