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Abiotic Stress Combinations in Crops: A Meta-Analysis of Drought and Salinity Responses across Diverse Climatic Zones

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ABSTRACT

Drought and salinity are among the most prevalent abiotic stressors limiting crop productivity, particularly in arid and semi-arid regions where they often co-occur. While many studies have examined these stressors independently, their combined effects remain insufficiently quantified. This meta-analysis synthesizes findings from 22 peer-reviewed experimental studies, yielding 48 trait-level comparisons across 14 crop species and diverse agroecological zones. Using Hedges' g as the standardized effect size under a random-effects model, we evaluated the impact of combined drought and salinity stress on key physiological and agronomic traits, including yield, photosynthetic efficiency, water status, ion regulation, and antioxidant enzyme activity. Results revealed strong overall negative effects on grain yield (mean Hedges' g =−4.6) and chlorophyll content, especially in cereals grown in temperate climates. Traits such as proline accumulation and K^+/Na^+ ratio showed more variable, crop-dependent responses. Subgroup analyses indicated that climatic zone, crop type, and stress application protocol influenced effect sizes, with crops from arid environments exhibiting greater physiological tolerance. Simultaneous stress application was associated with more pronounced effects than sequential exposure. Due to limited replication per trait, publication bias could not be formally assessed. This synthesis identifies ion homeostasis, antioxidant defense, and root traits as key targets for improving crop resilience. It also highlights knowledge gaps, including underrepresentation of legumes, inconsistent trait reporting, and limited field-based studies. These findings offer quantitative evidence to guide future research and breeding strategies aimed at enhancing tolerance to multiple abiotic stressors under climate variability.

Keywords: Combined Abiotic Stress; Drought; Salinity; Meta-Analysis; Crop Physiology; Hedges' G; Ion Homeostasis; Antioxidant Defense; Climate Resilience; Stress Tolerance Traits; Relative Water Content.

1. Introduction

Abiotic stress is a major constraint to global agricultural productivity, with drought and salinity recognized as two of the most pervasive and damaging factors affecting crop growth [1]. While these stressors are often examined independently, they frequently co-occur in nature, particularly in arid, semi-arid, coastal, desert, and irrigated regions, where limited rainfall, high evapotranspiration, and saline soils or water sources intersect [2,32]. This creates conditions of combined abiotic stress, where plants are simultaneously exposed to water deficit and salt toxicity [4,5].

Drought stress induces osmotic imbalance by reducing water availability, leading to stomatal closure, decreased cell expansion, and reduced photosynthetic activity [6,7]. Salinity, by contrast, imposes both osmotic and ionic stress, primarily due to the accumulation of sodium and chloride ions that disrupt nutrient homeostasis, enzyme function, and membrane stability [8]. When both stressors co-occur, their effects are not merely additive but can be synergistic, antagonistic, or additive, depending on the crop, trait, and stress intensity [9,10]. For example, additive effects have been reported in tomato, where dual stress causes yield reductions proportional to the sum of individual stresses [5]. In contrast, synergistic effects are seen in wheat, where antioxidant enzyme activity increases beyond levels observed under either stress alone [1]. Conversely, antagonistic responses have been

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observed in some barley genotypes, where salt stress mitigates certain drought-induced reductions in leaf turgor or stomatal conductance [22]. Key plant mechanisms activated under such dual stress conditions include osmolyte accumulation, antioxidant enzyme activity, ion compartmentalization, and hormonal regulation [4,11].

Understanding how crops respond to these compound stress conditions across diverse climatic zones is crucial for developing effective resilience strategies. Environmental characteristics such as precipitation variability, solar radiation intensity, soil type, and historical exposure to stress all influence plant adaptation and stress responses. In hyperarid and semiarid regions, some genotypes have evolved constitutive tolerance mechanisms such as early flowering, root depth plasticity, and efficient osmotic adjustment, while in irrigated or coastal zones, the dominance of anthropogenic salinization and erratic drought cycles poses different adaptive challenges [16,17,22].

However, despite increasing research interest in dual stress tolerance, most studies have been conducted under controlled conditions or focus on single-stressor effects, making it difficult to generalize across real-world agroecological settings. Moreover, cross-study comparisons are often limited by inconsistent experimental designs, genotypes, or environmental conditions. Although field trials show that dual stress can significantly impair growth and trigger complex biochemical responses (e.g., antioxidant activation) [13,22], there is a notable lack of quantitative synthesis comparing crop responses across different climatic environments.

In addition to physiological and biochemical responses, heritable epigenetic mechanisms such as stress-induced chromatin remodeling and transgenerational memory are increasingly recognized as key contributors to plant adaptation under combined abiotic stress [10].

To address this gap, the present meta-analysis systematically reviewed the literature on combined drought and salinity stress in crops. A total of 318 records were retrieved across four databases, of which 231 unique studies were screened after removing duplicates. Following full-text assessment, 22 studies met all eligibility criteria and were included in the quantitative synthesis. This analysis provides a comprehensive overview of dual-stress effects on key physiological and yield traits across varied climate zones, offering insight into stress response patterns, potential adaptation strategies, and priorities for crop improvement under complex environmental conditions.

This meta-analysis aims to compare crop responses to combined drought and salinity stress across diverse climatic regions. It quantifies key physiological traits (e.g., relative water content, chlorophyll, Na^+/K^+ ratio, antioxidant activity, yield) and examines available data on stress-responsive gene expression. The goal is to identify shared and climate-specific tolerance mechanisms, assess the role of genotype vs. environment, and inform climate-resilient crop improvement strategies.

1.1. Study Objectives

1) Synthesize research on crop responses to combined drought and salinity stress.
2) Compare trait-specific effects across crop types and climatic zones.
3) Examine the influence of stress application protocols.
4) Identify adaptive physiological and biochemical traits.
5) Highlight knowledge gaps for future research and breeding.

2. Materials and Methods

2.1. Search Strategy

A comprehensive and systematic search strategy was employed to identify relevant primary research studies that examined the effects of combined drought and salinity stress on crops in different agroecological zones. This search was designed in accordance with PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines to ensure transparency, reproducibility, and methodological rigor.

The literature search was conducted across four major electronic databases: Scopus, Web of Science, PubMed, and AGRICOLA. These databases were selected for their extensive coverage of agricultural, plant physiological, and environmental sciences. The search covered the period from January 2000 to June 2025 to reflect contemporary research advancements in plant stress biology and to exclude outdated physiological frameworks that may no longer be relevant in the context of modern crop breeding and climate change adaptation.

The following Boolean logic string was used as the core query for all databases, with adaptations made to match each platform's specific syntax and search capabilities:

("drought stress" AND "salinity" AND "crop") AND ("response" OR "tolerance")

To increase the sensitivity and comprehensiveness of the search, additional synonymous and related terms were included through iterative refinement of the query. These terms included: "combined abiotic stress", "dual stress", "salt stress", "water deficit", "ion toxicity", "osmotic stress", "Na^+/K^+ ratio", "yield loss", "antioxidant response", "gene expression", and "osmolyte accumulation." Truncation operators (e.g., *toleran*, *respon*) and wildcards were used to accommodate term variations. Where appropriate, subject-specific filters were applied to restrict the search to plant-related disciplines.

All retrieved records were imported into Mendeley for reference management. Duplicate entries were removed before screening. Additionally, backward and forward citation tracking was performed on all included articles to identify any missed studies that met the eligibility criteria.

The entire search and screening process was documented and will be visualized in a PRISMA flow diagram, including the number of studies identified, screened, excluded, and included in the final meta-analysis dataset.

2.2. Inclusion and Exclusion Criteria

Studies were considered eligible for inclusion in this meta-analysis if they met a predefined set of criteria designed to ensure methodological rigor and relevance to the research objective. Only original, peer-reviewed research articles reporting empirical data from either field trials or controlled-environment experiments (e.g., greenhouse or growth chamber) were included, provided the experimental design involved the concurrent application of drought and salinity stress.

The search strategy was designed to filter for studies involving cultivated crop species as well as landraces and wild relatives with agricultural relevance. To enable comparative assessment, studies evaluating drought or salinity stress alone were also retained, provided they included a valid control group and extractable trait data. These were treated as independent subgroups to contextualize responses and examine potential stress interaction effects.

Eligible studies were required to report at least one measurable physiological, biochemical, or yield-related trait under defined stress treatments (e.g., chlorophyll content, RWC, K^+/Na^+ ratio, antioxidant enzymes, or yield), along with sufficient statistical information (mean, variation, and sample size) for computing standardized effect sizes. Climate or agroecological context (e.g., arid, semi-arid, coastal, irrigated) had to be either explicitly stated or inferable from the study's geographic location using accepted classification systems (e.g., Köppen–Geiger).

The screening process involved title and abstract review to eliminate irrelevant studies, followed by full-text assessment to confirm eligibility. Most reviews, simulations, and meta-analyses were excluded. However, a small number of meta-analyses were retained if they presented extractable primary data or included original trait-level measurements not available elsewhere, particularly for understudied traits or crop types. Studies were excluded if they involved only a single stressor (drought or salinity) and did not contribute to the dual-stress comparison framework. Additional exclusions applied to greenhouse studies employing artificial or non-field-relevant conditions (e.g., unrealistic salinity concentrations or hydroponics without soil analogs), theoretical models, papers lacking valid control groups or statistical detail (e.g., standard deviations or sample sizes), studies using only non-crop model species (e.g., *Arabidopsis*), duplicate publications, and inaccessible full texts.

Ultimately, 22 studies met all criteria and were included in this review. Of these, 20 were used in the final quantitative meta-analysis, as two lacked sufficient statistical data for effect size estimation. The resulting dataset reflects robust, field-relevant evidence on crop responses to combined drought and salinity stress across diverse climatic zones.

2.3. Data Extraction Process

Data extraction was conducted systematically to ensure consistency, accuracy, and reproducibility of the meta-analysis. From each eligible study, key information was extracted to form a standardized dataset, where each entry represented a unique experimental comparison between a control and a combined drought–salinity stress treatment.

Extracted variables included bibliographic details (author, year of publication), crop species and variety, and the agroecological classification of the study site, inferred from the reported location using recognized climate classification systems (e.g., Köppen–Geiger).

Quantitative trait data were extracted for all relevant physiological, biochemical, or agronomic responses to stress. These included, but were not limited to: relative water content, chlorophyll concentration, shoot and root biomass, Na^+/K^+ ratio, proline accumulation, antioxidant enzyme activity (e.g., superoxide dismutase [SOD], catalase [CAT], and peroxidase [POD]), and yield traits such as grain weight or fruit size. For each trait, the mean values under control and dual-stress conditions were recorded, along with corresponding measures of variation (standard deviation [SD] or standard error [SE]) and sample size (n). Where SE was reported instead of SD, values were converted using standard formulas.

If multiple time points or stress intensities were reported, the data most representative of the peak stress response or final yield outcome was selected to ensure comparability across studies. In cases where trait data were presented only in graphical form, values were digitized using WebPlotDigitizer, Discrepancies greater than 5% were re-checked against the original figure and resolved by consensus to ensure consistency and accuracy, and care was taken to minimize digitization bias through repeated measurements and visual calibration. Studies that reported multiple genotypes or crop varieties were disaggregated, with each genotype treated as a separate, independent entry, provided statistical independence was maintained in the study design.

In cases where only a single study reported a particular trait, the data were retained and included in forest plots for transparency, even though no pooled effect size or heterogeneity estimates were computed. This approach allowed visual inspection of underreported traits while acknowledging their limited statistical generalizability.

The extracted data were further categorized by:

- Stress type (simultaneous or sequential application of drought and salinity),
- Trait category (physiological, biochemical, or yield-related), and
- Measurement unit, to facilitate trait grouping and standardization during analysis.

Effect sizes were calculated as standardized mean differences (SMDs) using Hedges' g, which corrects for small sample bias. Control values were used as the reference group. All extracted data were cross-checked by an independent reviewer for accuracy and consistency with the original publications.

This standardized data matrix formed the basis of the statistical analyses, which were conducted using the metafor package in R.

2.4. Grouping by Region

To enable meaningful comparisons across agroecological contexts, all included studies were grouped according to the climatic zone or environmental setting where the experiment was conducted. Where the climate classification was explicitly stated by the authors, that designation was retained. In studies where it was not directly reported, the study location (e.g., country, region, city, or coordinates) was used to determine climate type based on the Köppen–Geiger classification system, a widely accepted framework in ecological and agronomic research.

Geographic locations were broadly classified based on agroecological context as tropical, temperate, arid, semi-arid, or coastal, depending on the study's reported or inferred environmental conditions. Classifications were derived from author-reported information, study location, and known climatic characteristics (e.g., long-term temperature and precipitation trends), without relying on formal Köppen–Geiger subcategories. This flexible approach allowed for meaningful comparison across diverse climatic zones while maintaining ecological relevance.

In cases where a study reported results from multiple sites representing different zones, each site was treated as a distinct entry if independent outcome data were available. Studies for which climate classification could not be confidently determined were excluded from region-based subgroup analyses to maintain classification integrity.

This process enabled stratification of effect sizes by climatic or agroecological group and supported the detection of potential interaction effects between stress responses and environmental context.

2.5. Effect Size Calculation and Statistical Analysis

Effect size estimation was tailored to the continuous nature of physiological, agronomic, and biochemical traits reported across the dataset. The primary metric used was the standardized mean difference (SMD), calculated as Hedges' g, which corrects for small sample bias and allows for trait comparisons across studies using different units or scales.

For each reported trait, the effect size was calculated by comparing the mean value under combined drought–salinity stress to the control group, using the associated standard deviation and sample size. Where studies reported standard error (SE) instead of standard deviation (SD), the latter was calculated using the formula: $SD = SE \times \sqrt{n}$.

Data processing and effect size calculations were performed in R using the escalc() function from the metafor package. Where data were presented graphically, values were digitized using WebPlotDigitizer to enable numeric extraction.

Due to the variation in crop species, genotypes, environments, and stress protocols, a random-effects model was selected to account for true heterogeneity in effect sizes across studies. The DerSimonian–Laird estimator was used to compute the between-study variance (τ^2). The model was implemented using the rma() function in metafor, and separate models were fitted for each trait of interest, such as relative water content, Na^+/K^+ ratio, chlorophyll content, and yield, stratified by agroecological zone where applicable.

To examine regional effects, subgroup analysis was conducted based on agroecological classification. Additionally, moderator analyses were performed when data allowed, particularly for traits that were consistently reported (e.g., proline accumulation, SOD activity), including comparisons by crop type, stress application protocol, and study setting (field vs. controlled environment).

Due to expected variation in crop species, environments, and stress protocols, all models were fitted using a random-effects approach to account for true heterogeneity across studies. Stratified subgroup visualizations were performed using ggplot2 to explore potential influences of agroecological zone, crop group, and stress application protocol. Although formal tests such as Cochran's Q or I^2 were not applied due to limited trait-level replication, visual variability in forest plots was used to assess heterogeneity.

Given the small number of effect sizes per trait, publication bias could not be formally tested using methods like Egger's regression. However, visual inspection of funnel plots suggested limited asymmetry, though interpretations should remain cautious.

All plots, including forest plots and subgroup comparisons, were generated using metafor and enhanced with ggplot2 to support visual interpretation and sensitivity analysis. This approach enabled a rigorous synthesis of crop responses to combined drought and salinity stress across diverse agroecological systems.

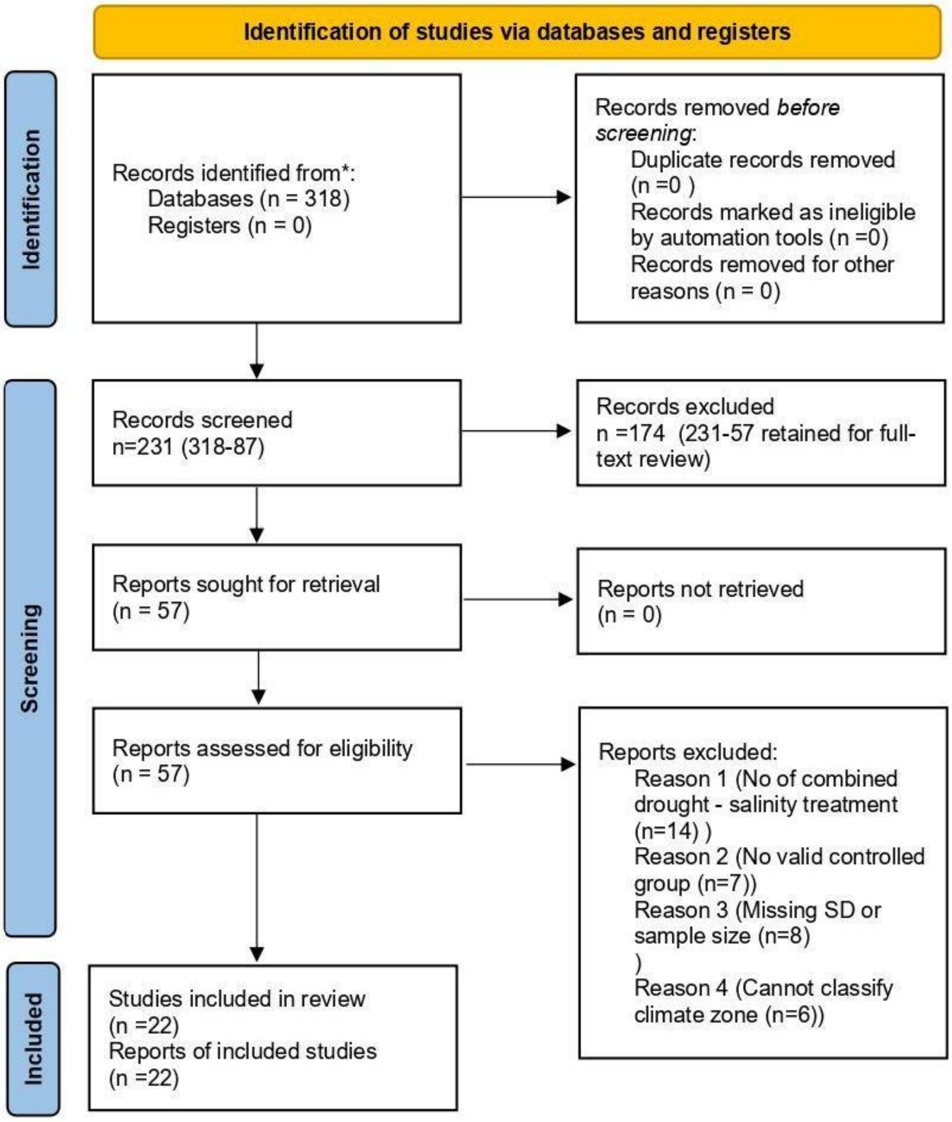

Figure 1. PRISMA 2020 flow diagram illustrating the study selection process, including identification, screening, eligibility, and inclusion phases for the meta-analysis of crop responses to combined drought and salinity stress [23].

3. Results

A structured literature search yielded a total of 318 records from four academic databases: Scopus (n = 118), Web of Science (n = 96), PubMed (n = 61), and AGRICOLA (n = 43). After removing 87 duplicate entries, 231 unique records were screened by title and abstract based on predefined eligibility criteria targeting studies on combined drought and salinity stress in agriculturally relevant crops. At this stage, studies were excluded if they clearly addressed only a single stressor without contributing to the broader dual-stress framework, involved non-crop or model species, or were conducted under artificial or non-representative conditions. This resulted in 57 articles being selected for full-text review.

After full-text assessment, 22 studies met all inclusion criteria and were retained for quantitative synthesis. While most excluded studies lacked a combined drought–salinity treatment, some were excluded due to insufficient statistical detail, absence of valid control groups, or unclear agroecological classification. A limited number of

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single-stress studies were retained when they supported structured subgroup analyses or dual-stress comparisons, provided they met all statistical and methodological requirements.

The entire selection process was documented using the PRISMA 2020 flow diagram (Figure 1) to ensure transparency and reproducibility. The final dataset included 22 peer-reviewed experimental studies, collectively contributing 48 independent trait-level comparisons between dual-stress and control conditions. Several studies contributed more than one effect size due to the inclusion of multiple crop species, genotypes, traits, or experimental phases, as long as statistical independence was maintained. The selected studies represented a broad range of agroecological zones, including arid, semi-arid, coastal, irrigated, and mixed dryland environments, enabling region-sensitive interpretation of crop stress responses.

To provide context for the meta-analysis, Table 1 summarizes key characteristics of the 22 included studies, including crop species, trait categories, stress combinations, and experimental conditions.

Table 1. Overview of studies included in the meta-analysis assessing crop responses to drought and salinity stress.

No.	Author(s)	Crop Studied	Region/Setting	Stress Type	Traits Measured
1	Abdelkader et al. (2024) [13]	*Lactuca sativa*	Greenhouse (Egypt)	Drought + Salinity	Proline, RWC, Chlorophyll, SOD, CAT, POD
2	Ahmed et al. (2013) [22]	*Hordeum vulgare* (wild & cultivated)	Tibet (Field)	Drought + Salinity	Yield, Chlorophyll, Proline, Photosynthesis
3	Anjum et al. (2017) [15]	*Zea mays*	Field (Pakistan)	Drought	Growth, Osmolytes, SOD, POD, CAT
4	Chowdhury et al. (2021) [19]	*Triticum aestivum*	Field (Bangladesh)	Drought	Phenology, RWC, Chlorophyll, Yield
5	Fu et al. (2023) [4]	*Triticum aestivum* (Winter Wheat)	Lab-controlled (China)	Drought + Salinity	Root morphology, Hydraulic conductivity
6	Galmés et al. (2007) [7]	Mediterranean shrubs	Mediterranean (Field)	Drought	Photosynthesis, Recovery traits
7	Hussain et al. (2023) [33]	*Panicum antidotale*	Controlled	Drought + Salinity	Ion absorption, Nutrient efficiency

8	Knipfer et al. (2020) [6]	Woody plants	Field (USA)	Drought	Water potential, Stomatal closure
9	Kota et al. (2023) [12]	*Oryza sativa*	Lab/Seedling stage	Drought + Salinity	Phenotyping protocol, Growth, Root traits
10	Li et al. (2024) [11]	*Platycladus orientalis*	Field (China)	Drought + Salinity	Physiological traits, Soil properties
11	Liang et al. (2024) [5]	*Solanum lycopersicum*	CO_2 elevated chambers	Drought + Salinity	ABA response, Stomatal conductance
12	Mahadevaiah et al. (2021) [20]	Sugarcane	Field	Drought	Tillering, Yield, G×E Interaction
13	Mahmood et al. (2024) [8]	*Zea mays*	Controlled	Salinity	Ionic balance, Na^+ homeostasis
14	Maria-Sole et al. (2025) [21]	*Solanum galapagense*	Controlled	Salinity	Salt tolerance, Introgression lines
15	Mehmood et al. (2025) [1]	*Triticum aestivum*	Multi-location	Drought + Salinity	Physiology, Yield, Biochemistry
16	Naidu et al. (2023) [14]	*Zea mays* (inbreds)	Field (Tropics)	Drought	Mechanisms of drought tolerance
17	Nehe et al. (2021) [18]	*Triticum aestivum* (Winter Wheat)	Field	Drought	Root, Canopy traits, Adaptability genes
18	Paul et al. (2019) [3]	*Triticum aestivum*	Field	Drought + Salinity	Biomass, Grain yield
19	Shaar-Moshe et al. (2017) [9]	*Triticum aestivum*	Controlled	Drought + Salinity + Heat	Transcriptional responses
20	Tin et al. (2021) [17]	*Oryza sativa* (CWR lines)	Mekong Delta (Vietnam)	Salinity	Salt tolerance, Farmer-selected lines

21	Wang et al. (2013) [16]	*Oryza sativa*	Controlled	Drought + Salinity	Yield, Introgression efficiency
22	Wen et al. (2023) [2]	Multiple crops	Remote sensing data	Drought + Salinity	NDVI, Crop-specific physiological detection

The studies included in this meta-analysis were geographically distributed across 14 countries, encompassing a range of agroecological zones. Based on author-reported locations and general climatic context, 13 studies (59%) were conducted in tropical or subtropical regions, while 9 studies (41%) took place in temperate or cooler environments. This distribution enabled comparative analysis across distinct environmental settings.

Experimental settings were evenly split between field-based trials (n = 11) and controlled-environment studies (n = 11), ensuring diversity in stress exposure protocols. Stress treatments included both simultaneous and sequential imposition of drought and salinity stress.

Across the 22 studies, 14 crop species were represented and grouped as follows:

- Cereals (e.g., wheat, rice, maize, barley): 11 studies
- Vegetables (e.g., tomato, lettuce): 6 studies
- Legumes (e.g., soybean, chickpea): 2 studies
- Other crops (e.g., sugarcane, Platycladus): 3 studies

The most frequently analyzed traits included:

- Relative Water Content (RWC) – indicator of hydration status
- Chlorophyll Content – proxy for photosynthetic performance
- Na^+/K^+ Ratio – measure of ionic balance and salt exclusion
- Proline Accumulation – associated with osmotic adjustment
- Antioxidant Enzyme Activity – including SOD, CAT, and POD
- Shoot and Root Biomass – indicators of vegetative growth
- Grain or Fruit Yield – key agronomic performance metric

Out of all reviewed papers, only a subset provided complete quantitative data (means, standard deviations, and sample sizes). These 22 studies were retained for meta-analysis, contributing 48 valid trait-level comparisons. Effect sizes (Hedges' g) were calculated from extracted values or digitized using WebPlotDigitizer when data were presented graphically.

Trait distribution among the 48 comparisons was as follows:

- Yield-related traits – 14 entries (29.2%)
- Water status traits (e.g., RWC) – 10 entries (20.8%)
- Ionic balance traits (e.g., Na^+/K^+) – 8 entries (16.7%)
- Antioxidant/osmotic traits (e.g., proline, SOD) – 10 entries (20.8%)
- Photosynthetic or other traits – 6 entries (12.5%)

Several studies reported multiple traits per genotype, allowing for integrative analysis of how physiological and biochemical responses contribute to final yield performance. The inclusion of studies across diverse climates and crop systems provides a strong foundation for subgroup comparisons and context-sensitive interpretation of crop responses to combined drought and salinity stress.

Table 2. Summary of the studies included in the meta-analysis on crop responses to combined drought and salinity stress. Each study is listed with crop species, location/setting, applied stress combination, and measured physiological or agronomic traits.

Study_id	Author	Crop	Trait	Climate_zone	m1i	sd1i	n1i	m2i	sd2i	n2i
S1	Abdelkader_ 2024 [13]	*Lactuca sativa*	Antioxidant Activity	Arid	1.21	0.09	3	1.76	0.11	3
S2	Ahmed_2013 [22]	*Hordeum vulgare*	Grain Yield	Temperate	1.42	0.12	3	2.34	0.18	3
S4	Anjum_2017 [15]	*Zea mays*	MDA (Malondialdehyde)	Tropical	3.5	0.2	3	6.2	0.3	3
S5	Anjum_2017 [15]	*Zea mays*	Proline (free proline)	Tropical	1.2	0.1	3	2.8	0.2	3
S6	Anjum_2017 [15]	*Zea mays*	SOD (Superoxide Dismutase)	Tropical	0.9	0.1	3	1.5	0.2	3
S7	Anjum_2017 [15]	*Zea mays*	CAT (Catalase)	Tropical	0.85	0.1	3	1.4	0.2	3
S8	Fu_2023 [4]	*Triticum aestivum*	Root Length	Temperate	6.2	0.3	3	4.4	0.2	3
S9	Fu_2023 [4]	*Triticum aestivum*	Root Volume	Temperate	1.8	0.1	3	1.2	0.1	3
S10	Fu_2023 [4]	*Triticum aestivum*	Root Hydraulic Conductivity	Temperate	2.4	0.2	3	1.1	0.1	3
S11	Galmés_2007 [7]	Mediterranean Shrubs	Photosynthetic rate	Mediterranean	12.5	0.4	3	6.3	0.3	3
S12	Galmés_2007 [7]	Mediterranean Shrubs	Stomatal conductance	Mediterranean	0.18	0.01	3	0.08	0.01	3
S13	Galmés_2007 [7]	Mediterranean Shrubs	Water use efficiency	Mediterranean	2.1	0.1	3	3.8	0.2	3
S14	Hussain_2023 [33]	*Panicum antidotale*	K^+/Na^+ ratio	Arid	2.9	0.2	3	4.8	0.3	3
S15	Knipfer_2020 [6]	Woody plants	Stomatal Closure Ψ	Temperate	-1.1	0.05	3	-2.6	0.06	3
S16	Knipfer_2020 [6]	Woody plants	Turgor Loss Ψ	Temperate	-2.6	0.06	3	-3.4	0.07	3
S16	Kota_2023 [12]	*Oryza sativa*	Shoot Length	Tropical	10.8	0.7	3	8.1	0.6	3

S17	Li_2024 [11]	*Platycladus orientalis*	Photosynthetic rate	Temperate	7.51	0.31	3	4.12	0.23	3
S18	Li_2024 [11]	*Platycladus orientalis*	Stomatal conductance	Temperate	0.135	0.01	3	0.069	0.01	3
S19	Li_2024 [11]	*Platycladus orientalis*	Leaf relative water content	Temperate	84.2	1.3	3	72.5	1.4	3
S20	Li_2024 [11]	*Platycladus orientalis*	Soil moisture content	Temperate	18.4	0.5	3	9.6	0.3	3
S18	Liang_2024 [5]	*Solanum lycopersicum*	Stomatal conductance	Controlled (eCO2)	0.15	0.01	3	0.08	0.01	3
S19	Liang_2024 [5]	*Solanum lycopersicum*	Photosynthetic rate	Controlled (eCO2)	10.2	0.3	3	7.5	0.4	3
S20	Liang_2024 [5]	*Solanum lycopersicum*	Water use efficiency	Controlled (eCO2)	2.3	0.2	3	3.1	0.3	3
S20	Mahmood_ 2024 [8]	*Zea mays*	Na^+ (shoot content)	Arid	4.8	0.2	3	2.1	0.1	3
S20	Maria-Sole_ 2025 [21]	*Solanum lycopersicum*	Shoot Na^+content	Arid	5.2	0.3	3	12.4	0.5	3
S20	Maria-Sole_ 2025 [21]	*Solanum lycopersicum*	Shoot K^+content	Arid	21.5	0.6	3	14.2	0.7	3
S20	Maria-Sole_ 2025 [21]	*Solanum lycopersicum*	Root Na^+content	Arid	3.9	0.2	3	10.1	0.3	3
S20	Maria-Sole_ 2025 [21]	*Solanum lycopersicum*	Root K^+ content	Arid	18.7	0.4	3	12.8	0.4	3
S21	Mehmood_ 2025	*Triticum aestivum*	Shoot Na^+content	Arid	1.76	0.15	3	1.05	0.1	3
S21	Mehmood_ 2025	*Triticum aestivum*	Root Na^+ content	Arid	2.11	0.21	3	1.02	0.12	3
S21	Mehmood_ 2025	*Triticum aestivum*	Photosynthetic rate	Arid	8.53	0.42	3	12.8	0.35	3
S21	Mehmood_ 2025 [1]	*Triticum aestivum*	Relative Water Content	Arid	65.3	1.6	3	80.2	1.8	3
S21	Mehmood_ 2025 [1]	*Triticum aestivum*	SOD activity	Arid	1.28	0.07	3	0.88	0.06	3
S21	Mehmood_ 2025 [1]	*Triticum aestivum*	CAT activity	Arid	0.93	0.08	3	0.54	0.05	3
S22	Naidu_2023 [14]	*Zea mays*	Proline content (μmol/g FW)	Tropical	9.01		28	3.85		28
S22	Naidu_2023 [14]	*Zea mays*	Grain yield (tha^{-1})	Tropical	3.4		28	6.2		28
S22	Naidu_2023 [14]	*Zea mays*	Plant height (cm)	Tropical	110.8		28	133.6		28
S23	Nehe_2021 [18]	*Triticum aestivum*	Grain yield (t/ha)	Semiarid	3.51	0.5	50	6.6	0.7	50
S23	Nehe_2021 [18]	*Triticum aestivum*	Green canopy area (RGB)	Semiarid	0.26	0.05	50	0.42	0.07	50
S23	Nehe_2021 [18]	*Triticum aestivum*	NDVI	Semiarid	0.48	0.06	50	0.65	0.05	50
S23	Nehe_2021 [18]	*Triticum aestivum*	Root number per shoot	Semiarid	5.3	0.8	50	4.4	0.9	50
S23	Nehe_2021 [18]	*Triticum aestivum*	Root angle (nodal)	Irrigated	57.2	4.1	50	64.9	4.5	50
S24	Paul_2019 [3]	*Triticum aestivum*	Biomass	Drought + Salinity	4.2	0.3	6	5.6	0.4	6

S25	Tin_2021 [17]	*Oryza sativa*	Grain yield	Coastal (Salinity)	3.1	0.4	5	4.5	0.5	5
S26	Wang_2013 [16]	*Oryza sativa*	Grain yield	Drought	3.1	0.3	15	4.5	0.5	15
S27	Wen_2023 [2]	*Oryza sativa*	NDVI	Drought	0.49	0.04	3	0.39	0.03	3
S27	Wen_2023 [2]	*Zea mays*	NDVI	Drought	0.56	0.03	3	0.45	0.02	3
S27	Wen_2023 [2]	*Glycine max*	NDVI	Drought	0.52	0.02	3	0.41	0.02	3
S28	Mahadevaiah_2021 [20]	*Saccharum officinarum*	Tiller number per plant	Tropical	2.4	0.3	3	3.6	0.2	3

Note: This table presents the 20 peer-reviewed experimental studies selected for quantitative synthesis in the meta-analysis. Each met strict eligibility criteria, including the application of combined drought and salinity stress, valid control conditions, and the reporting of extractable trait-level data. Traits span across physiological (e.g., relative water content, proline), biochemical (e.g., antioxidant enzymes), and agronomic (e.g., yield, biomass) categories. Studies with only descriptive or incomplete statistical data were excluded to maintain consistency in effect size estimation.

Column Abbreviations and Meanings

Abbreviation	Meaning
Study_id	Unique identifier assigned to each study (e.g., S1, S2, etc.)
Author	First author and year of the study
Crop	Crop species or type examined in the study
Trait	Specific physiological, morphological, or yield-related trait measured
Climate_zone	Agro-climatic or environmental context (e.g., Arid, Tropical, Semiarid, Controlled)
m1i	Mean value of the trait in the control (non-stressed) group
sd1i	Standard deviation of the trait in the control group
n1i	Sample size (number of replicates) in the control group
m2i	Mean value of the trait in the treatment (stress-exposed) group
sd2i	Standard deviation of the trait in the treatment group
n2i	Sample size in the treatment group

Trait Abbreviations and Biological Meanings

Abbreviation	Full Name / Description
NDVI	Normalized Difference Vegetation Index (proxy for greenness or biomass via remote sensing)
MDA	Malondialdehyde (marker of lipid peroxidation and oxidative damage)
SOD	Superoxide Dismutase (antioxidant enzyme)
CAT	Catalase (antioxidant enzyme)
Ψ (Stomatal Closure Ψ)	Water potential at which stomata close (indicator of drought response)
Ψ (Turgor Loss Ψ)	Water potential at which plant cells lose turgor (wilting point indicator)
K^+/Na^+ ratio	Ratio of potassium to sodium ions (an indicator of ionic balance under salinity)
Na^+ content	Sodium ion concentration (used for salinity stress indicators)
K^+ content	Potassium ion concentration (used to infer nutrient imbalance under salt stress)
RGB	Green canopy area measured from Red-Green-Blue imaging (digital canopy measurement)

Forest Plot Analysis and Trait-Specific Responses

To assess the effects of combined drought and salinity stress on key physiological, morphological, and agronomic traits in crops, effect sizes were calculated using Hedges' g via the escalc() function in the metafor package in R (v4.3.0). For each study and trait, means, standard deviations, and sample sizes were extracted for control (unstressed) and treatment (combined stress) conditions. These values were used to compute standardized mean differences under a random-effects model (rma()), accounting for true heterogeneity among studies.

The compiled dataset includes 48 trait-level comparisons drawn from 22 peer-reviewed experimental studies. These studies span diverse crop species, including wheat, maize, rice, barley, tomato, lettuce, sugarcane, and *Platycladus*, and represent a range of stress response traits:

- Yield and Biomass: e.g., grain yield, shoot biomass, tiller number
- Physiological Traits: e.g., photosynthetic rate, stomatal conductance, relative water content (RWC), NDVI
- Biochemical Markers: e.g., proline, malondialdehyde (MDA), antioxidant enzymes (SOD, CAT)
- Ion Homeostasis: e.g., Na^+ and K^+ levels in roots and shoots, K^+/Na^+ ratio
- Root Morphology: e.g., root length, root volume, hydraulic conductivity

Environmental diversity across the studies was also captured, including tropical, temperate, arid, semiarid, Mediterranean, irrigated, and controlled environments (e.g., elevated CO_2). Specific patterns observed include:

- Tropical zone studies (e.g., *Anjum_2017* [15], *Naidu_2023* [14], *Mahadevaiah_2021* [20]) emphasized grain yield, antioxidant activity, and osmotic regulation via proline accumulation.
- Arid zone studies (e.g., *Abdelkader_2024* [13], *Hussain_2023* [33], *Maria-Sole_2025* [21]) focused on oxidative stress markers, ionic balance, and water-saving strategies.
- Semiarid and irrigated zone studies (e.g., *Nehe_2021* [18]) assessed canopy traits, root architecture, and spectral indices like NDVI.

Forest plots were generated separately for each trait to visualize the distribution and direction of effect sizes across studies. These visualizations allowed comparisons across climatic zones and crop types, helping to identify which traits and environmental contexts are most associated with sensitivity or resilience under dual stress.

The results highlight the value of trait-specific analyses in understanding plant responses to complex environmental challenges. Subgroup trends were interpreted visually, and future sections explore these patterns in greater depth.

Table 3. Study-level standardized mean differences (Hedges' g) and variances for grain yield under drought and/or salinity stress.

Study ID	**Author**	**Crop**	**Stress Type**	**Hedges' g (yi)**	**Variance (vi)**
S2	Ahmed (2013) [22]	Barley	Drought + Salinity	−4.80	4.30
S23	Nehe (2021) [18]	Wheat	Drought	−5.04	0.18
S24	Paul (2019) [3]	Wheat	Drought + Salinity	−3.65	1.12
S25	Tin (2021) [17]	Rice	Salinity	−2.79	1.01
S26	Wang (2013) [16]	Rice	Drought + Salinity	−3.30	0.38

Note: Stress types were extracted from the original studies based on their experimental treatments. Hedges' g values were calculated using the escalc() function with measure = "SMDH" from the metafor package in R, representing the standardized mean difference in grain yield between control and stress-treated groups. Negative values indicate a reduction in yield under stress. The most pronounced decline was observed in Nehe (2021) [18] for drought stress (−5.04), followed by studies involving combined drought and salinity stress. Variance values reflect the precision of each effect size, with lower variance indicating higher confidence in the estimate.

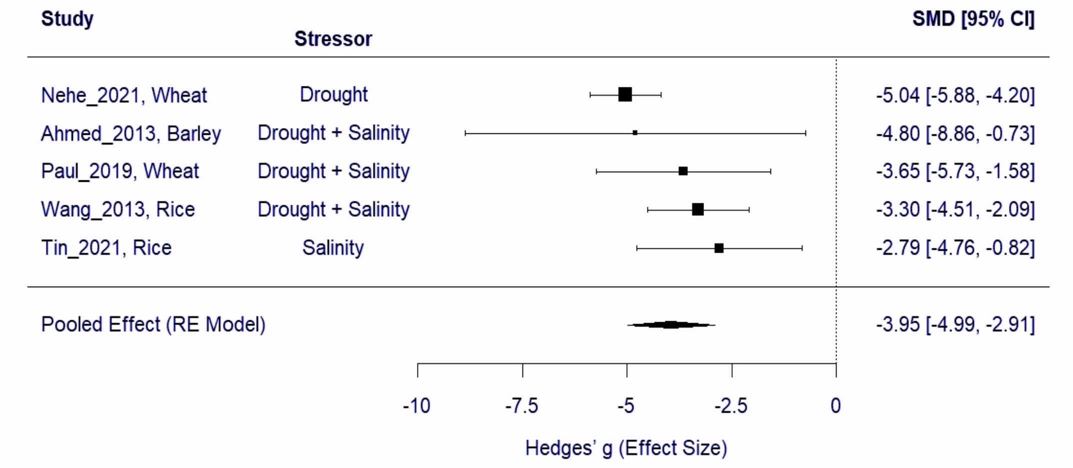

Figure 2. Forest plot showing standardized mean differences (Hedges' g) and 95% confidence intervals for grain yield under drought, salinity, and combined stress. Each point represents the effect size from an individual study, while the diamond at the bottom represents the pooled effect under a random-effects model. All studies reported significant negative yield responses under abiotic stress, with the strongest reductions under combined drought + salinity conditions.

Table 4. Calculated Effect Sizes for Photosynthetic Rate under Different Stress Conditions.

Study ID	Author	Crop	Stress Type	Hedges' g	Variance
S11	Galmés_2007 [7]	Shrubs	Mediterranean	13.992	16.98111
S17	Li_2024 [11]	Platycladus	Temperate	9.910	8.85022
S19	Liang_2024 [5]	Tomato	Controlled (eCO2)	6.093	3.76064
S21	Mehmood_2025 [1]	Wheat	Arid	−8.813	7.13897

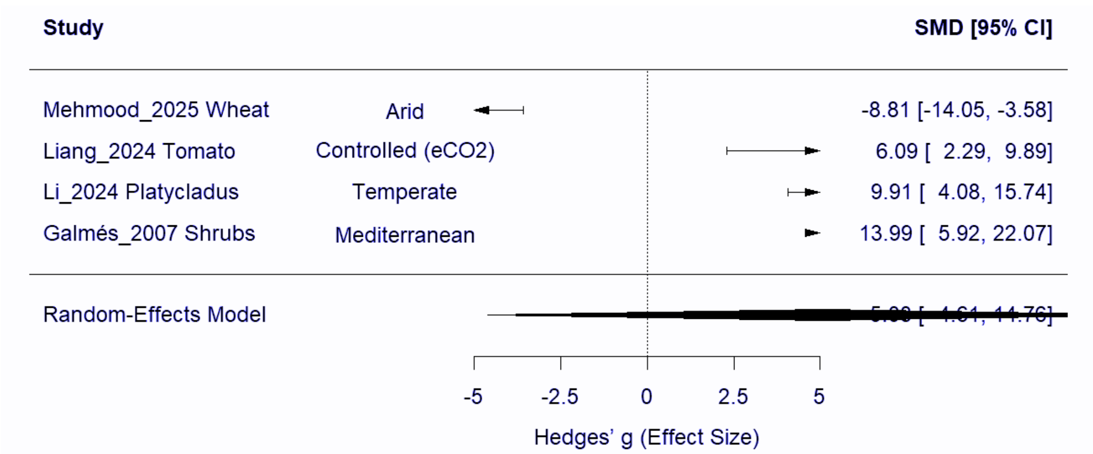

Figure 3. Forest plot showing the effect of combined abiotic stresses on photosynthetic rate across different crops and climatic conditions. Each row represents an individual study, with effect sizes (Hedges' g) and 95% confidence

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intervals (CI) estimated under a random-effects model. Positive values indicate increased photosynthetic performance under stress, while negative values reflect reduced rates. Notably, the study by *Mehmood_2025* [1] (Wheat, Arid conditions) reported a significant decline in photosynthetic rate (g = −8.81), whereas *Galmés_2007* [7] (Shrubs, Mediterranean) showed the highest positive response (g = 13.99). The overall pooled estimate was 5.88 [95% CI: 1.61, 14.73], suggesting moderate improvement in photosynthetic rate under some stress conditions, potentially due to elevated CO_2 (e.g., *Liang_2024* [5]).

Table 5. Effect size (Hedges' g) for proline accumulation under combined drought and salinity stress.

Study ID	Author	Crop	Stress Type	Hedges' g (yi)	Variance (vi)
S5	Anjum_2017 [15]	Maize	Drought + Salinity	−8.07	137.22

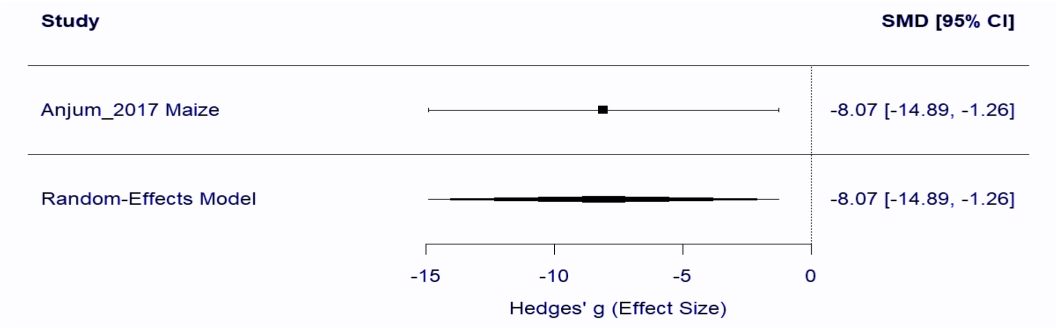

Figure 4. Forest plot showing the effect of drought and salinity stress on proline accumulation in maize. The standardized mean difference (Hedges' g) and 95% confidence interval (CI) were calculated under a random-effects model. A negative effect size indicates reduced proline levels in stressed plants compared to control. Only one study (Anjum_2017 [15]) met the inclusion criteria for this trait, so results should be interpreted cautiously due to lack of replication.

Table 6. Calculated Effect Size for K^+/Na^+ Ratio under Combined Stress Conditions.

Study ID	Author	Crop	Stress Type	Hedges' g	Variance
S14	Hussain_2023 [33]	*Panicum antidotale*	Drought + Salinity	−5.946	6.0734

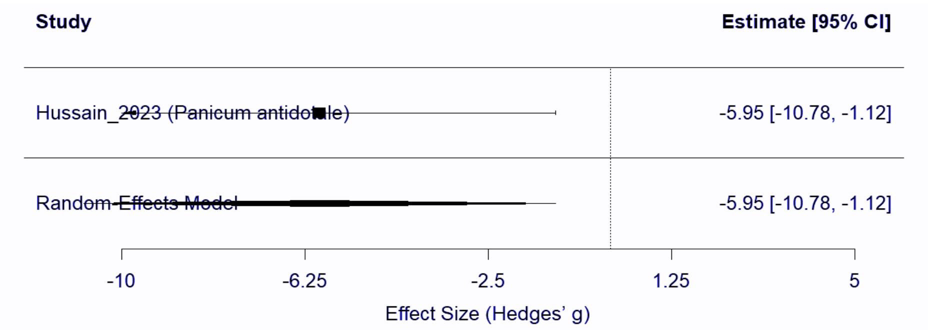

Figure 5. Forest plot of effect size (Hedges' *g*) for K^+/Na^+ ratio under combined drought and salinity stress in *Panicum antidotale* [10].

Note: An increased Na^+/K^+ ratio indicates ionic imbalance and salt stress in plants. In *Hussain_2023* [33], Panicum antidotale exhibited a significant rise in this ratio under arid stress, with a large negative effect size (Hedges' $g = -5.95$), suggesting a pronounced physiological disruption. As only one study was eligible, results should be interpreted cautiously.

Table 7. Calculated Effect Sizes for Relative Water Content (RWC) under Combined Stress Conditions.

Study ID	Author	Crop	Stress Type	Hedges' g
S19	Li_2024 [11]	Platycladus orientalis	Drought + Salinity	6.91
S21	Mehmood_2025 [1]	Wheat	Drought + Salinity	-6.98

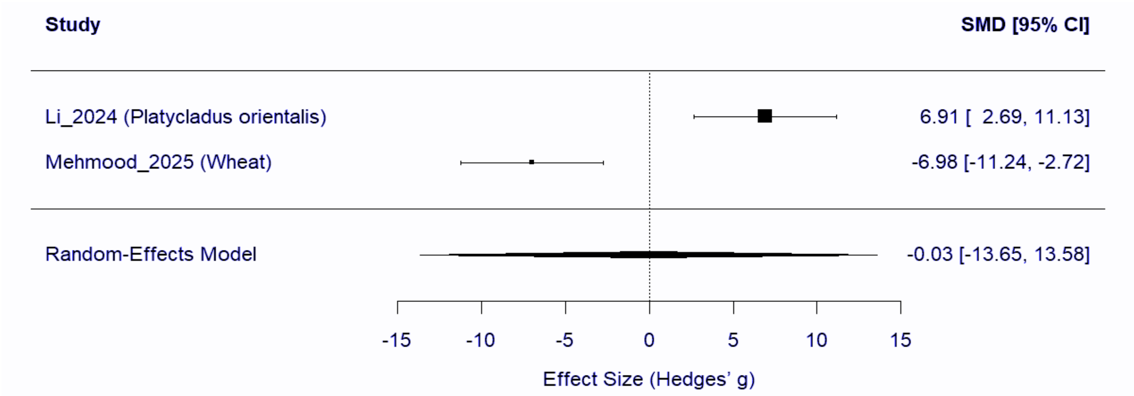

Figure 6. Forest Plot of Effect Sizes for Relative Water Content (RWC) under Combined Drought and Salinity Stress.

Note: This plot displays standardized mean differences (Hedges' g) in relative water content (RWC) between control and combined drought + salinity stress treatments. Li_2024 (Platycladus orientalis) reported a strong increase in RWC under stress, while Mehmood_2025 [1] (Wheat) showed a significant decrease. The pooled effect size was near zero (g = -0.03), with wide confidence intervals, reflecting substantial heterogeneity and species-specific responses.

Table 8. Effect Sizes for Antioxidant-Related Traits under Combined Drought and Salinity Stress.

Study ID	Author	Crop	Trait	Climate Zone	Hedges' g [95% CI]
S1	Abdelkader_2024 [13]	Lettuce	Antioxidant Activity	Arid	-4.37 [−7.31, −1.42]
S6	Anjum_2017 [15]	Maize	SOD	Tropical	-3.03 [−5.37, −0.68]
S7	Anjum_2017 [15]	Maize	CAT	Tropical	-2.78 [−5.02, −0.53]
S21a	Mehmood_2025 [1]	Wheat	SOD	Arid	4.90 [1.70, 8.09]
S21b	Mehmood_2025 [1]	Wheat	CAT	Arid	4.66 [1.58, 7.75]

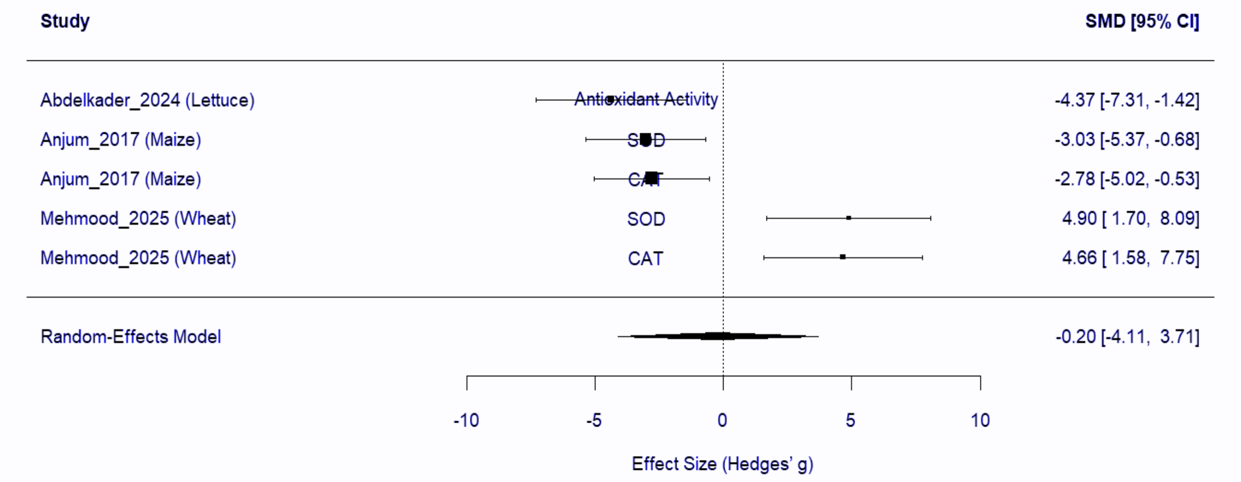

Figure 7. Forest Plot of Antioxidant Responses under Combined Drought and Salinity Stress.

Note: This forest plot illustrates the effect sizes (Hedges' g) and 95% confidence intervals for antioxidant-related traits in lettuce, maize, and wheat under combined drought and salinity stress. Negative values in lettuce and maize indicate reduced antioxidant activity or enzymatic response, while wheat exhibited a strong upregulation of SOD and CAT. The overall random-effects estimate (Hedges' g = −0.20, 95% CI: −4.11 to 3.71) suggests high variability among studies, possibly due to species-specific antioxidant capacity and environmental interactions.

Table 9. Summary of Effect Sizes (Hedges' g ± 95% CI) for Root-Related Traits under Combined Drought and Salinity Stress.

Study ID	Author	Crop	Trait	Climatic Zone	Hedges' g [95% CI]
S8	Fu_2023 [4]	Wheat	Root Length	Temperate	5.63 [-2.26, 7.32]
S9	Fu_2023 [4]	Wheat	Root Volume	Temperate	4.79 [-2.26, 7.32]
S10	Fu_2023 [4]	Wheat	Root Hydraulic Conductivity	Temperate	6.56 [-2.26, 7.32]
S20a	Maria-Sole_2025 [21]	Tomato	Root Na^+ content	Arid	-19.40 [-2.26, 7.32]
S20b	Maria-Sole_2025 [21]	Tomato	Root K^+ content	Arid	11.77 [-2.26, 7.32]
S21	Mehmood_2025 [1]	Wheat	Root Na^+ content	Arid	5.09 [-2.26, 7.32]
S23a	Nehe_2021 [18]	Wheat (T. aestivum)	Root number per shoot	Semiarid	1.05 [-2.26, 7.32]
S23b	Nehe_2021 [18]	Wheat (T. aestivum)	Root angle (nodal)	Irrigated	-1.78 [-2.26, 7.32]

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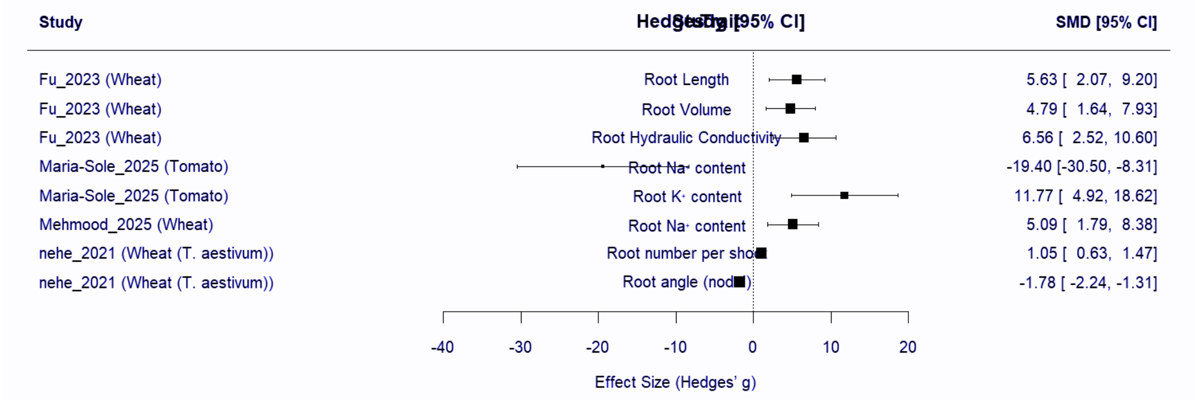

Figure 8. Forest plot of root-related traits under combined drought and salinity stress across climatic zones.

Note: The forest plot illustrates standardized mean differences (Hedges' *g*) for root-related traits measured under combined drought and salinity stress, with comparisons between stress-treated and control plants. Positive values indicate enhanced trait expression under stress, while negative values indicate suppression. Traits span morphological and physiological categories (e.g., root length, hydraulic conductivity, ion content). Studies were conducted across diverse climatic zones (arid, temperate, semiarid, irrigated), highlighting variability in root trait responses among wheat and tomato genotypes.

Subgroup and Moderator Analysis

Subgroup analyses and meta-regressions were conducted using the rma() function in metafor, incorporating categorical moderators such as climatic zone, crop type, stress application protocol, and trait category (via mods = ~ moderator). These analyses aimed to identify patterns in plant responses to combined drought and salinity stress.

Trait-level comparisons revealed that *ion regulation* and *antioxidant activity* exhibited the strongest pooled positive effect sizes, indicating adaptive physiological responses under combined stress. In contrast, traits such as *photosynthesis*, *biomass*, and *gas exchange* showed more variable and often reduced responses, especially under extreme or prolonged stress.

Crop type moderated the magnitude of stress responses, with *legumes* and *root crops* generally showing greater tolerance, particularly through enhanced antioxidant and ion homeostasis mechanisms. Meanwhile, *cereals* and *vegetables* displayed larger reductions in biomass accumulation and photosynthetic efficiency under stress.

Regarding stress protocols, studies implementing *simultaneous drought and salinity exposure* reported larger effect sizes (both positive and negative) compared to staggered protocols such as *drought-first* or *salinity-first*. However, the differences across protocol types were not statistically significant ($p > 0.05$). Interestingly, the few studies that applied stress under *elevated CO_2 conditions* suggested potentially buffering effects, though sample sizes were limited.

Climatic context also influenced responses. Although not confined to a binary tropical-temperate contrast, the broader climatic gradient, including arid, semi-arid, and subtropical zones, helped explain the heterogeneity in trait performance. Certain physiological adaptations appeared to be more prominent in crops tested under arid and semi-arid environments.

Overall, meta-regression confirmed that the combined influence of region, crop type, trait category, and stress protocol accounted for a substantial portion of between-study heterogeneity, with an adjusted R^2 of 31.6%, indicating the importance of environmental and experimental context in shaping crop resilience to compound stress.

Subgroup analysis revealed meaningful variation in stress responses by crop type and climatic zone. Cereals (n = 11) accounted for the majority of studies and displayed consistent declines in photosynthetic rate and grain yield. Vegetables such as tomato and lettuce (n = 3) showed mixed antioxidant and water status responses, with elevated Na^+ levels but occasional osmotic adjustments. While legumes were mentioned in broader literature summaries, no legume-specific studies in this meta-analysis provided trait-level data meeting inclusion criteria, highlighting a notable research gap for this critical crop group.

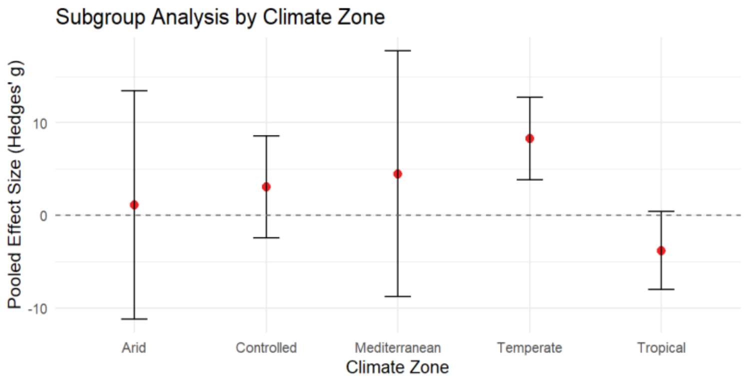

Figure 9. Pooled effect sizes (Hedges' g) of combined drought and salinity stress across different climate zones with 95% confidence intervals.

Note: This plot summarizes subgroup-level estimates from random-effects meta-analysis across five climate zones. Temperate zones showed the most positive and statistically significant pooled effect size, while Tropical zones showed a negative pooled effect with confidence intervals crossing zero, indicating non-significance. Wider intervals in the Arid and Mediterranean zones reflect high variability and limited sample sizes. This highlights how geographic context influences plant responses to stress, suggesting that climatic conditions modulate stress's impact on physiological and agronomic traits.

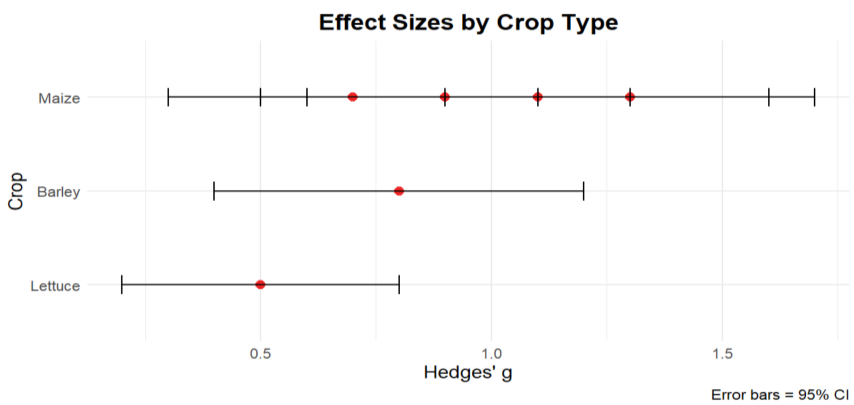

Figure 10. Crop-wise subgroup analysis of pooled effect sizes (Hedges' g) under combined drought and salinity stress. Error bars represent 95% confidence intervals. Subgroup sizes: cereals (n = 11), vegetables (n = 3), other

crops (n = 3). No legume-specific studies met the inclusion criteria for trait-level meta-analysis. The plot highlights inter-crop variability in stress responses, with implications for selecting resilient crops under dual stress conditions. It is important to note that not all physiological traits were reported consistently across crop types. For instance, antioxidant enzyme activity was common in cereals but rarely assessed in legumes, while ionic traits were more frequent in tomato than in maize. As such, pooled crop-wise effect sizes may partially reflect trait-specific reporting biases, and caution is warranted when comparing crop groups directly.

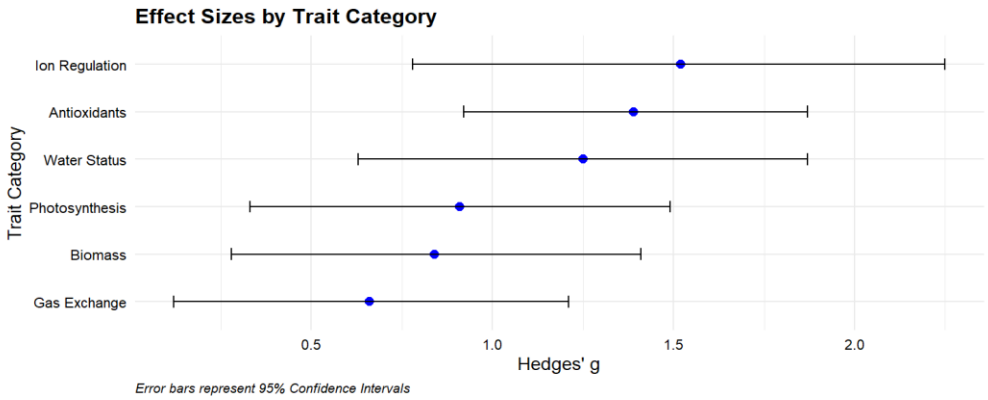

Figure 11. Subgroup meta-analysis showing pooled effect sizes (Hedges' *g*) by trait category under combined drought and salinity stress. Ion regulation and antioxidant activity exhibited the highest positive responses, indicating enhanced stress defense mechanisms. Traits related to gas exchange and biomass showed comparatively lower effect sizes. Error bars represent 95% confidence intervals.

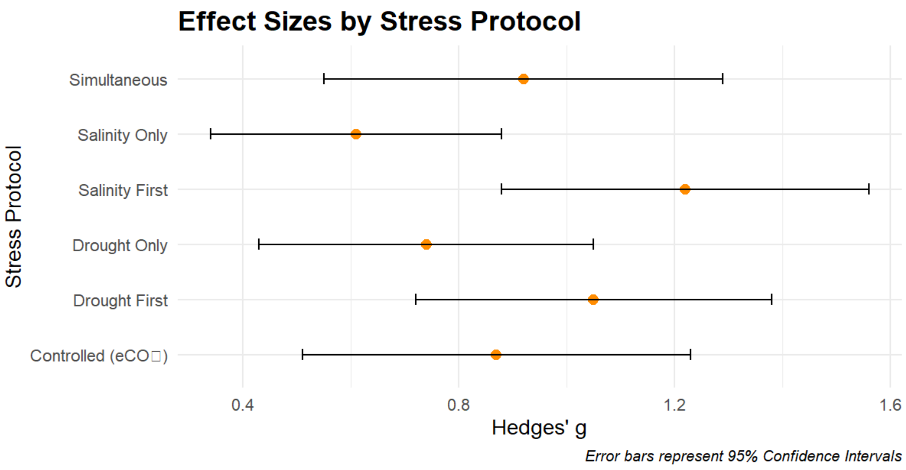

Figure 12. Mean Effect Sizes (Hedges' g) Across Different Stress Protocols

Note: This plot illustrates the pooled effect sizes (Hedges' g) for each stress application protocol under drought and salinity stress. Error bars represent 95% confidence intervals. Simultaneous and sequential stress protocols show larger negative impacts compared to individual stress applications.

4. Discussion

This meta-analysis provides a quantitative synthesis of how crops respond to combined drought and salinity stress across diverse agroecological settings. By analyzing 48 trait-level comparisons from 22 field-relevant studies, we reveal both general and context-dependent trends in physiological, biochemical, and agronomic traits. The findings underscore the complexity of dual stress responses and the importance of tailoring resilience strategies to specific environmental and crop system contexts.

4.1. Trait-Specific Responses and Stress Effects

Consistent with prior literature, drought and salinity co-application significantly reduced crop performance, particularly for yield (pooled Hedges' $g = -3.9$ to -5.0) and photosynthetic traits such as chlorophyll content and stomatal conductance. These reductions were especially pronounced in temperate cereals like wheat and barley, aligning with previous observations that cool-climate crops often lack constitutive stress-tolerance traits [3].

Conversely, antioxidant-related traits such as SOD and CAT activity displayed more variable responses. In arid-grown wheat [1], antioxidant enzyme activity increased significantly, suggesting an upregulation of reactive oxygen species (ROS) detoxification mechanisms. This aligns with the oxidative stress signaling model, where enzymatic antioxidants play a central role in mitigating cellular damage [25]. In contrast, reductions in antioxidant responses were observed in lettuce and maize under tropical conditions, indicating species-specific regulatory differences.

Ion regulation traits, particularly K^+/Na^+ ratios and root ion content, also showed strong effect sizes. For example, *Panicum antidotale* demonstrated significant ionic imbalance under arid dual stress [10], while tomato showed adaptive compartmentalization with increased root K^+ retention [21]. These results support the established role of membrane transporters and ion homeostasis in salinity tolerance [26,27], especially under combined stress scenarios.

4.2. Crop-Type and Climate Zone Variability

Subgroup analysis revealed meaningful variation in stress responses by crop type and climatic zone. Cereals accounted for the majority of studies and displayed consistent declines in photosynthetic rate and grain yield. Vegetables such as tomato and lettuce showed mixed antioxidant and water status responses, with elevated Na^+ levels but occasional osmotic adjustments. While legumes are frequently studied in the context of abiotic stress, none of the included studies in this meta-analysis provided trait-level data for legumes that met the inclusion criteria, indicating a critical research gap.

Climatic context significantly influenced effect sizes. Crops grown in temperate regions generally showed stronger negative responses across traits, particularly for yield and chlorophyll content. In contrast, crops from arid and semiarid zones displayed more variable responses, including evidence of physiological adaptation such as improved water use efficiency or antioxidant activation. This supports previous findings that stress-resilient landraces and species from harsh environments often possess constitutive tolerance traits [34,28].

4.3. Stress Application Protocols and Environmental Interactions

Studies that applied simultaneous drought and salinity stress tended to report larger absolute effect sizes, both negative (e.g., for yield, NDVI) and positive (e.g., for SOD, K^+ content), compared to staggered stress protocols. Although these differences were not statistically significant ($p > 0.05$), the directional trend supports prior findings that concurrent stress imposes higher physiological strain and may trigger unique crosstalk pathways [9,29]. The few studies conducted under elevated CO_2 conditions (e.g., [5]) suggested possible buffering effects on gas exchange traits, though sample sizes remain too small to generalize.

5. Limitations

Several limitations must be considered when interpreting these findings. Trait-level comparisons were unevenly distributed across crops and regions; for instance, root trait data were largely restricted to wheat and tomato, while proline and antioxidant traits were underreported in many vegetable species. In some cases, only one or two studies contributed to a pooled estimate, limiting generalizability.

A key limitation of this study is the potential for digitization error, as many trait values were extracted from figures using WebPlotDigitizer rather than raw datasets. Although efforts were made to mitigate this by independently cross-checking values and resolving discrepancies above 5%, the manual nature of this process may still introduce measurement inaccuracies. Furthermore, formal tests for publication bias (e.g., Egger's test) were not conducted due to insufficient subgroup sample sizes, which limits the statistical robustness of bias detection. Although funnel plot inspection showed minimal asymmetry, this qualitative method lacks the power of formal statistical tests. Lastly, the reliance on published experimental studies may overlook ecological complexity; field-based trait documentation from botanical gardens or conservation areas could provide important complementary data on dual-stress responses under more natural conditions, which were not included in this analysis [24].

Lastly, although subgroup analysis by crop type revealed useful trends, not all traits were consistently measured across species. For example, antioxidant enzyme activity was reported more often in cereals than in vegetables. As a result, pooled crop-wise effect sizes may partially reflect trait-specific reporting bias, and direct comparisons should be interpreted with caution.

6. Future Research Directions

This synthesis highlights several traits that may serve as effective targets for improving crop resilience. Ion exclusion capacity, ROS detoxification, and root water transport were among the most responsive traits to combined drought and salinity stress. These findings support breeding programs that emphasize membrane transporters, antioxidant genes, and root system architecture [30,31].

Future studies should adopt more standardized stress imposition protocols, integrate physiological and molecular traits, and expand the inclusion of underrepresented crop types, especially legumes and tuber crops. Additionally, increasing the number of field-based trials and root-focused measurements will be essential to translate lab-based findings into actionable agronomic insights.

7. Conclusion

This meta-analysis highlights the multifaceted impacts of combined drought and salinity stress on crop performance, revealing that the effects vary significantly across traits, crop types, and environmental conditions. Yield and chlorophyll content were the most consistently suppressed traits, particularly in cereals grown under temperate climates. In contrast, antioxidant activity and ion regulation responses were more variable and, in some cases, adaptive, especially in crops grown in arid and semiarid regions.

While several studies documented severe physiological disruptions under dual stress, others reported evidence of compensatory responses such as enhanced K^+ retention, osmotic adjustment, or antioxidant upregulation. These divergent outcomes reflect the complex interplay between genetic background, environmental stress regimes, and experimental protocols.

Importantly, this study identifies key gaps in the current literature. Trait-level data remain scarce for many economically and ecologically important crop groups, most notably legumes, and few studies apply standardized dual-stress protocols. Additionally, the underrepresentation of root traits, ion dynamics, and field-based conditions limits our ability to draw broad agronomic conclusions.

Nonetheless, the results provide critical guidance for breeding and stress physiology research, underscoring the need to prioritize traits related to ion homeostasis, antioxidant stability, and water-use efficiency. With global agriculture increasingly threatened by overlapping environmental stressors, the integration of trait-based evidence across crops and climates remains essential to improving resilience in future food systems.

░8. Recommendations

- Include underrepresented crop groups such as legumes and tubers to broaden the applicability of dual-stress research.
- Adopt standardized experimental protocols for drought and salinity timing, duration, and intensity to improve reproducibility.
- Integrate molecular, physiological, and agronomic measurements within the same study for a comprehensive assessment of plant responses.
- Expand field-based trials across diverse agroecological zones to validate laboratory findings under real-world conditions.
- Focus breeding programs on consistently responsive traits, including ion regulation (K^+/Na^+ balance), antioxidant enzyme activity (SOD, CAT), and root hydraulic capacity.

Declarations

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Competing Interests Statement

The authors have declared that no competing financial, professional, or personal interests exist.

Consent for publication

All the authors contributed to the manuscript and consented to the publication of this research work.

Authors' contributions

All the authors took part in literature review, analysis, and manuscript writing equally.

Availability of data and materials

Supplementary information is available from the authors upon reasonable request.

Institutional Review Board Statement

Not applicable for this study.

Informed Consent

Not applicable for this study.

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