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ORIGINAL RESEARCH

Tree Species Germination: A Comprehensive Meta-Analysis and its Implications for Pre-Sowing Treatment in Bangladesh

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ABSTRACT: In Bangladesh, pre-sowing treatments significantly impact forestry species, employing water, temperature, and chemical methods to enhance seed germination. This meta-analysis, encompassing 17 research articles, emphasizes the prevalence of these treatments, with 11 studies dedicated to pre-sowing techniques and 6 as a comparison group without treatment. Findings reveal substantial heterogeneity attributed to low replications and ecological factors highlighted in articles. To address this, we recommend a balanced number of replications, considering ecological factors, to enhance research reliability in forest restoration and seed germination. Factors affecting seed germination, such as pressure, temperature, sunlight, and water stress, unfold in five stages: imbibition, respiration, light effect, mobilization of reserves, and embryo development. The seed coat layer impedes germination, and various pre-sowing treatments in Bangladesh, including mechanical, water soaking, heat, and chemical treatments, mitigate this hindrance. While this meta-analysis sheds light on ecological factors and seed performance, its limited scale underscores the need for broader studies assessing treatment effects using standardized measures.

KEYWORDS: Meta-analysis, seed germination, publication bias, pre-sowing

1. Introduction

Seed germination, influenced by factors like pressure, temperature, sunlight, and water stress (Flores et al., 2016), and is crucial for plant development. The germination and initial growth of seedlings depend on internal and external factors, differing for monocotyledonous and dicotyledonous seeds (Mahmud, 2005). Two types of seed germination exist, classified in, with five sequential stages: imbibition, respiration, light effect, mobilization of reserves, and embryo development (Lima et al., 2020). Internal factors, especially the seed coat, can impede germination, prompting the use of pre-sowing treatments to reduce this hindrance (Haider et al., 2016). Seed morphological parameters like shape, size, and seed coat layer significantly impact germination, with larger, thinner seed coats correlating with better performance (Do Nascimento et al., 2019). The permeability of the seed coat, crucial for water and nutrient imbibition, becomes a determining factor in germination success (Khan & Shankar, 2014). In cases of thick seed coats, pre-treatment is essential to enhance germination percentages (Saxena et al., 2013). Pre-sowing treatment of forestry tree species is crucial for enhancing seed germination and ensuring robust seedling development in nursery management. A common method focuses on seed coat treatments for high coated seeds, as the seed coat can be a significant barrier to water uptake and germination due to its hard, impermeable nature. Various techniques like scarification, which involves physically or chemically abrading the seed coat, can break this barrier. Mechanical scarification may involve rubbing seeds with sandpaper or nicking them with a knife (Azad et al., 2012), while chemical scarification typically uses acids such as sulfuric acid to erode the seed coat (Hasnat et al., 2018). Alternatively, thermal treatments like hot water soaking can soften the seed coat (Haider et al., 2016, Das, 2014 and Azad et al., 2011). For instance, in Bangladesh, the seeds of *Castanopsis Indica* often undergo hot water treatment to break dormancy (Hasnat et al., 2019). Similarly, the seeds of *Acacia auriculiformis* are commonly treated with sulfuric acid to improve germination rates (Azad et al., 2011). These pre-sowing treatments are tailored to the specific seed characteristics of different tree species, ultimately promoting more uniform and timely germination by facilitating water absorption and gas exchange, which are essential for the seeds' metabolic activities and growth initiation. Bangladesh employs various pre-sowing treatments, including mechanical, water soaking, heat, and chemical methods, tailored to species and seed coat quality (Saxena et al., 2013). Research activities in Bangladesh, led by institutions like the Bangladesh Forest Research Institute (BFRI) and forestry-focused universities, contribute to the sector's development (Shinde & Chavan, 2017). However, the scale of meta-analysis on seed germination and plant growth is limited, presenting a gap in scientific understanding. High-altitude ecosystems provide valuable insights into seed germination through meta-analysis, considering ecological factors such as light intensity, heavy metal uptake, root system modification, plant invasions, seed priming effects, dormancy breakage, seed shape-soil relationship, plant responses to water stress, plant diversity impact, seed limitation, growth response to substances, and forest litter effects (Hossain et al., 2020; Rahman et al., 2018; Uddin et al., 2020). While authors outside Bangladesh have conducted meta-analyses on various forestry aspects, including economic value and ecosystem services, a significant gap exists in Bangladesh's meta-analysis research, particularly in seed germination (Ashrafuzzaman et al., 2021; Jagtap & Bapat, 2010). Indian authors contribute studies on forest management, species richness, carbon sequestration in agroforestry, land use change effects, and bovine brucellosis prevalence in forest ecosystems (Miah et al., 2023). This study aims to bridge gaps in understanding seed germination in Bangladesh's forestry sector by conducting a meta-analysis of research from 2000 to 2024. It addresses identifies effective pre-sowing treatments, guides future research, and aids practical applications. The study's objectives include reviewing and analyzing existing research, comparing germination percentages, seedling length, and collar diameter, along with standard errors and the number of observations, and providing recommendations. Addressing this research gap, the study's research question aims to determine heterogeneity in seed germination percentages, seedling length, and collar diameter between studies employing pre-sowing treatments and those without. Hypotheses are formulated as follows: no heterogeneity among studies' effect sizes and heterogeneity between studies' effect sizes. This study seeks to enhance understanding and contribute valuable insights to the field of seed germination in the context of Bangladesh's forestry sector.

2. Methods

2.1. Data collection

To analyze the features of this research, we collected several research articles from various electronic sources, conducting our research within the timeframe of 2023 to 2024. We initially identified a broad set of articles on seed germination and pre-sowing treatments using specific keywords, focusing on studies from 2000 to 2024 related to Bangladesh or its associated species. Out of the first 100 articles, we reviewed abstracts and data to determine relevance and quality, ensuring they presented empirical data and included key metrics such as germination percentage, seedling length, collar diameter, standard errors, and the number of observations. We excluded duplicates and studies with the same species and methods to maintain consistency.

Table 1. Germination percentages and observations, summarized from articles reviewed in the meta-analysis.

References	Experimental design	Statistical test	Species	Seed treatment
Azad et al., (2012)	RBD	DMRT	*Albizia procera*	CHWT
Marium et al.,(2022)	NA	NA	*Xcoecaria agallocha*	NA
Dey et al., (2021)	RCBD	DMRT	*Terminalia citrina*	WST
Haider et al., (2016)	CRD	DMRT	*Sapindus mukorossi*	CHWT
Sultana et al., (2021)	CRD	LSD	*Swietenia macrophylla*	WST
Hasnat et al.,(2019)	CRD	DMRT	*Vitex peduncularis*	SMP
Hasnat et al.,(2017)	CRD	DMRT	*Canarium resiniferum*	CTs
Hasnat et al.,(2019)	CRD	DMRT	*Castanopsis Indica*	CHWT
Das, (2014)	RBD	DMRT	*Acacia catechu*	CHWT, CTs
Azad et al., (2006)	NA	NA	*Xylia kerrii*	CHWT, CTs
Hasnat et al.,(2018)	RCBD	DMRT	*Protium serratum*	CTs, CT_h
Azad et al., (2011)	NA	DRMT	*Acacia auriculiformis*	CHWT, CTs
Mozumder et al., (2019)	CRBD	DMRT	*Tamarindus indica*	CHWT, CTs
Hossain et al., (2005)	RCBD	DMRT	*Terminalia chebula*	CHWT
Mahmud, (2005)	RCBD	DMRT	*L. leucocephala*	PVS
Hasnat et al.,(2021)	RCBD	DMRT	*P. semisagittatum*	SP
Khan et al.,(2018)	RCBD	DMRT	*Cucumis sativus L.*	Ar

Note. Pre-sowing treatment (PS), No pre-sowing treatment (NPS), Cold and hot water treatment (CHWT), Water soaking (WST), Water stress (WST), Soil media proportion (SMP), Chemical treatment: sulphuric acid and hydrochloric acid (CTs and CT_h), Plantation in various site (PVS), Sowing position (SP), Arsenic solution (Ar), Randomized complete block design (RCBD), Complete block design (CBD), Randomized block design (RBD), Duncan's multiple range test (DMRT).

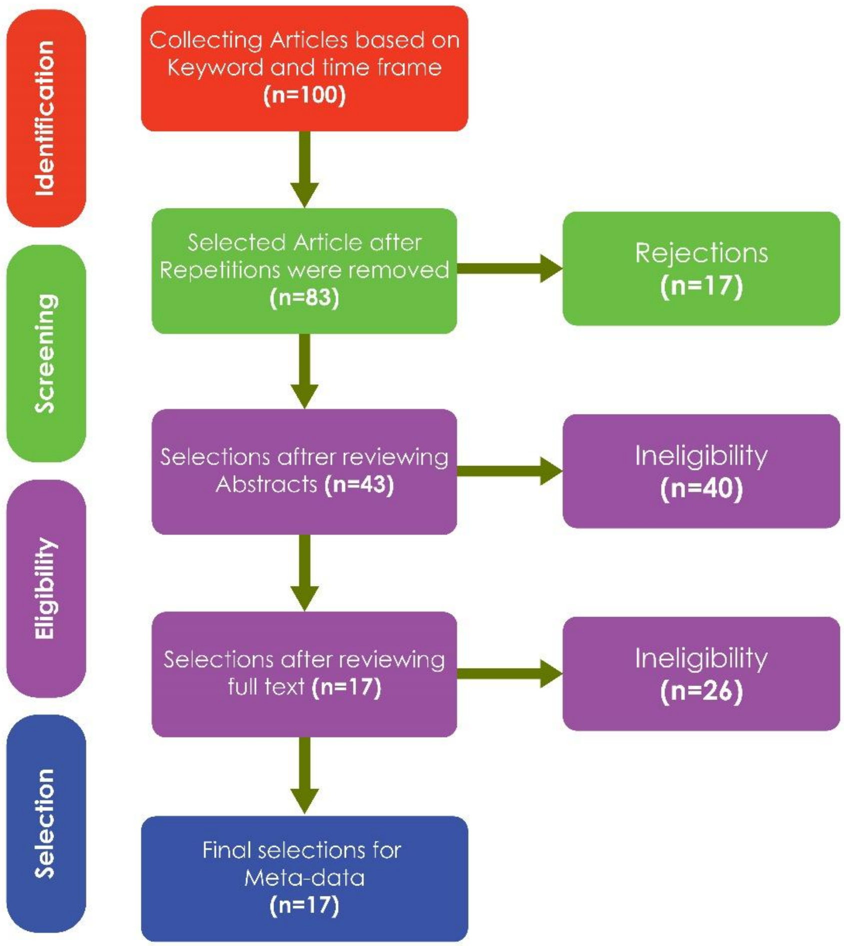

Figure 1. Flow diagram of the literature search process.

Graphically represented germination percentages were included only if clear and logical. The timeframe from 2000 to 2024 was chosen due to improved internet accessibility in Bangladesh post-2000, allowing for a comprehensive analysis of studies. After applying these criteria, 17 articles met all requirements for inclusion in the meta-analysis, focusing on studies from 2010 to 2024 for this analysis (Figure 1 and Table 1). For subgroup data collection, we selected two groups: one undergoing pre-sowing treatment and the other without pre-sowing treatment. In the case of pre-sowing, mean germination and observations or repetitions were taken into consideration. However, for the group without pre-sowing treatment (Sultana et al., 2021), we selected articles that conducted different treatments, considering the control groups from those studies as the no pre-sowing treatment group. In this systematic review process, we utilized a specific string of keywords to find as many articles as possible that would help answer our research question: ('seed germination' OR 'pre-sowing' OR 'effect of treatment on' OR 'germination energy' OR 'germination index' OR 'soil media of plant germination' OR 'treatment application on plants' OR 'seasoning of seed plant growth' OR 'seed survivability').

2.2. Data extraction

For each study, we recorded the following information: i) Study year, ii) Country, iii) Geographical region, iv) Species, v) Treatment, vi) No pre-sowing treatment (primarily the control group from various research articles), vii) Germination percentage, Seedling length, Collar diameter at 2 months age, viii) Standard error, ix) Number of observations, and x) Author (Table 1 and 2). In identifying subgroups, we excluded articles that conducted research on the same species in different timeframes using the same methodological approach. In some instances, the germination percentage was presented graphically. In such cases, we considered this representation an easy, logical, and scientific method for calculation and included it in our analysis, while others were excluded from the data extraction process. We did not include review papers and government reports. We maintained records of article searches and the number of included and excluded articles at each step of this study according to the PRISMA guidelines (Figure 1). The collected data were stored in an Excel file and analyzed using R version 4.2.2. Meta-analytical method: a. Inverse variance method, restricted maximum-likelihood estimator for tau^2, Q-Profile method for confidence interval of tau^2 and tau, Logit transformation Figures was created with Adobe Illustrator. We also used Mendeley software for citation and bibliography management.

While extracting data for meta-analysis, we applied the following criteria: a) When studies reported a single control and several treatments of pre-sowing, including seed germination percentage, germination energy, and germination index of forest species (highlighting the treatment with the highest germination percentage along with its standard error and number of observations), and b) When the studies reported a control group and did not use pre-sowing treatments, focusing on alternative treatment media like nitrogen application, temperature, and water stress. The mean was considered in the meta-analysis as a germination percentage, and the standard error and number of observations were also noted.

2.3. Meta-Analysis

Originally developed for use in the medical and social sciences, meta-analysis has been a staple in these fields for decades prior to its adoption in ecology, as noted by (Gogtay & Thatte, 2017). The unique empirical variability present in ecological research has led to the customization of systematic review and meta-analytical methods, including specialized approaches for synthesizing data (Cheung & Vijayakumar, 2016), computing effect sizes (Hansen et al., 2022), and conducting meta-regression analyses (Ince et al., 2019; Van Iddekinge et al., 2018). However, the application of meta-analysis in ecology has not been without criticism, with several researchers pointing out its misapplication within the field (Cheung, 2019; Del Re, 2015; Van Assen et al., 2015; Wong & Raabe, 1996). To assist with the conduct and interpretation of ecological meta-analyses, various guidelines have been proposed (Ince et al., 2019). Despite these advances, the challenges specific to conducting meta-analyses in the context of forest biodiversity—such as dealing with spatially arranged plots, long-term study durations, and the variability in study design quality—remain significant and largely unaddressed. These challenges, while not exclusive to, are especially significant in the study of forest biodiversity within ecological meta-analyses.

2.4. Statistical analysis

Meta-analysis involves assessing the effects of treatments across various studies by utilizing a standardized measure known as effect size. This measure is derived by calculating the natural logarithm of the response ratio (*ln R*), based on the formula by Hedges et al. (1999),

$$\ln (R) = \ln ((X_P)/(X_C))$$

Where X_p represents the average outcome of the priming treatment and X_C the average outcome of the control group. The importance of each study is determined by its number of replications, as outlined by Linquist et al. (2013),

$$W_i = n$$

With the weight w_i assigned to the i^{th} observation and n representing the replications for each treatment combination.

Table 2. Statistical Data used to perform Meta-Analysis compiled from all the Study.

References	n	Germination Percentages			Seedling length			Collar diameter			Subgroup
		GP%	SE	Z	SL	SE	Z	CD	SE	Z	
Azad et al., (2012)	300	71.8	3.2	1.0	-	-	-	-	-	-	PS
Marium et al.,(2022)	30	70	0.3	4.7	-	-	-	-	-	-	NPS
Dey et al., (2021)	15	75	0.5	13.1	26	1.9	0.9	3.9	0.6	0.06	PS
Haider et al., (2016)	30	70	2.5	0.6	20	1.3	-3.1	-	-	-	PS
Sultana et al., (2021)	30	60	6.2	-32.	0			-	-	-	NPS
Hasnat et al.,(2019)	90	40	2.5	-32.6	38	1.9	7.1	-	-	-	NPS
Hasnat et al.,(2017)	15	33	1.5	-11.4	25	0.7	0.9	-	-	-	PS
Hasnat et al.,(2019)	50	43.3	1.7	-14.8	20.9	1.9	-1.7	-	-	-	PS
Das, (2014)	30	85.9	3.6	5.6	-	-	-	-	-	-	PS
Azad et al., (2006)	50	84.2	2.3	-0.8	-	-	-	-	-	-	PS
Hasnat et al.,(2018)	50	28.3	1.2	-0.3	26	1.0	1.6	9.2	0.3	14.5	PS
Azad et al., (2011)	400	83	2.1	6.8	25	0.3	1.9	3.9	0.1	0.3	PS
Mozumder et al., (2019)	70	82.1	3.2	-42							PS
Hossain et al.,(2005)	15	66.7	2.0	4.1	38.6	1.9	7.4	5.4	0.6	2.3	PS
Mahmud, (2005)	70	18	1.2	4.2	18.5	0.8	-6.5	1.7	0.3	-6.9	NPS
Hasnat et al.,(2021)	50	86.7	3.2	6.8	24	1.0	-0.2	1.9	0.3	-5.3	NPS
Khan et al.,(2018)	30	68	1.2	-1.3	14.5	1.3	-7.2	1.8	0.4	-4.3	NPS

Note: Pre-sowing (PS), No pre-sowing (NPS), A z-value (Z) close to 0 indicates that the study's germination percentage (GP%), Seedling length (SL), Collar diameter (CD) are close to the overall weighted mean, while a positive z-value indicates a higher than average and a negative z-value indicates a lower than average. n and SE for observations and standard error.

This weighting system favors larger studies by giving them more influence, a method considered beneficial for synthesizing broad conclusions (Gurevitch and Hedges, 1999). The aggregate effect sizes are then computed, where (lnR_i) denotes the effect size relating to the observed characteristics (such as seed germination percentage and rate, seedling emergence, and crop yield) from the I^{th} study. Confidence intervals for the mean log response ratio e determined following the method by Heges et al. (1999).

$$\frac{\sum (\ln R_i \times W_i)}{\sum W_i}$$

For ease of understanding, these effect sizes are converted back and presented as percentage changes due to seed priming compared to controls, with positive values indicating improvements and negative values denoting declines ($[R-1] \times 100$). The significance of treatment effects is established when their 95% confidence intervals do not include zero. Furthermore, distinctions between different treatment groups are deemed significant if their 95% confidence intervals do not intersect, as supported by multiple studies (Linquist et al., 2013).

2.5. Study heterogeneity and Publication bias

In our effort to evaluate the degree of variation among the effect sizes incorporated into the meta-analysis, we performed a comprehensive heterogeneity test, which included Cochrane's Q test, I^2, and P-value. The I^2 statistic served as a key indicator, providing insights into the extent of heterogeneity within the selected studies. Specifically, I^2 values were interpreted as follows: a) I^2 = 0% denoted an absence of heterogeneity, b) I^2 = 25% indicated low heterogeneity, c) I^2 = 50% suggested moderate heterogeneity, d) I^2 > 75% pointed to high heterogeneity, and e) I^2 = 100% represented maximum heterogeneity. Additionally, to investigate the potential presence of publication bias in our selected articles, we employed a funnel plot—a graphical representation of study precision against effect size. Furthermore, we utilized Egger's regression test, a statistical method for quantifying asymmetry in the funnel plot, providing a more in-depth examination of publication bias. This multifaceted approach allowed for a thorough exploration of both the heterogeneity and potential bias within the meta-analysis results, ensuring a comprehensive understanding of the robustness and reliability of the synthesized data.

3. Results

3.1. Exploring Heterogeneity (Subgroup analysis)

The forest plot demonstrates the effect of germination (X) on outcome (Y) across multiple studies, including a significant overall effect size of 0.64 (Figure 3). The sample sizes for the largest study (Azad et al., 2006) are noteworthy, consisting of 400 observations, followed by the second-largest study (Azad et al., 2012) with 300 observations, and the smallest studies with 15 observations, depicted in square shapes along the horizontal line. The p-values associated with each study indicate the statistical significance of the observed effect, with demonstrating a significant positive effect of germination percentage on the outcome (P<0.01). Heterogeneity analysis, measured by I^2 (92%) in the case of pre-sowing treatments, suggests a high variety in studies. Carries a high weight (Common: 24%), suggesting similarity with (Azad et al., 2012).

Regarding the highest heterogeneity in pre-sowing treatments (I^2 = 92%), the study shows the highest germination mean among pre-sowing at 71.83, with 400 replications (Figure 2). This study focuses on the pre-sowing treatment of *Albizia procera* at Khulna University. Among these, 17 observations were identified for the calculation of the overall effect size; however, these studies may exhibit higher heterogeneity due to mechanical and chemical treatment processes, the number of replications, and ecological factors affecting the germination process (Dey et al., 2022; Haider et al., 2016; Hasnat et al., 2019; Hasnat, Hossain, & Hossain, 2016; Hasnat, Hossain, Bhuyian, et al., 2016).

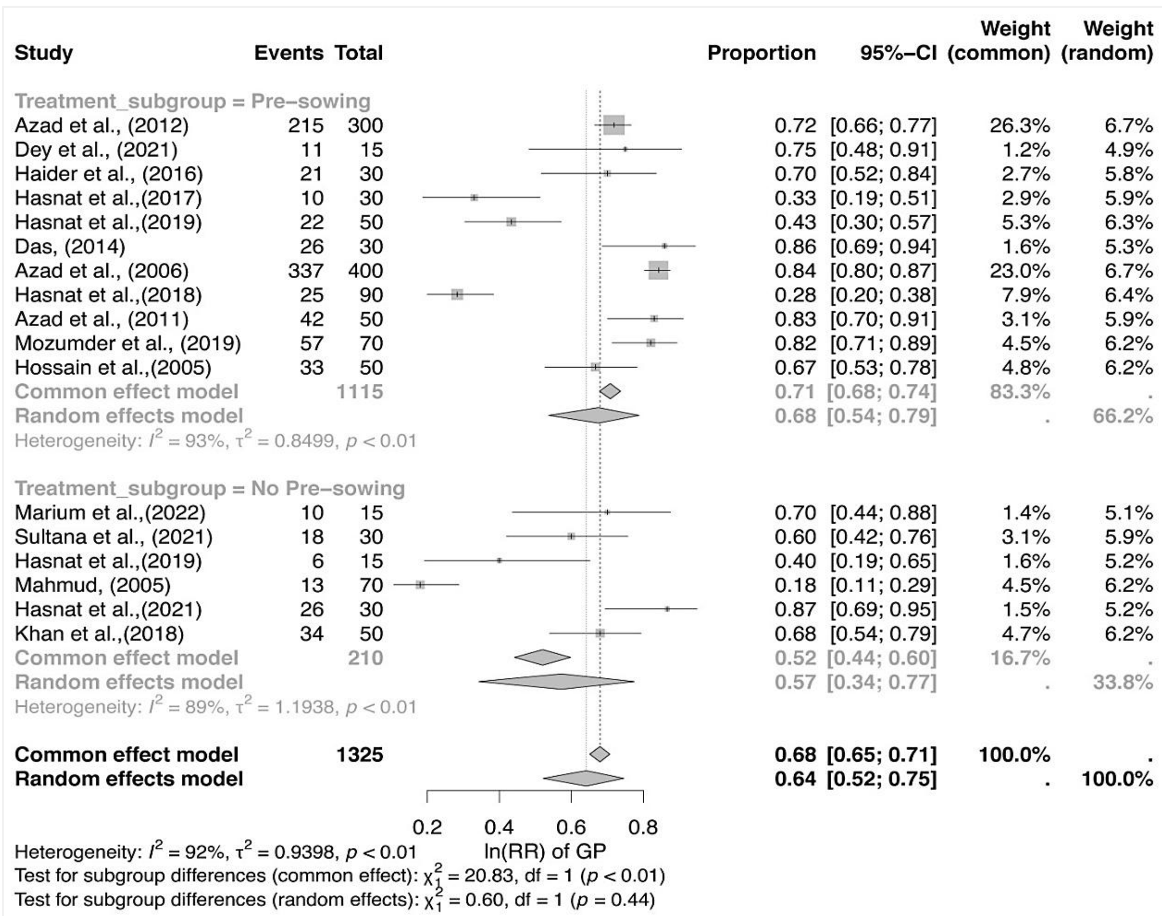

Figure 2. A meta-analysis employing a standardized measure (SM) termed effect size (EE) to assess the performance of GP% (n=17, with 11 pre-sowing and 6 without pre-sowing). A dashed vertical line explained the line of no effect on the forest plot. The size of markers for point estimates in individual studies reflects the precision of the estimate, with error bars indicating 95% confidence intervals. The stretched diamond marker denotes the overall random effects estimate for each study alongside its 95% confidence intervals. Additionally, CI stands for Confidence Interval, and Q represents the I^2-test of heterogeneity among the studies.

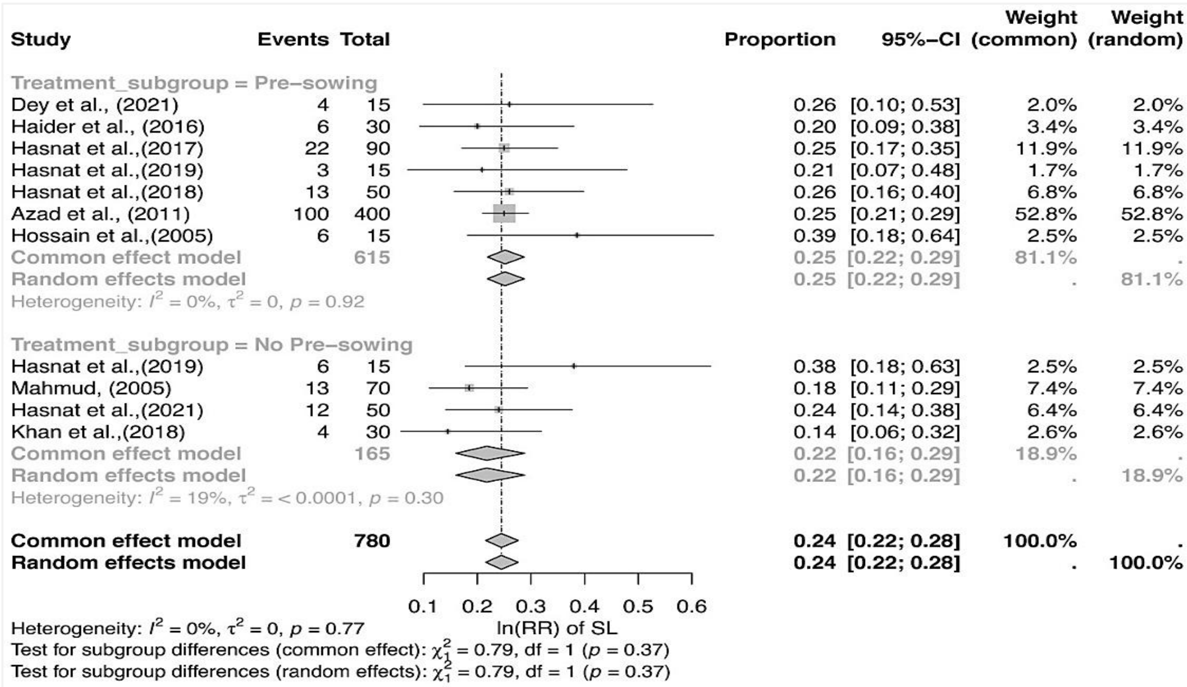

Figure 3. A meta-analysis employing a standardized measure (SM) termed effect size (EE) to assess the performance of Total length seedling (cm) at 2 months of age across studies (n=11, with 7 pre-sowing and 4 without pre-sowing). A dashed vertical line explained the line of no effect on the forest plot. The size of markers for point estimates in individual studies reflects the precision of the estimate, with error bars indicating 95% confidence intervals. The stretched diamond marker denotes the overall random effects estimate for each study alongside its 95% confidence intervals. Additionally, CI stands for Confidence Interval, and Q represents the I^2 -test of heterogeneity among the studies.

3.2. Publication metrics

This summary delves into a meta-analysis encompassing 17 studies, comprising a total of 1325 observations, with an estimated count of approximately 906.71 events. Due to considerable heterogeneity among the studies, the random effects model yields a slightly lower pooled proportion estimate of 0.65. The analysis reveals a notable level of heterogeneity, with an I^2 value of 92.2% and a *tau²* of 0.93. The Cochran's Q statistic is 3.85, indicating highly significant heterogeneity (p<0.0001), affirming that the observed variability is not merely by chance. Regarding Collar Diameter (CD), the I^2 value stands at 98.1%, with a Cochran's Q statistic of 7.21. For SL, the I^2 value is 0%, with a Cochran's Q statistic of 1 (P=0.77), suggesting negligible heterogeneity (Figure 5).

3.3. Subgroup Analysis

3.3.1. Common Effect Model

In the Common Effect (CE) model, the GP% proportion is 0.67 (n=16) for the subgroup with pre-sowing treatment and 0.70 (n=11), 0.52 (n=6) for the subgroup with no pre-sowing treatment. The treatment subgroups, pre-sowing (Q=137.80) and no pre-sowing (Q=45.87), exhibit distinct characteristics. For SL, both CE and RE show the same proportion of 0.24. Additionally, CE for pre-sowing and no pre-sowing treatment subgroups have proportions of 0.25 and 0.21, respectively. The comparison both between and within group's yields p-values of 0.37 and 0.77. In terms of

CD, the CE model reveals a mean difference of 3.85 cm, with a Z-score of 37.20 (P=0.0001, n=7). The comparison between subgroups and within groups also shows significant differences (P=0.0001) (Figure 3, 4, and 5).

3.3.2. Random Effects Model

In the Random Effects (RE) model, the GP% proportion (P=0.4377) differs between groups, with proportions of 0.67 for pre-sowing and 0.57 for no pre-sowing treatment. Similarly, for SL (P=0.37), the RE proportion differs between groups, with proportions of 0.25 for pre-sowing and 0.21 for no pre-sowing treatment. Regarding CD, the RE model reveals a mean difference of 3.96 cm and a Z-score of 3.86 (P=0.0001, n=7). The comparison between subgroups yields a significant difference (P=0.002).

3.4. Germination and Species

The highest number of observations was documented in Azad et al.'s research (2012), conducted at Khulna University. The findings from this study are particularly noteworthy, characterized by lower heterogeneity. The selected species for investigation in this research was *Albizia procera*, and pre-sowing treatment involved cold and hot water treatments. The University of Chittagong, encompassing the Institutes of Forestry and Environmental Sciences, contributed significantly to the study (n=9/17).

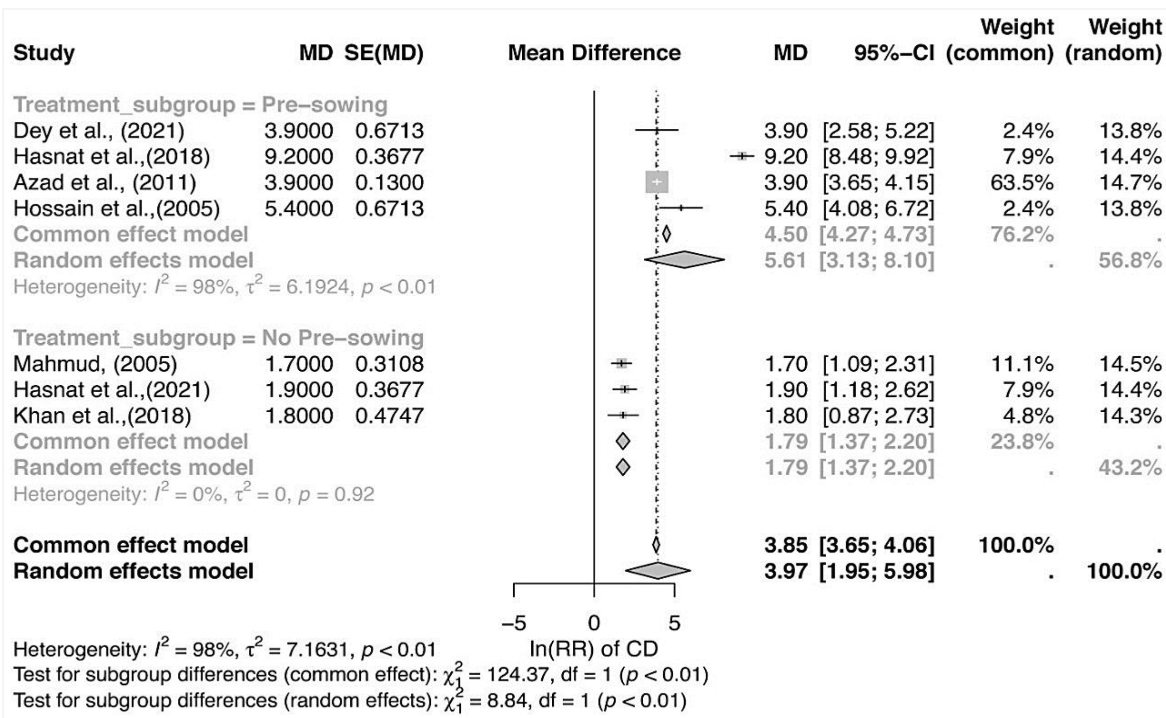

Figure 4. A meta-analysis utilizing a standardized measure called effect size to investigate Collar diameter (mm) performance across studies (n=7, with 4 pre-sowing and 3 without pre-sowing). The forest plot features a dashed vertical line representing the line of no effect. The size of markers for point estimates in individual studies correlates with the precision of the estimate, and error bars indicate 95% confidence intervals. The stretched diamond marker depicts each study's overall random effects estimate alongside its 95% confidence intervals. Additionally, CI denotes the Confidence Interval, and Q represents the I^2*-test* of heterogeneity among the studies.

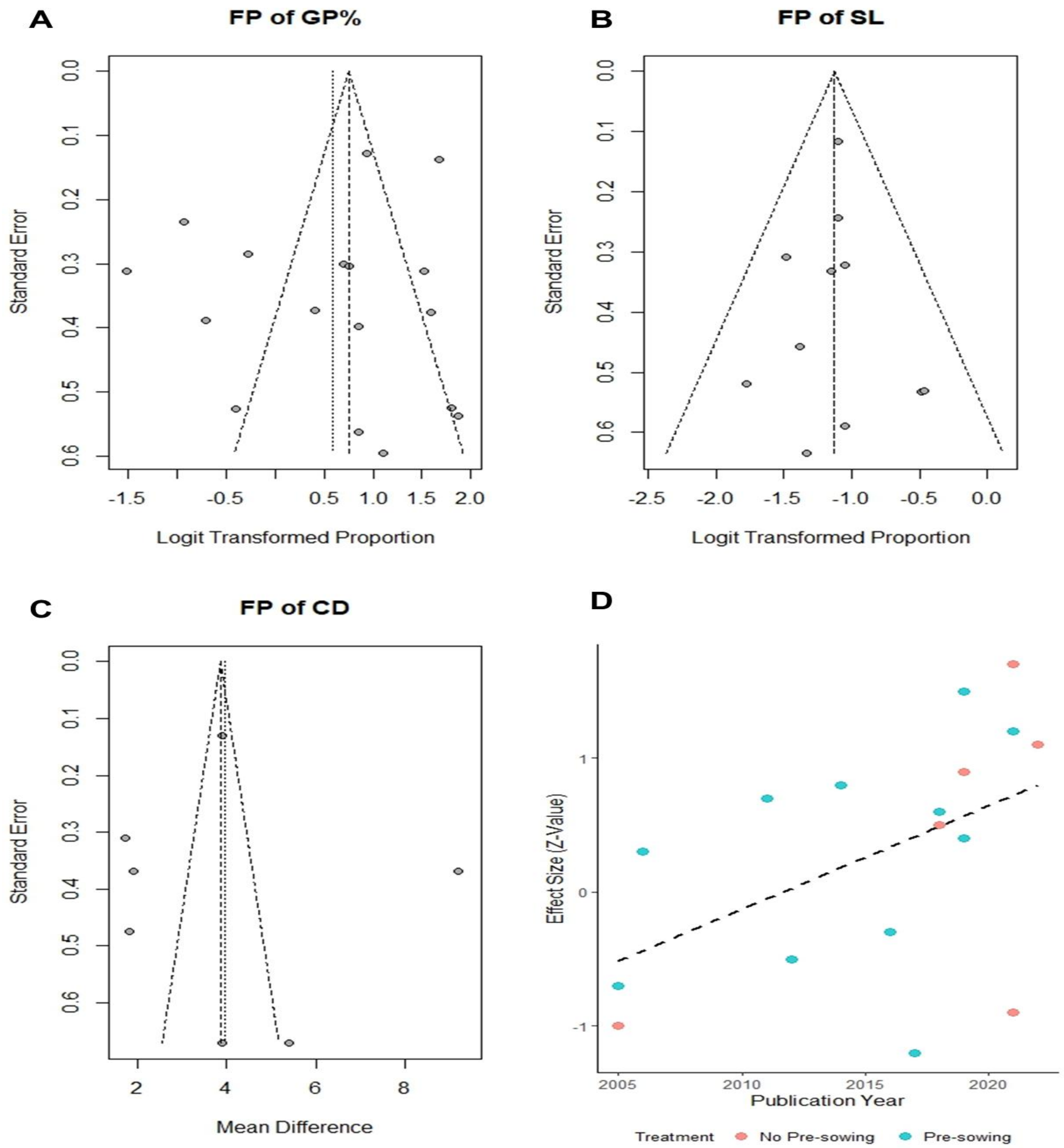

Figure 5. A) Germination percentages (GP%) are displayed using data from 17 articles. The articles are grouped according to whether they utilized pre-sowing treatments or not. B) Seedling length (SL) data is presented from 11 articles, with 7 utilizing pre-sowing treatments and 4 without pre-sowing treatments. C) Collar diameter (CD) data is shown from 7 articles, with 4 employing pre-sowing treatments and 3 without pre-sowing treatments. D) The plot likely depicts the effect size and publication year, indicating the relationship between the magnitudes of the effect observed in each study and the year in which the study was published.

Khulna University (Figure 5-D), specifically within the Forestry and Wood Technology discipline, also offered a conducive environment for forest research (n=3/17). In the case of pre-sowing treatments (n=11/17), their prevalence was apparent. Water treatments, including water shocking (n=6/17), and temperature applications (n=8/17), involving both cold and hot water treatments, were commonly utilized. Chemical treatments (n=6/17), such as the application of hydrochloric acid and sulfuric acid at varying concentrations, were relatively rare in pre-sowing treatments in Bangladesh. The mean number of observations considered in this meta-analysis was 62.7. The selected publication time frame spanned from 2000 to 2010 (n=3/17), with a notable increase in articles considered from 2010 to 2020 (n=10/17). Articles from 2021 to the present constituted the remainder (n=4/17). These findings highlight that different pre-sowing treatments effectively break seed dormancy attributed to hard seed coats. Additionally, they contribute valuable insights into various sowing treatments. Studies without pre-sowing treatments also offer diverse information, including details about media composition (e.g., a 1:3 ratio of dung and soil) and methods for pre-sowing seeds in germination media, influencing changes in germination percentages (Figure 2, 3, and 4).

4. Discussion

The meta-analysis revealed significant heterogeneity (I^2 = 92.2%) and varied effectiveness of pre-sowing treatments on seed germination, particularly for seeds with hard coats. Pre-sowing treatments, such as cold and hot water treatments (Azad et al., 2012), significantly enhance germination percentages, aligning with findings from regional studies in Bangladesh (Haider et al., 2016; Hasnat et al., 2019). This substantial variability in treatment efficacy can be attributed to differences in treatment methods, seed types, and ecological factors, suggesting the need for context-specific adaptations and standardized approaches to optimize results across diverse environments. Pre-sowing treatments notably improve seed germination percentages, with significant enhancements observed for hard-coated seeds. Cold and hot water treatments are particularly effective, demonstrating increased germination percentages that underscore their potential for application in forestry and conservation projects. These treatments enhance the seed's ability to overcome dormancy and improve overall germination success, aligning with findings from regional research institutions (Dey et al., 2022; Haider et al., 2016), which highlight localized expertise as crucial for advancing global biodiversity conservation efforts.

Despite the overall positive outcomes, the significant heterogeneity highlights the imperative for further research to standardize pre-sowing treatment methods. The presence of notable bias, evident in the asymmetry observed in funnel plots and the results of Egger's test, raises concerns about publication bias, echoing similar issues previously observed in forestry research. This suggests that smaller-scale studies (Hasnat et al., 2019) may disproportionately influence the overall estimation of effect size. The variability in effectiveness indicates that ecological factors and specific treatment protocols play pivotal roles in determining outcomes. Therefore, future studies should prioritize expanding the diversity of studied species, increasing the number of observations, and validating laboratory findings in field conditions. These steps are crucial for bridging the gap between experimental efficacy and practical application in forestry and conservation.

The significant role of regional research institutions in conducting these studies highlights the potential for localized expertise to contribute to global biodiversity conservation efforts. By leveraging local knowledge and adapting pre-sowing treatments to specific ecological contexts, these institutions can enhance the effectiveness of reforestation strategies and ecological restoration practices (Mahmud, 2005). This research not only provides valuable insights into the germination process but also paves the way for improving reforestation strategies and ecological restoration practices, ultimately contributing to more effective and sustainable biodiversity conservation efforts. Pre-sowing treatments have demonstrated considerable potential in enhancing seed germination, particularly in the context of forestry and ecological restoration. Significant improvements in germination rates were observed, with cold and hot water treatments effectively breaking seed dormancy. This aligns with findings from similar studies, such as those by Hossain et al. (2020) and Rahman et al. (2019), who reported increased germination success with these methods. The role of regional research institutions, such as the Bangladesh Forest Research Institute, has been pivotal in adapting these treatments to local species and conditions, underscoring the importance of localized expertise. However, the meta-analysis also identified significant variability in the outcomes of pre-sowing treatments, highlighting the need for further research to refine these methods. This variability is likely due to differences in treatment duration, water temperature, seed coat thickness, and ecological conditions. Future research should focus on standardizing treatment protocols and expanding studies to include a broader range of species and environmental conditions (Uddin et al., 2020). Additionally, validating laboratory findings in field settings is crucial to ensure the practical applicability of these treatments in large-scale reforestation and restoration projects. The findings of this meta-analysis underscore the importance of pre-sowing treatments in enhancing seed germination, with significant implications for forestry and biodiversity conservation (Hossain et al., 2020; Rahman et al., 2018). By improving the germination percentages of hard-coated seeds, these treatments can facilitate the establishment of robust plant populations, contributing to the success of reforestation and restoration initiatives. The involvement of regional research institutions in these studies highlights the potential for localized knowledge to inform global conservation strategies, ensuring that pre-sowing treatments are tailored to the specific needs of different species and ecosystems.

5. Conclusion

This meta-analysis synthesizes findings from 17 studies to evaluate the impact of pre-sowing treatments on the germination of various forest species, including *Albizia procera*, within the context of Bangladesh. The studies demonstrate that mechanical, temperature-related, and chemical pre-sowing methods significantly improve germination percentages, crucial for successful forest restoration and conservation projects. Despite a high degree of heterogeneity, indicating complex ecological interactions, both common and random effects models show positive outcomes, boosting germination percentages and enhancing seedling growth metrics like seedling length and collar diameter. The consistent improvements in germination outcomes highlight the effectiveness of these treatments in overcoming dormancy barriers. The geographical focus on Bangladesh offers valuable insights for tropical and subtropical reforestation efforts, emphasizing the need for localized research strategies. The meta-analysis also reveals a concentration of research within academic institutions, suggesting robust pre-sowing practices but indicating a need to expand the research base to diverse ecological and geographical contexts.

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