Effects of various seed priming methods on vegetable crops: A Meta-Analysis

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Abstract

Considerable research has been done globally in recent years around the world to study the effect of various seed priming methods on crops. Surprisingly, many of these seed priming methods on yields show *dissimilar* or even contradictory results. *Meta-analysis* is a new research direction in Agriculture/horticulture science that sheds light on the strengths and weaknesses of previous studies on seed priming methods and helps us to obtain accurate and precise conclusions. Interestingly, the effect of seed priming methods on germination metrics, seedling emergence, and morphological, physiological, and biochemical attributes in vegetables under stressful and non-stress conditions has not been *quantitatively* performed using meta-analysis methods so far. For the first time, we performed a meta-analysis study based on a dataset we collected over a 50-year period of research in seed priming methods. Our meta-analysis consists of 183 studies and articles and covers 57 species from 17 plant families using 8441 observations. According to previous studies, we know that seed priming before planting (1) *enhances* germination indices, seedling vigor, growth, and productivity of vegetable seeds, and (2) *reduces* most adverse effects compared to non-primed seeds *even* under undesirable conditions. While many published works of literature have already confirmed the positive effects of priming, a meta-analysis is essential for *quantitatively and accurately* evaluating these positive effects. Accordingly, this kind of comprehensive review helps and gives an overview for many vegetable researchers to establish the global picture in their research precisely for seed priming methods and enable them to distinguish knowledge gaps among these numerous existing studies that have been used in this review.

Keywords: “germination, horticultural crop seeds, seed priming, seed vigor, meta-analysis”.

1. Introduction

Climate change has *increasingly* come with changes in *global rainfall patterns* and *rises* in temperatures. Global warming leads to the limitation of water availability and displays detrimental effects on major crop production and yield. Different methods have been used to *improve* stress *tolerance* in crop *plants. Some methods take a lot of time, and some* are unpopular around the world, such as plant genetic manipulation. Seed priming is a method for managing the hydration of seeds in water or a solution with a lower osmotic gradient in order to commence the germination process without radical protrusion. In this method, plants imbibe *antioxidant* and *signaling molecules*, *phytohormones*, amino acids, and trace elements to improve *plant* endurance. Seed priming is capable of increasing photosynthetic pigments, adjusting ionic toxicity, activating the metabolism of important enzymes, amending osmotic pressure, and enhancing antioxidant defense mechanisms under various *stressful conditions* in comparison to non-primed seeds (Taylor et al. 1998; Ashraf and Foolad 2005, Waqas et al. 2019; Chen et al. 2022).

Seed priming is classified by several methods, including hydropriming, halopriming, osmopriming, hormonal priming, solid matrix priming, biopriming, etc. In hydropriming, the seeds are directly submerged in water before being sown, allowing for each plant species to radical protrude. Halopriming is the process of soaking seeds in various ratios of inorganic salts in aerated settings. The seeds are steeped in a solution containing sugars or polyethylene glycol in osmopriming. Hydropriming and osmopriming are two examples of controlled and restricted hydration used in matrix priming. These solid matrix materials can hold a lot of water while having a minimal mass volume and osmotic potential. It is an innovative seed treatment method based on physiological and biological factors (Reddy 2012; Rakshit et al. 2015). Biopriming has lately been employed as a potential technique for reducing pathogens identified in soil and seeds. Under both ideal and unfavorable circumstances, seeds are treated with rhizobacteria, hormones, and other *biological* sources to increase crop uniformity, growth, and yield. Plants' germination percentage, vigor parameters, root morphology, physiological activity, biomass production, and other developmental metrics are all increased by seed priming (Hussain et al. 2016a). Furthermore, seed priming promotes plant metabolism via increasing hydrolase activity, nitrate reductase (NR) production, and dissolving sugar concentrations during germination (Anaytullah and Bose 2007).

Meta-analysis is performed using statistical software like SPSS, Stata, SAS, and R. However, since these software packages are not primarily designed for meta-analysis, they require explicit procedures or coding. The researcher can access these, but they are typically difficult to comprehend or modify. There are specific software programs that have been enhanced expressly for doing meta-analysis. The Cochrane Collaboration's free software package, RevMan (The Cochrane Collaboration 2014), requires the researcher to complete every step of a systematic review. Commercial software with user-friendly interfaces includes Metawin (Rosenberg 2000) and Comprehensive Meta-analysis (Borenstein et al. 2005). The latter has a purchase fee but accepts many sorts of data than the former, which only admits three basic data types. Although it is capable of performing complex analyses, the graphic display of data still has limitations, especially for descriptive data; personalize, the forest plot is disallowed by Comprehensive Meta-analysis (CMA). By setting the input type to "continuous" is applicable for analyzing descriptive data. However, the free version only supports built-in datasets and does not support the analysis of original data. There are several other choices that aren't offered, including FAST PRO (Eddy DM: FAST*PRO 1992), and others that are currently in the early stages of development, like Meta-Analyst (Wallace et al. 2009). However, the application of Excel software in implementing met analysis calculation is beneficial because of its easy-to-use, free software and plot graphs quickly and easily in Excel besides a mean effect sizes estimate, SE, and confidence intervals calculation (Kontopantelis and Reeves 2009).

The aim of this study was to quantify the impact of seed priming on various stages of plant growth, including germination, emergence, and post-germination events such as photosynthetic and transpiration parameters, biochemical characteristics, hydrolytic enzymes, ROS activities, and yield metrics in vegetables. The findings from this meta-analysis will demonstrate directions for future research.

2. Materials and Methods

2.1. Literature survey

The data for meta-analysis were surveyed within the literature published over the five decades (1970–up to March 2022) through online databases of Google Scholar and the Research Gate network with the following keyword combinations (seed priming+vegetable crops, seed priming+fruit crops, seed priming+ horticultural crops, pre-sowing, pre-sowing seed priming, seed priming+germination, and post-germination). Additionally, we surveyed all the article’s reference lists of previous reviews and individual studies on this topic.

The abstracts of the obtained articles were scrutinized to ensure their relevance to our selected topic. Therefore, unrelated studies, including reviews, editorials, reports, conference proceedings, grey literature, and dissertation, were eliminated. The remaining articles were studied attentively, and articles were considered to be the right for our selected criterion: (a) included studies that there was the replication of the experimental treatments, (b) articles that assessed reported mean values for treatment and untreated control, (c) included studies related to horticultural crops (vegetables) and (d) articles included original research data. We omitted 188 articles that did not contain vegetable crops. Moreover, 93 review articles were eliminated from our database. Finally, we terminated this meta-analysis with a dataset comprising 183 studies that were evaluated for eligibility by studying the entire text including 57 species from 17 plant families. Our database consisted of numerous plant attributes containing germination indices (germination percentage, germination rate, germination index, seed and seedling vigor index) and traits related to emergence (percentage and rate) and morphological characteristics (seedling length, plant height, seedling dry, and fresh weight), traits related to photosynthetic pigments (leaf area, chlorophyll a and b, carotenoids, net photosynthetic rate, absolute growth rate), biochemical attributes (malondialdehyde, phenolic, proline, etc.), antioxidant enzymes (Ascorbate peroxidase, ascorbic acid, catalase, peroxiredoxin, superoxide dismutase), hydrolytic enzymes (protease, α-amylase) and seed yield, harvest index, and biological yield.

2.2. Data extraction and processing

We entered into a Microsoft Excel program the pertinent information for each paper with the following categories: (a) author name, title, year of publication, (b) species name, number of species, plant family, (d) number of repetition or observation, seed priming types, treated and untreated treatments, and detail of the treatments (Supplementary information). For each article, data or experiment information was drawn out from graphs, tables, figures, and text of the selected papers. Data or mean values reported in graphical form were extracted using the freely available software program (GetData graph digitizer version 2.26) to attain values numerically (Rohatgi 2015). We did not consider papers that contained combinational treatments, only experiments with individual treatments to be considered when they were conducted on different species to discover the actual effects of each treatment. All data processing, calculation, analysis, and drawing graphics were complemented with the Microsoft Excel program (Soltani et al. 2018; Soltani et al. 2020).

2.3. Meta-analysis and synthesis

For all the parameters mentioned above, the effect of seed priming types was calculated by evaluating effect size (Soltani et al. 2020). An effect size applied for quantifying the result of two-group experimental designs for meta-analysis studies is known as the response ratio when carrying a divided treatment mean (X_T) and control mean (X_C) and the response ratio (RR) is defined as X_T/X_C that we took the natural logarithm of the response ratio or change in the means of a treatment and control group before evaluating it (Hedges et al. 1999). Effect size estimation was considered by data transformation linearization with the distribution of natural log whose distribution is more normal for R in small samples (Hedges et al. 1999).

$$\boldsymbol{ln\,R = ln\left(\frac{\overline{X}_T}{\overline{X}_C}\right)} \tag{1}$$

For evaluating the mean effect($\boldsymbol{ln\,R}$), the average effect size is a weighted mean value of the experimental studies involved in a meta-analysis. The benefits of integrating primary studies through a meta-analysis in place of assessing the primary studies separately and individually are that the average effect size is commonly nearby the actual average effect size and increased statistical power for testing the null hypothesis of no effect in a meta-analysis (Borenstein et al. 2009) therefore by allocating weights, we generate assessments about the distribution of precise effect sizes for the mean effect (Gurevitch and Hedges 1999):

$$\boldsymbol{\overline{ln\,R} = \frac{\sum(ln\,R_i \times w_i)}{\sum(w_i)}} \tag{2}$$

Wi is the weight given to the i or number of repetitions in a study i. 95% confidence intervals (CI) have to be estimated for the between-study variance. The width of a confidence interval displays the accuracy of the estimate. The wider the interval, the less the precision. Where *lower limits* $\mathbf{CL_L}$ and *upper limits* $\mathbf{CL_U}$ of the *95*% CI for effect were calculated as the displayed formula:

$$\mathbf{CL_L = \overline{L^*} - Z_{a/2}\ SE\ (\overline{L^*}) \leq \mu_{\bar{\lambda}}\ \overline{L^*} + Z_{a/2}\ SE\ (\overline{L^*})\ CL_U} \tag{3}$$

3. Results and Discussion

3.1 Description of the Dataset

A total of 464 studies were found in the databases, of which only 183 articles, including 8441 observations, were accepted for current meta-analysis and systematic review (Fig. S1 and Table S1, S2: details are available in supplementary information)[1]. Published studies on seed priming have been increasing considerably in the life sciences over the past ten years (133 out of 183 articles or 72.7%), so we saw in the recent decade a sharp *increase* in studies on all methods of seed priming being published in scientific journals. This meta-analysis study prepares a synthesis of beneficial findings across a considerable number of experimental studies on various pre-germination seed treatments (Fig. S2 details are available in supplementary information)[2] that were organized on different aspects of germination metrics, morphological, physiological, and biochemical attributes of seed science quantitatively. The study is based on 17 botanical families, Fabaceae comprises 21% of all plant families, displaying the most role in this meta-analysis (Table 1). In this meta-analysis, we assessed the effect of various seed priming techniques which include(s) bio, halo, hormone, hydro, organic, osmo, and solid matrix priming with diverse parameters, and different species on germination and seedling quality. Based on Table 1, all the species used in this meta-analysis belong to horticultural crops seeds, such as onion (*Allium cepa* L.), cabbage (*Brassica oleracea* L.), lettuce (*Lactuca sativa* L.), carrot (*Daucus carota* L.), pumpkin (*Cucurbita pepo* L.), bell pepper (*Capsicum annuum* L.), watermelon (*Citrullus lanatus* L.), etc. Studies reflect the relationship between seed priming methods and germination, and growth, both in optimum and under salt (NaCl) or osmotic (PEG) stresses. Results indicate that seed priming ameliorates seed germination, seedling quality, and viability. Of the total observation included in the present investigation, a total of 576 observations (~8%) were affected by abiotic (salt and osmotic) stress, and ~92% of observations from different studies for this meta-analysis were reported in optimum condition (Figure. 1-6). Approximately 1.125 billion hectares of farming area are subjected to high salinity conditions (Sunjeet et al. 2021). Abiotic stresses (like salt and PEG stress) are one of the major obstacles affecting horticultural losses. Accordingly, awareness of the mechanisms for plant tolerance helps us to develop agricultural/ horticultural productivity with appropriate strategies/techniques. Also, meta-analysis as a procedure enables us to quantify the potential priming value for future research directions, trends, and essential conclusions/decisions (Zulfiqar 2021).

[1] Fig. S1: Diagram of the studies selected for meta-analysis and Table S1 and Table S2
[2] Fig. S2: Various seed priming methods used in present meta-analysis

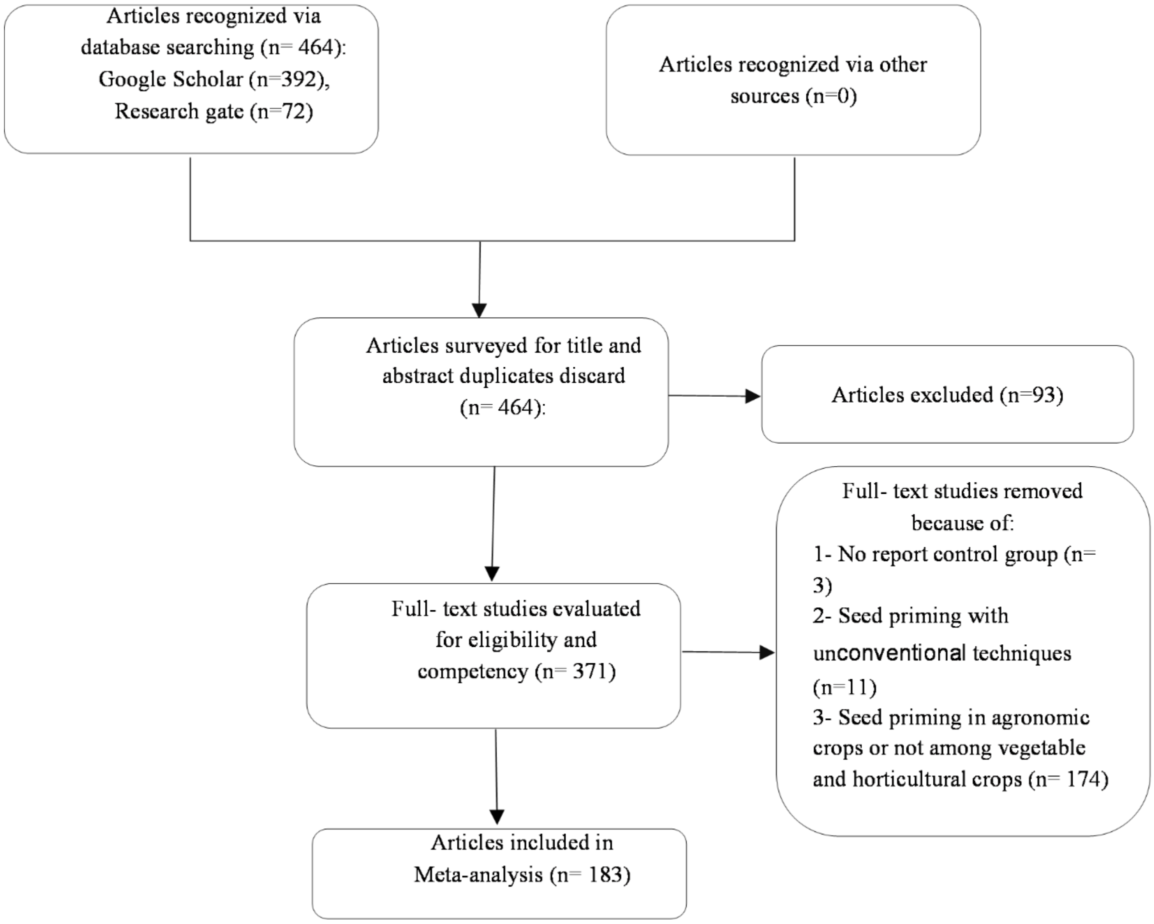

Fig. S1: Diagram of the studies selected for meta-analysis

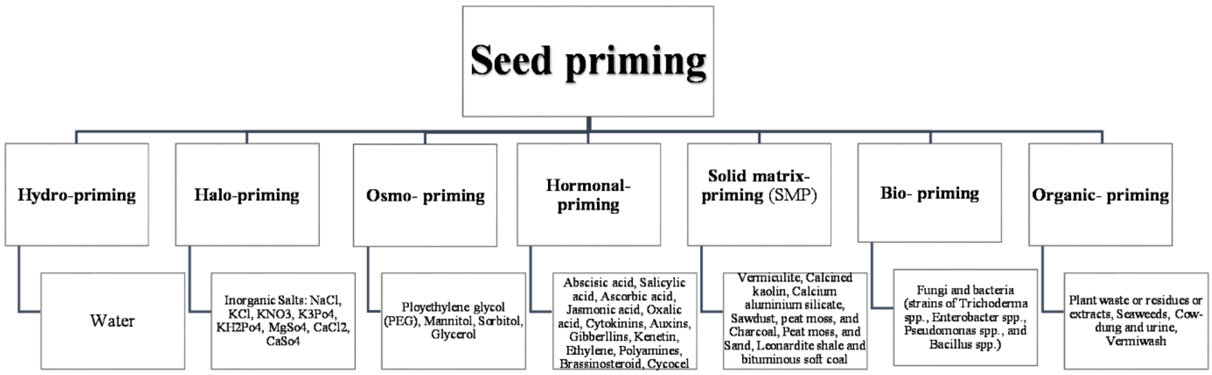

Fig. S2: Various seed priming methods used in present meta-analysis

Table1- Family and number of species applied in meta-analysis

Family	Number of species
Alliaceae	1
Amaranthaceae	2
Amaryllidaceae	2
Annonaceae	1
Apiaceae	7
Apocynaceae	1

Family	Number of species
Asparagaceae	1
Asteraceae	3
Brassicaceae	5
Cucurbitaceae	7
Fabaceae	12
Lamiaceae	3
Linaceae	1
Malvaceae	2
Moringaceae	1
Ranunculaceae	1
Solanaceae	7

3.2 Effect of various seed priming methods on seed germination parameters

The population of the world will grow by 2050 to approximately 10 billion people, which requires global demand for sustainable agriculture which is a crucial objective for all researchers (FAO 2016). Vegetable crops play a significant part in food and nutritional security (mainly as a healthy diet) due to comprise many vitamins, essential sources of minerals, fiber, antioxidants, and therapeutic properties (Dhal et al. 2022). The results of this meta-analysis displayed that the whole seed priming methods were found beneficial in increasing the germination metrics as compared to the control (Figure. 1). Seed germination parameters with 4186 observations (49.6% data in this study) include 1838 data for germination percentage (Figure. 1i), 1391 observations for germination rate (Figure. 1ii), 208 for germination index (Figure. 1iii), 272 data including seed vigor index (Figure. 1iv) and 477 for seedling vigor index (Figure. 1v). Among the seed priming techniques, organic priming showed a substantial impact on germination up to +66.58%, germination index by +171.13%, seed vigor index by +254.75%, seedling vigor index +78.45%, and osmo priming showed a higher germination rate of +78.64% as if compared with the control (non-primed) treatment. The promotive role of organic extracts like seaweeds is due to the presence of plant essential macro and micronutrients, and plant growth regulators, Including cytokinins, gibberellins, vitamins, IAA, phenylacetic acid, carbohydrates and also choline chloride, and glycine betaine (Taylor and Wilkinson 1977; Möller and Smith 1998; Mostafa and Zheekh 1999). The organic extract controls many physiological feedbacks in plants and thus affects cellular metabolism in treated seeds, which positively acts on the germination indices of many crops (Rayorath et al. 2008; Mondal et al. 2015; Layek et al. 2018). Our results in this study are in line with *findings* attained in seeds of lettuce, tomato, and pepper by Jain and Van Staden 2007; Hernández-Herrera et al. 2014; Mavi 2016, Masondo et al. 2018.

According to the findings of this meta-analysis, seed priming improves germination indices in saline conditions. Similar findings have also been gained by Ghoohestani et al. 2012 that pre-treatment of tomato seeds was the best alleviation of salinity. Also, Halmer 2004; Piri et al. 2009 reported that seed priming is commonly performed to improve growth and yield, mostly in plants under abiotic stress. In other words, the hydration of primed seeds in such a manner to a certain extent enables the seed to tolerate stress conditions in a more effective way (Savvides et al. 2016).

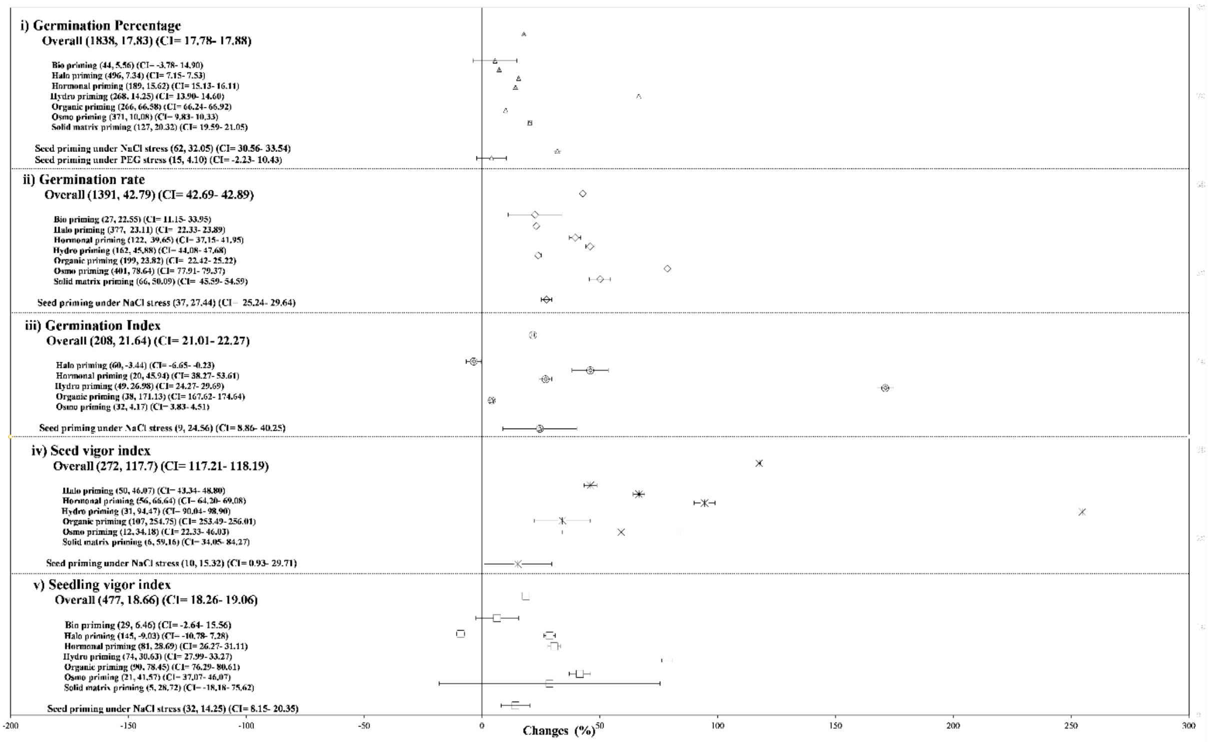

Figure (1) Influence of seed priming methods on traits related to germination parameters on vegetables: (i) germination percentage, (ii) germination rate, (iii) germination index, (iv) seed vigor index, (v) seedling vigor index. Symbols exhibit mean percent change when compared to control treatment. Numbers inside the parenthesis are the number of observations used in the meta-analysis and percent change, respectively.
Error bars represent the mean ± 95% confidence interval.

3.3 Effect of various seed priming methods on Emergence, seedling quality, and morphological parameters

The results shown in Figure. 2 indicate that different seed priming methods significantly enhanced the emergence and seedling attributes over the control (Figure. 2i-vi). Notably, the organic priming treatments in seedling length (+53.57%), seedling dry weight (+58.97%), fresh weight (+83.96%), and hydro priming for plant height (+45.39%) showed the highest values as compared to the control treatment. Seed priming under NaCl stress also gave a positive effect on morphological parameters. Seed priming concentrates on shortening the emergence period with earlier germination and emergence, rapid and more uniform emergence in order to enhance tolerance in front of the undesirable situation, which causes high crop uniform stand and improved yield (Gardarin et al. 2016). Seed priming increases different metabolic events such as α-amylase activity which prepares starch in storage tissues in seeds like endosperm and brings more carbohydrates for embryo respiration during seed germination (Farooq et al. 2017). Our results are similar to studies that showed priming with NaCl improves early seedling growth and yield of cucumber (Passam and Kakouriotis 1994), pepper cultivar (Khan et al. 2009), snap bean (Osman and Salim 2016), tomato (Pill et al. 1991) and for several crops (Basra et al. 2005; Esmaielpour et al. 2006; Sivritepe and Sivritepe 2007).

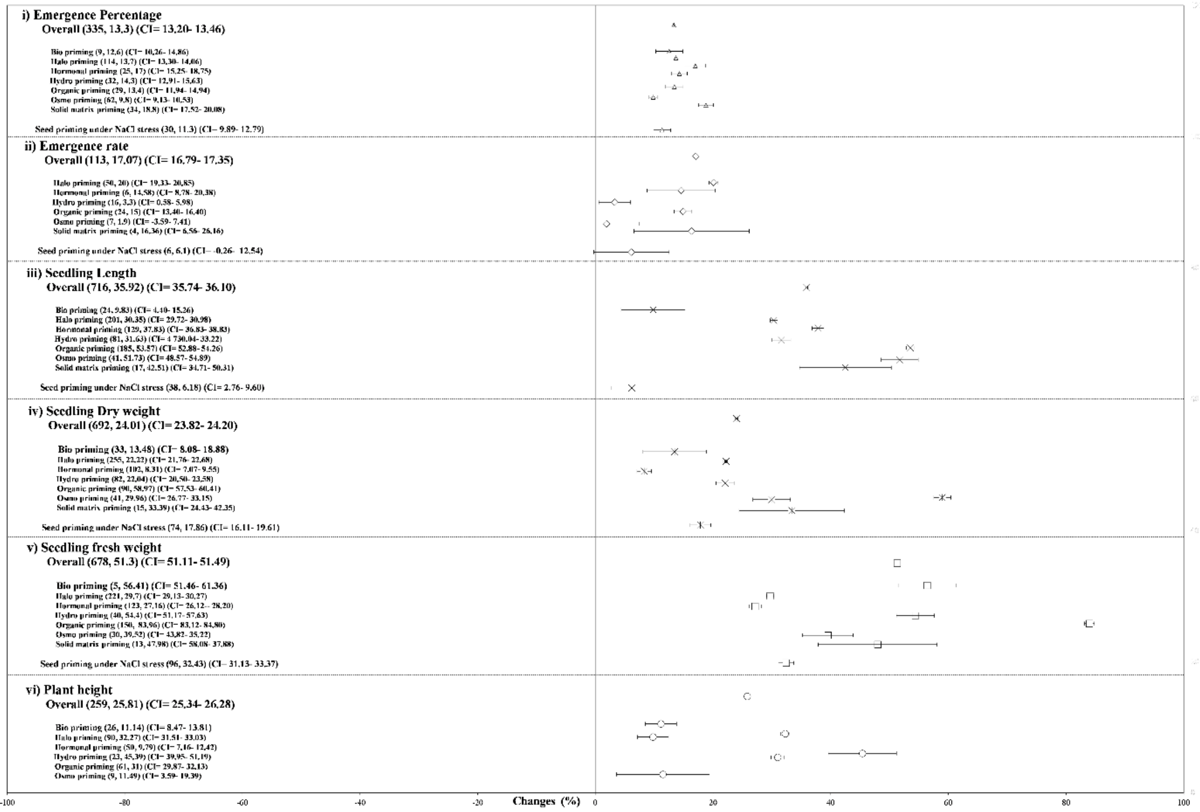

Figure (2) Influence of seed priming methods on traits related to emergence parameters, seedling quality, and morphology on vegetables: (i) emergence percentage, (ii) emergence rate, (iii) seedling length, (iv) seedling dry weight, (v) seedling fresh weight, (vi) plant height. Symbols exhibit mean percent change when compared to control treatment. Numbers inside the parenthesis are the number of observations used in the meta-analysis and percent change, respectively.

3.4 Effect of various seed priming methods on photosynthetic and transpiration parameters

The present study revealed that organic priming was a helpful method for increasing Chlorophyll a (+89.84%) and Chlorophyll b (+48.17) contents over non-primed ones, as shown many studies *have* proven that seed priming increases photosynthetic in Figure. 3. Although pigments. Seed priming under NaCl salinity stress negatively affected Chlorophyll a (-20.40%), Chlorophyll b (-11.66%), and also Carotenoid contents (-14.5%) over control treatment (Figure. the more pronounced increase in leaf area (+20.26) was achieved with seed while 3i-iii) priming under salinity stress (Figure. 3iv). Results of the studies showed that the presence of saline conditions in chloroplast caused thylakoid membranes to become more susceptible and led to chloroplast content leakage. On the other hand, salt stress enhanced the degradation of chlorophyll enzyme chlorophyllase activity (Boughalleb et al. 2008). It also improved the prohibition of pigment synthesis and damaged protein-pigment-lipid complexes via declining accumulation of Mg ions (Amuthavalli and Sivasankaramoorthy 2012) that caused to fall off total chlorophyll content (Singh and Dubey 1995). Improving photosynthetic pigments with seed priming caused to increase in photosynthetic and transpiration rates (+38.24%, +45.47%), respectively (Figure. 3v-vi). Similarly, several seed priming methods gave a strong impact on carotenoids, and leaf area among the treatments over non-primed ones (Rafique et al. 2011; Kasim et al. 2016), and the same results were also achieved in this meta-analysis review. Seeds, when primed with bioflavonoid, increased the content of total phenolic amount, and also enhanced the content of photosynthetic pigments (Singh et al. 2016). *Osmopriming* with *PEG* like the present meta-analysis has the potential to *improve the* content of *photosynthetic pigments* (Bose et al. 2018).

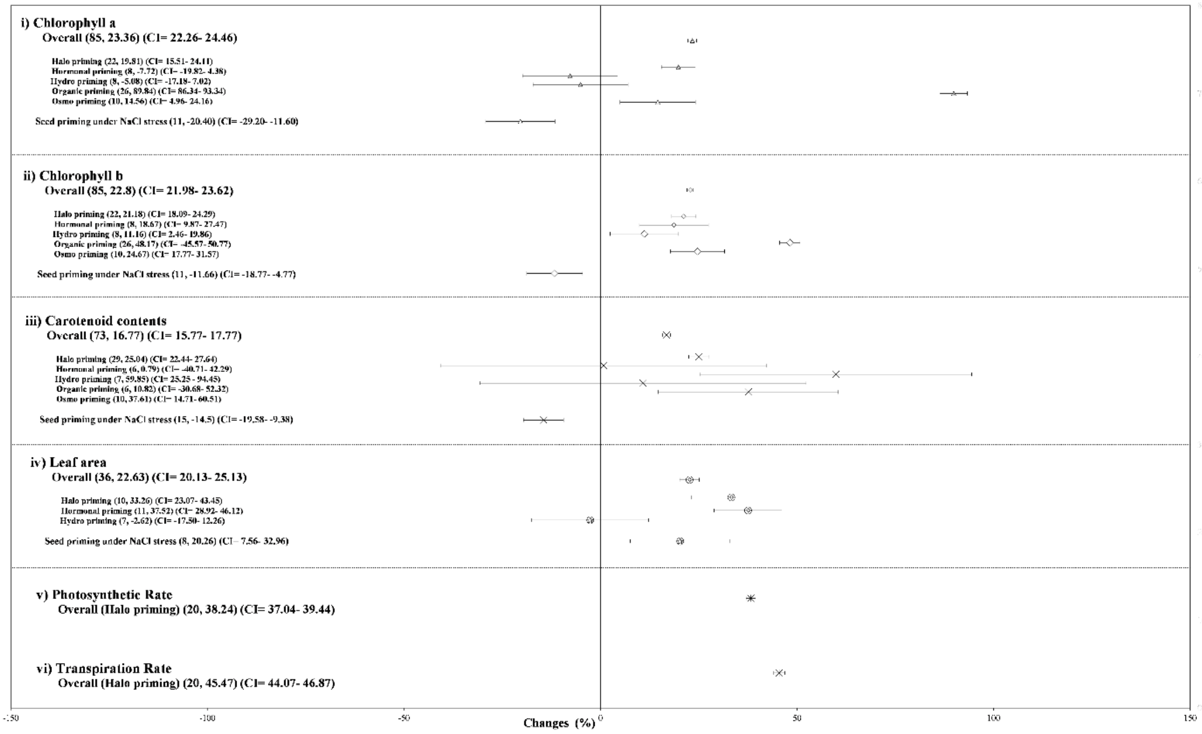

Figure (3) Influence of seed priming methods on traits related to photosynthetic and transpiration parameters (chlorophyll a, b & carotenoids, etc.) on vegetables: (i) Chlorophyll a, (ii) Chlorophyll b, (iii) carotenoids, (iv) leaf area, (v) photosynthetic rate, (vi) transpiration rate. Symbols exhibit mean percent change when compared to control treatment. Numbers inside the parenthesis are the number of observations used in the meta-analysis and percent change, respectively.

3.5 Effect of various seed priming methods on biochemical traits

Results of this meta-analysis study showed that, in general, the primed seeds showed an increase in biochemical attributes under the non-stressed conditions over non-primed ones. Among biochemical traits, proline content (+45.40%) showed the highest overall value. For malondialdehyde content, halo priming (+30.78%) gave the best response, but Osmo priming (-59.8%) showed a negative response (Figure. 4i). Primed seeds that were grown under salt-stressed conditions showed a negative response for both malondialdehyde content (-13.4%) and phenolic compounds (-10.3%) (Figure. 4i, ii), but seed priming before planting is helpful in declining adverse effects of salt stress for proline (+9.57%), protein (+21.7%), sugars (+28.24%) contents (Figure. 4iii-v). Ashraf and Rauf (2001); Afzal et al. (2005), and Rafique et al. (2011) for pumpkin reported the same results that seed priming diminished the intensity of the salt stress. The beneficial effects of seed priming are correlated with the enhancement of metabolic activities and physiological performance in plants, and also the accumulation of these organic materials (proline, soluble protein, and sugar contents) in order to resist in front of osmotic pressure (Liu et al. 2011; Moaveni 2011). Proline act as a protective function or as a potential osmoprotectant via scavenging free radicals and osmotic adjustment (Hasegawa et al. 2000). On the other hand, in drought stress conditions, sugar resources accumulate to maintain membrane stability and preserve protein degradation, and enzyme inactivation (Lipiec et al. 2013). Seed priming may alleviate the detrimental effects of salinity stress via antioxidation activities and proline accumulation in the plant (Tari et al. 2004). In other words, seed priming prevents oxidative stress (Ibrahim 2016) through the induction of the enzymatic antioxidation system (Azooz 2009). Seed priming can be effective probably due to the prohibition of the reduction of growth regulators levels in plants (IAA and cytokinin) (Shakirova et al. 2003). It also ensures water availability, alongside its role in the intensification of the photosynthetic rate and preservation of the membrane during germination (El Tayeb 2005). Improving rapeseeds germination with PEG priming was observed by the highest expression of 952 genes and 75 proteins (Kubala et al. 2015a). Salinity leads to *metabolic* changes by restricting *storage reserve mobilization and* diminishing water uptake and also altering the structure of proteins that collectively inhibit seed germination (Machado Neto et al. 2004). Seed priming enhances *protein synthesis* potential in plant tissue by activating specific proteins to endure stress conditions (Ji et al. 2017).

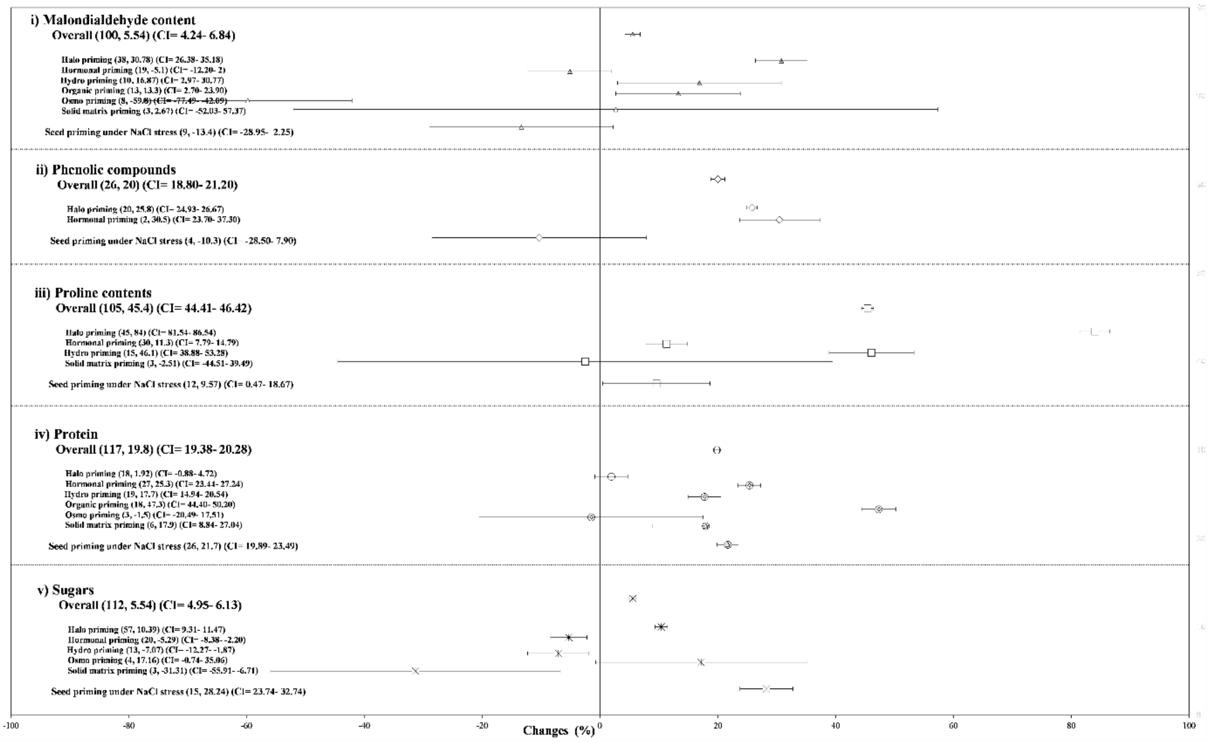

Figure (4) Influence of seed priming methods on biochemical attributes on vegetables: (i) malondialdehyde content, (ii) phenolic compounds, (iii) proline contents, (iv) protein, (v) sugars. Symbols exhibit mean percent change when compared to control treatment. Numbers inside the parenthesis are the number of observations used in the meta-analysis and percent change, respectively.

3.6 Effect of various seed priming methods on antioxidant and hydrolytic enzymes or ROS activities

According to the overall obtained results, all antioxidant and hydrolytic enzymes were positively affected by various seed treatments when compared to non-treated seeds. Also, the effect of seed priming subjected to stress conditions on ROS activities provided a positive response (Figure. 5i-vii). In order to restrain the detrimental impacts of abiotic and biotic conditions, a collection of defense mechanisms are created for plants (Bartels and Sunkar 2005). Antioxidant enzymes such as ascorbate peroxidase, superoxide dismutase, catalase, and peroxidase, etc., as well as non-enzymatic antioxidants like ascorbic acid perform a crucial function in stabilizing and coping with oxidative damage and free radical scavenging (Musa et al. 2015; Hussain et al. 2016a, b; Bali et al. 2020). These compounds enhance solutes such as proline content in plants under stress for maintaining membrane permeability and osmotic balance (Zhang et al. 2015). Seed priming enhances seed vigor via the intensified *activity* of α-*amylase and* protease that lead to protein and *starch* degradation and prepare the nutrition substances for the growth and development of the *embryo* (Miransari and Smith 2014). The plus point of seed priming on germination indices and growth could be because of antioxidative enzyme expression and its remarkable activity as one way to boost *stress tolerance* (Bolkhina et al. 2003) based on the result obtained by the present meta-analysis (Figure. 5i-vii). Seed priming leads to an increase in the activity of the catalase enzyme and also shows a reduction in H_2O_2 content, singlet oxygen, and hydroxyl radicals (Posmyk et al. 2001; Kibinza et al. 2011). It also, reconstructs proteins in plant tissue through the reactivation of the L-isoaspartyl methyltransferase enzyme, causing germination rates were increased (Kester et al. 1997).

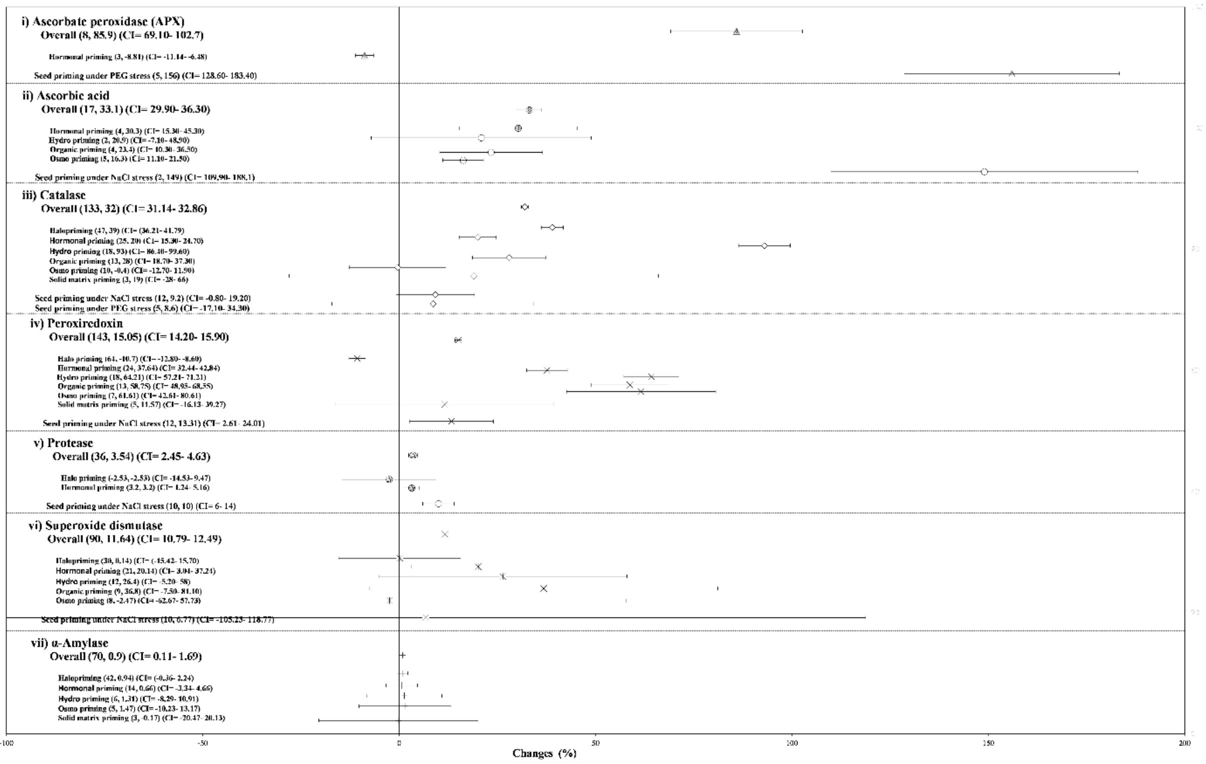

Figure (5) Influence of seed priming methods on traits related to antioxidant and hydrolytic enzymes or ROS activities (Reactive oxygen species) on vegetables: (i) ascorbate peroxidase (APX), (ii) ascorbic acid, (iii) catalase, (iv) peroxiredoxin, (v) protease, (vi) superoxide dismutase, (vii) α-Amylase. Symbols exhibit mean percent change when compared to control treatment. Numbers inside the parenthesis are the number of observations used in the meta-analysis and percent change, respectively.

3.7 Effect of various seed priming methods on yield traits

The result attained from this study suggested that all various seed priming treatments used in this meta-analysis gave a better effect on yield traits than the non-primed treatment (Figure. 6i-iii), The most significant response to different priming for seed yield was seen in organic priming (+47.16%). The same observation was reported by Mazed et al. 2015 and Srikanth et al., 2021 that the effect of seed priming on yield traits showed better results. Seed priming before sowing even under energy-starved status could increase some legumes' yield parameters (Musa et al. 2001; Grant et al. 2005; Khan et al. 2008; Bhowmick et al. 2013). Soltani and Soltani (2015) assessed through the meta-analysis method that seed priming led to 27% and 28% enhancement in crop yield parameters in eudicots and monocots plants, respectively. Seed priming increases the crop yield with early germination, and seedling growth leads to better crop stand *establishment* (Rashid et al. 2002). 186 observations (~2% of total observations) for yield traits (seed yield, harvest index, and biological yield) indicated less research attention was given to these pivotal parameters, especially the lack of abiotic stresses studies that are the most destructive agent for crop yield/production via threatening global food security. So meta-analysis studies that identify knowledge gaps can hopefully upgrade knowledge for future field studies.

High-yield traits in vegetable crops and their capability to deal with many abiotic stresses mainly are related to seedling health and early emergence (Cantliffe 2003). Seed priming has been exhibited as a simple method applied to increase early seed emergence and activate a number of biochemical events needed for germination (Asgedom and Becker 2001) that lead to achieving high vigor and yield. Zhang et al. 1998 expressed that early and synchronized seedling growth and plant nutrition cause an increase in biological yield. Results showed seed priming boosts the source-sink relationship and yield potential, higher LAI and CGR due to expansion of the root system, and brings high partition of photoassimilates to reproductive parts of chickpeas (Ebadi and Sajed 2009).

Finally, our meta-analysis showed that among the seed priming techniques, organic priming gave a strong impact on germination indices and seedling vigor. Osmo priming showed a higher germination rate of +78.64% compared to the non-primed treatment. Besides that organic priming was the most effective treatment for Chlorophyll a (+89.84%) and Chlorophyll b (+48.17%) over non-primed treated seeds. Seed priming under NaCl salinity stress negatively affected Chlorophyll a (-20.40%), Chlorophyll b (-11.66%), and also Carotenoid contents (-14.5%) compared with the non-primed treatment whiles the more pronounced increase in leaf area (+20.26) was achieved with seed priming under salinity stress. Primed seeds with both malondialdehyde content (-13.4%) and phenolic compounds (-10.3%) were grown under salt-stressed conditions and showed a negative response, but showed a positive response to priming for proline (+9.57%), protein (+21.7%), sugars (+28.24%). Additionally, an overall positive effect of seed priming effect on yield traits was obtained (15-20%).

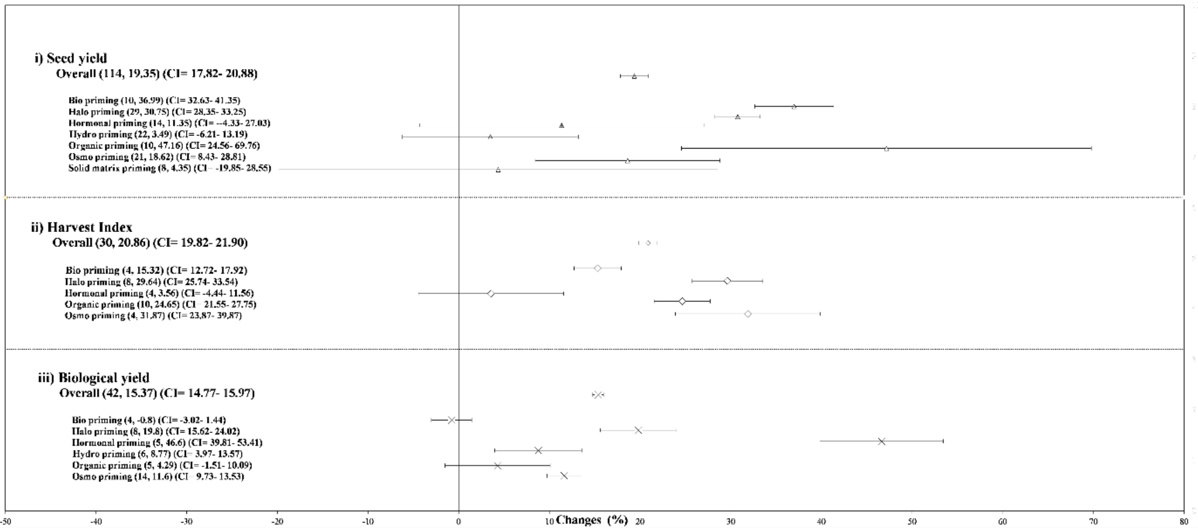

Figure (6) Influence of seed priming methods on yield traits on vegetables: (i) seed yield, (ii) harvest index, (iii) biological yield. Symbols exhibit mean percent change when compared to control treatment. Numbers inside the parenthesis are the number of observations used in the meta-analysis and percent change, respectively.

4. Conclusions

To sum up, this study represents the first extensive review and meta-analysis conducted to *quantitatively* assess the overall effects of different seed priming methods on plant growth traits in vegetable crops. The findings suggest that seed priming holds significant potential for enhancing agricultural crop productivity, even in the presence of salt and PEG stress conditions. The application of seed priming is shown to improve growth and bolster antioxidative defense mechanisms by facilitating the accumulation of various metabolites, notably proline. This, in turn, contributes to its role as both an osmoprotectant and an antioxidant, effectively mitigating oxidative stress induced by abiotic stressors. The results described here demonstrated that seed priming treatments can be a more cost-effective, promising, and simple approach, reduce the application of chemicals, and accelerate the transition to sustainable agriculture practice for a better world.

Supplemental online material: The following supplementary material is available for the Meta-analysis article: Fig. S1: Diagram of the studies selected for meta-analysis and Fig. S2: Various seed priming methods used in the meta-analysis, and Table S1 and Table S2.

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