

Systematic Review

Cadaverine as an Overlooked Regulator of Plant Growth and Abiotic Stress Responses: A Systematic Review, Evidence Map, and Exploratory Meta-Analysis

João Everthon da Silva Ribeiro ^{1,*} , Toshik Iarley da Silva ¹ , Ester dos Santos Coêlho ² ,
Pablo Henrique de Almeida Oliveira ² , Jackson Silva Nóbrega ³  and Aurélio Paes Barros Júnior ² 

¹ Center for Agricultural, Environmental and Biological Sciences, Federal University of Recôncavo da Bahia, Cruz das Almas 44380-000, Brazil; toshik@ufbr.edu.br

² Department of Agronomic and Forest Sciences, Federal Rural University of the Semi-Arid Region, Mossoró 59625-900, Brazil; estersantos12@hotmail.com (E.d.S.C.); pabloalmeidaagro@gmail.com (P.H.d.A.O.); aurelio.barros@ufersa.edu.br (A.P.B.J.)

³ Campus Universitário de Rurópolis, Federal University of Western Pará, Rurópolis 68165-000, Brazil; jacksonnobreaga@hotmail.com

* Correspondence: j.everthon@hotmail.com; Tel.: +55-83-98171-6327

Abstract

Cadaverine is a lysine-derived diamine that remains less studied than the canonical plant polyamines putrescine, spermidine, and spermine. Its polycationic nature suggests it may influence membrane stability, ionic balance, redox regulation, and stress-related metabolic adjustments, but its specific contribution to plant resilience to abiotic stress remains poorly characterized. This systematic review, evidence map, and exploratory meta-analysis synthesized the published literature on cadaverine-associated responses in plants exposed to abiotic stress. The object of analysis was the existing body of literature, and the quantitative component summarized data extracted from eligible studies rather than generating new experimental results. The review examined whether the available literature supports a role for cadaverine beyond its description as a stress-associated metabolite, particularly regarding transport, oxidative stress mitigation, photosynthetic protection, water status, ionic homeostasis, and growth maintenance. The evidence indicates that cadaverine is primarily associated with beneficial physiological responses to stress, particularly when applied exogenously. However, the magnitude of the response varies across species, stress types, doses, application methods, and response variables. Mechanistically, cadaverine may contribute to stress tolerance by activating antioxidant enzymes, reducing oxidative damage, stabilizing membranes, protecting the photosynthetic apparatus, promoting osmotic adjustment, and modulating cation transport. However, endogenous cadaverine dynamics and several proposed signaling connections remain insufficiently validated. Overall, cadaverine emerges as a promising regulatory candidate for fundamental research on plant stress physiology. In contrast, its agronomic use still requires standardized dose–response studies, comparative analysis with other polyamines, and greenhouse and field validation.



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1. Introduction

The intensification of abiotic stressors is one of the main constraints to plant growth, productivity, and physiological stability in agricultural and natural systems. Environ-

mental pressures such as salinity, water deficit, temperature extremes, toxic metals, and nutritional imbalance disturb core physiological functions by affecting photosynthetic performance, redox control, membrane stability, water relations, ion uptake, and carbon–nitrogen metabolism. These responses are highly interconnected: osmotic and ionic disturbances can impair photosynthesis and membrane integrity, whereas oxidative stress can amplify metabolic damage and compromise growth. Therefore, plant tolerance is not determined by a single pathway, but by integrated networks involving metabolism, signaling, and cellular protection [1–4].

In this context, polyamines have received increasing attention as small nitrogenous compounds involved in plant growth, development, senescence, membrane stabilization, redox homeostasis, and acclimation to adverse environmental conditions. Although putrescine, spermidine, and spermine are the most extensively studied plant polyamines, cadaverine remains comparatively underexplored. This lysine-derived diamine is structurally related to other polyamines and shares their polycationic character. However, available evidence suggests that it may also participate in stress responses and developmental processes through mechanisms that are not yet fully understood [2,5,6].

Cadaverine occupies a unique position in the metabolism of plant polyamines because it is located simultaneously inside and outside the canonical axis dominated by putrescine, spermidine, and spermine. While putrescine derives mainly from the decarboxylation of arginine and/or ornithine, functioning as the most recognized entry point for the biosynthesis of higher polyamines, cadaverine results from the direct decarboxylation of L-lysine by lysine decarboxylase (LDC), forming 1,5-diaminopentane [1]. This biochemical difference is not merely structural; it implies a particular interface between amino acid metabolism, carbon–nitrogen balance, pH homeostasis, stress response, and growth regulation. Putrescine, spermidine, and spermine have historically been integrated into a linear metabolic narrative, in which putrescine provides the initial diamine skeleton and the successive addition of aminopropyl groups, dependent on decarboxylated S-adenosylmethionine, generates spermidine and spermine by the action of spermidine synthase and spermine synthase [3]. Cadaverine, on the other hand, does not fit directly into this classical aminopropylated pathway, which has contributed to its conceptual marginalization.

The historical neglect of cadaverine stems largely from an analytical and conceptual asymmetry in the study of polyamines. Putrescine, spermidine, and spermine were recognized early as molecules associated with cell division, differentiation, membrane stabilization, nucleic acid modulation, senescence, and tolerance to abiotic stressors, while cadaverine remained frequently classified as a non-classical diamine, accessory product, secondary metabolic marker, or circumstantial accumulation compound [4]. This reductive interpretation was reinforced by methodological limitations: many polyamine profiles were optimized to detect putrescine, spermidine, and spermine, while cadaverine was quantified irregularly, omitted in metabolic panels, or treated as a peripheral signal without mechanistic integration. In addition, because it is a structurally simple diamine, cadaverine has often been interpreted as a minor functional analog of putrescine, despite having a distinct biosynthetic origin, a different chain length, and its own ability to interact with membranes, organic acids, cell walls, organic cation transporters, and redox components.

However, the accumulating evidence suggests that cadaverine should not be considered only a secondary metabolite of lysine metabolism, but rather a regulatory node capable of modulating growth, signaling, and resilience under abiotic stress. Studies in *Mesembryanthemum crystallinum* have shown that heat can induce systemic accumulation and translocation of cadaverine, while salinity and ethylene modulate its accumulation in plant tissues [7–9]. In *Brassica juncea*, exogenous application of cadaverine attenuated the effects of NaCl, Cd, and Pb on germination, growth, pigments, nitrate reductase activity,

and ionic accumulation, suggesting a functional role in mitigating multiple stressors [10]. In maize under salinity, cadaverine content was modulated by nitric oxide, indicating a possible connection between diamine and stress-associated signaling pathways [11].

In addition to the effects directly linked to stress tolerance, studies in *Arabidopsis thaliana* indicate that cadaverine is associated with root growth regulation, organic cation transport, polyamine metabolism, and biotin biosynthesis. Natural variation in the expression of ORGANIC CATION TRANSPORTER 1 (OCT1) was associated with differences in the primary root length response to cadaverine; mutants of polyamine metabolism exhibited differential sensitivity to the diamine; and inhibition of the biotin pathway has been proposed as a modulating mechanism of primary root growth [12–14]. This evidence supports the hypothesis that cadaverine may participate not only as a secondary metabolic product but also as a functional component in networks linking development, transport, primary metabolism, and signaling [12–14].

It is precisely this paradox, low bibliographic centrality but high functional plausibility, that justifies the present systematic review, evidence map, and exploratory meta-analysis. Unlike putrescine, spermidine, and spermine, whose literature already supports relatively well-established models of biosynthesis, catabolism, transport, conjugation, and stress response, cadaverine remains dispersed across studies conducted in different species, at different doses, under different stressors, and within heterogeneous experimental systems. This fragmentation limits the interpretation of isolated studies. It is difficult to determine from the literature as a whole whether cadaverine-associated responses reflect specific regulatory functions, partial functional overlap with putrescine or other polyamines, endogenous metabolic adjustment to stress, or the broader action of a cationic polyamine.

This study does not report new plant experiments. Instead, it uses the published literature as the object of analysis. It applies systematic review procedures, evidence mapping, scientometric characterization, and exploratory quantitative synthesis to evaluate responses associated with cadaverine under abiotic stress. The evidence map allows the distribution of studies to be examined across stress types, plant response groups, and evidence categories. The exploratory meta-analysis allows comparable quantitative results to be summarized by response direction and magnitude, while subgroup and sensitivity summaries help identify potential sources of heterogeneity rather than confirm causal mechanisms. Specifically, we aimed to identify response patterns, summarize comparable quantitative evidence, clarify mechanistic convergences, define interpretative boundaries, and highlight scientific gaps and priorities for future research on cadaverine in plant responses to abiotic stress.

2. Materials and Methods

2.1. Study Design

This study was designed as a systematic review, an evidence map, a complementary scientometric analysis, and an exploratory meta-analysis. It was conducted and reported in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses 2020 statement (PRISMA 2020) [15]. The PRISMA flow diagram is presented in Figure 1, and the completed PRISMA 2020 checklist is provided as Supplementary Material.

The review focused on studies involving plants subjected to abiotic stressors in which cadaverine was evaluated as an exogenous treatment, endogenous response, or mechanistic component related to growth regulation, physiological performance, and stress responses. The scientometric component was incorporated to characterize the corpus's temporal evolution and to identify journals, thematic groupings, and emerging frontiers. The quantitative synthesis was treated as exploratory because of the limited number of independent studies and methodological heterogeneity.

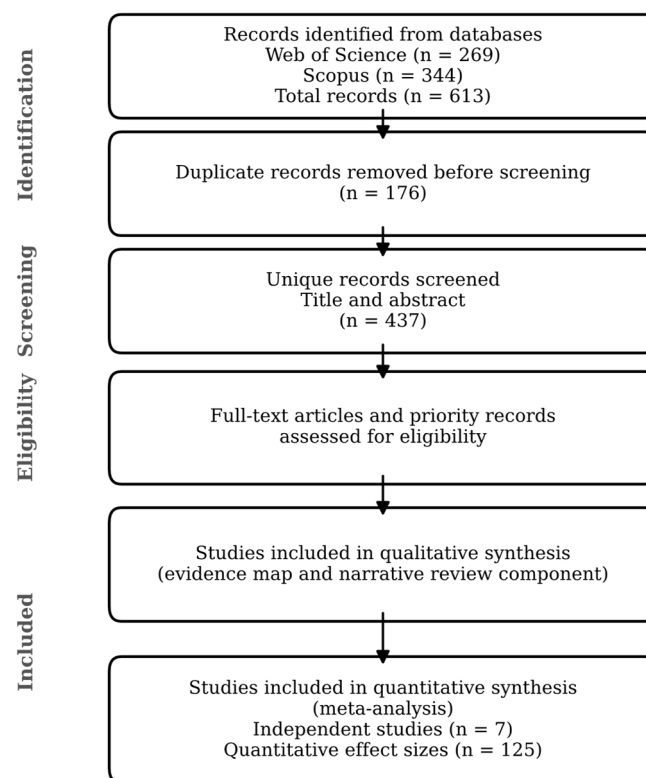


Figure 1. PRISMA flow diagram of study identification and selection. The diagram summarizes database retrieval, duplicate removal, title and abstract screening, full-text eligibility assessment, qualitative synthesis for the evidence map and narrative review, and quantitative synthesis for the exploratory meta-analysis.

The review protocol was not prospectively registered on a public platform. This absence is acknowledged as a methodological limitation because prospective registration can reduce the risk of selective reporting in systematic reviews and meta-analyses. To improve transparency and reproducibility, the search strategy, eligibility criteria, screening procedures, data extraction procedures, synthesis decisions, and analytical structure were explicitly described in the Methods section and documented before the final consolidation of the quantitative dataset.

2.2. Bibliographic Search Strategy

The search was conducted in the Web of Science Core Collection and Scopus databases, with no publication year restriction. The searches were last performed on 5 June 2026. A combination of terms related to cadaverine, plants, and abiotic stressors was used: (“cadaverine” OR “1,5-diaminopentane”) AND (plant* OR crop* OR seed* OR seedling* OR root* OR leaf OR leaves OR “in vitro”) AND (stress* OR salinity OR salt OR drought OR “water deficit” OR “osmotic stress” OR heat OR cold OR chilling OR “heavy metal” OR “heavy metals” OR cadmium OR chromium OR lead OR arsenic OR oxidative OR toxicity). In the Web of Science, the search was performed in the Topic field; in Scopus, it was performed in the TITLE-ABS-KEY field. The number of records retrieved from each database is reported in the Results section and summarized in the PRISMA flow diagram.

2.3. Management of Records and Eligibility Criteria

After exporting the records, duplicate entries were identified and removed before title and abstract screening. Screening was conducted in two stages: title and abstract screening, followed by full-text evaluation of studies classified as relevant or potentially relevant. Studies were considered eligible for the systematic review when they involved plants,

seeds, seedlings, or plant tissues; addressed or evaluated cadaverine as an exogenous treatment, endogenous response, or mechanistic component; included at least one abiotic stressor; and reported morphological, physiological, biochemical, molecular, hormonal, or productive responses. For the quantitative synthesis, eligible comparisons required plants exposed to abiotic stress without cadaverine and plants exposed to the same stress condition with cadaverine treatment, in addition to the availability of the mean, a measure of variation, and the available or extractable sample size.

2.4. Data Extraction and Organization

The data were organized in a long format, containing the identification of the study, species, experimental system, type and intensity of stress, form and dose of cadaverine, method of application, stage of development, variables evaluated, functional category of response, means, measures of variation, number of biological replicates, source of data, and methodological observations. The variables were grouped into biological categories: germination, growth, biomass, survival, photosynthetic pigments, gas exchange, chlorophyll fluorescence, water status, oxidative damage, antioxidant enzymes, osmolytes, ionic homeostasis, nitrogen metabolism, hormonal responses, and endogenous polyamine metabolism.

2.5. Graph Digitization and Validation

When numerical data were not available in tables, the values were extracted by digitizing published figures. The extracted values were checked for coherence with the axes, units, treatments, and error bars presented in the original articles. Comparisons derived from figures were identified in the database to allow sensitivity analysis and cautious interpretation. Digitization focused on the studies that form the core of quantitative synthesis, especially Ozmen et al. [16], Balci et al. [17], and Tomar et al. [10], thereby allowing the differentiation of tabulated data, digitized data, and data used only in exploratory or sensitivity analyses.

2.6. Evidence Map and Scientometrics

An evidence map was constructed to synthesize the distribution of studies according to abiotic stress type and plant response group. For each stress-response combination, the number of extracted effects and the predominant biological direction of the response were summarized. Response direction was classified as beneficial, detrimental, mixed or inconsistent, or descriptive/uncertain, according to the biological interpretation of each variable.

In parallel, the deduplicated bibliographic corpus was classified into interpretive thematic groupings based on title, abstract, keywords, and biological focus. The scientometric component was used to describe the temporal distribution of publications and the main thematic structure of the literature. This analysis was intended to characterize the evolution and organization of the field rather than to perform a full bibliometric network analysis.

2.7. Effect Measure, Quantitative Synthesis, and Heterogeneity Assessment

The effect measure used in the exploratory meta-analysis was the natural logarithm of the response ratio (lnRR), calculated as $\ln RR = \ln(X_{Cad + Stress} / X_{Stress})$, where $X_{Cad + Stress}$ denotes the mean of the cadaverine treatment under stress, and X_{Stress} denotes the mean of the treatment under the same stress without cadaverine. Eligible quantitative comparisons required a matched pair: plants exposed to abiotic stress without cadaverine and plants exposed to the same stress condition with cadaverine treatment. For variables whose reductions indicate biological improvement, such as H_2O_2 , MDA, LPO, Na^+ , Cd, and Pb, the effect sign was inverted to obtain a unidirectional benefit metric, so that positive values consistently indicate a beneficial or stress-mitigating response.

When means, dispersion measures, and sample sizes were available, the sampling variance of $\ln RR$ was estimated as $v(\ln RR) = [SD^2_{Cad} + Stress / (n_{Cad} + Stress \times X^2_{Cad} + Stress)] + [SD^2_{Stress} / (n_{Stress} \times X^2_{Stress})]$, where SD is the standard deviation, n is the sample size, $X_{Cad} + Stress$ is the mean of the cadaverine treatment under stress, and X_{Stress} is the mean of the stress treatment without cadaverine. When standard errors were reported, they were converted to standard deviations using $SD = SE \times \sqrt{n}$. Sample size was defined as the number of biological or experimental replicates reported for each treatment group. Technical subsamples were not treated as independent replicates unless the original study clearly defined them as independent experimental units. Comparisons were included in variance-weighted analyses only when the mean, a dispersion measure convertible to SD , and the sample size were available for both the stress control and the corresponding cadaverine-treated stress group. Comparisons without sufficient information on mean, dispersion, or sample size were retained for descriptive evidence mapping when appropriate but were not included in variance-weighted analyses. No imputation of missing sample sizes or dispersion measures was performed.

Because several studies contributed multiple effect sizes across different response variables, doses, stress levels, or sampling conditions, non-independence was addressed by treating each independent study as the primary unit of analysis in the main synthesis. For the main forest plot, multiple effect sizes from the same study were first harmonized to a common beneficial direction and then aggregated into a single study-level estimate, so that each independent study contributed only one effect size to the primary meta-analytic summary. This approach was used as a conservative unit-of-analysis correction to minimize pseudo-replication and to avoid treating biologically related outcomes from the same experiment as independent observations. Cluster robust variance estimation was not applied because the number of independent study clusters was small, which would make cluster-based inference unstable.

The overall synthesis was designed as a hypothesis-generating quantitative summary of the available evidence, not as a confirmatory estimate of a single biologically universal cadaverine effect. More homogeneous subsets, such as exogenous cadaverine application under salinity, were considered conceptually and examined descriptively when possible. However, the number of independent studies within these subsets was too small to support reliable separate meta-analyses. Therefore, additional syntheses by stress type and response group were treated as exploratory summaries rather than confirmatory subgroup tests. Formal subgroup Q tests were not emphasized because several stress categories were represented by only one or two independent studies, which would make subgroup inference underpowered and potentially misleading.

Study-level heterogeneity was assessed using Cochran's Q test, the inconsistency index I^2 , and the between-study variance component τ^2 . Cochran's Q is a heterogeneity statistic that tests whether the variability among study-level effect sizes exceeds that expected by sampling error alone. The degrees of freedom (df) for the Q test were calculated as the number of independent studies minus one. The inconsistency index I^2 was calculated as $I^2 = \max[0, (Q - df)/Q] \times 100$, where Q is Cochran's heterogeneity statistic, and df represents the degrees of freedom. The between-study variance τ^2 was estimated using the DerSimonian and Laird method. Because the number of independent studies was small, these heterogeneity statistics were interpreted with caution and used to support an exploratory, rather than confirmatory, interpretation of the meta-analysis.

Dose-response meta-regression was not performed because cadaverine doses, chemical forms, application methods, stress types, and response variables were heterogeneous across studies, and the number of independent studies per dose range was insufficient for reliable moderator analysis. Formal assessment of publication bias was not performed

because the number of independent studies included in the quantitative synthesis was insufficient for reliable funnel-plot or regression-based small-study effect analyses.

2.8. Analytical Tools

The organization of the database, curation of records, and preparation of spreadsheets were carried out in a spreadsheet-based environment. The cleaning, consolidation, restructuring, analytical summaries, and visualization of the data were conducted using Python v.3.10 and R v.4.4.1. WebPlotDigitizer v.4.7 was used as an auxiliary tool for extracting and verifying values shown only in graphs. The figure panels were prepared with black text, and the captions were separated from the graphic elements.

3. Results

3.1. Search Flow and Corpus Composition

The search strategy retrieved 613 records from the two databases, including 269 records from the Web of Science Core Collection and 344 from Scopus. After removing 176 duplicate records, 437 unique records remained for title and abstract screening. This deduplicated corpus formed the basis for the systematic review, evidence mapping, and scientometric characterization. The identification, duplicate removal, screening, eligibility assessment, and inclusion steps are summarized in Figure 1. The qualitative synthesis comprised the curated full-text corpus used for the evidence map and narrative review, whereas the quantitative synthesis was restricted to studies with comparable numerical data. After full-text curation, seven independent studies provided sufficient data for the exploratory meta-analysis, yielding 125 quantitative effect sizes.

3.2. Scientometric Patterns and Thematic Groupings

The scientometric component indicated that research on cadaverine-related responses in plant abiotic stress remains a relatively small but steadily expanding field. The temporal distribution of records showed an irregular pattern, with a clear increase in publication frequency in recent decades and higher annual counts in the 2020s (Figure 2). Thematic curation grouped the 437 unique records into eight categories, with the largest groups corresponding to exogenous cadaverine application under abiotic stress, endogenous cadaverine and polyamine metabolism, off-scope or non-plant records, and plant–microbe interactions involving cadaverine-related stress alleviation (Figure 3). In contrast, records specifically focused on redox/antioxidant mechanisms or molecular signaling, transport, and developmental regulation were less frequent, indicating that these mechanistic aspects remain comparatively underexplored. Together, these patterns suggest that cadaverine has been investigated across multiple biological contexts, but that direct mechanistic evidence in plant abiotic stress remains limited and fragmented.

3.3. Evidence Map

The evidence map showed that the quantitative evidence was unevenly distributed across stress categories and response groups (Figure 4). Nitrate toxicity contributed the most extracted effects, mainly in gas exchange, chlorophyll fluorescence, oxidative damage, and water status. Salinity, heavy metal stress, multiple stress, and osmotic/drought stress were represented by fewer combinations of stress type and response category. Growth, pigments, germination, oxidative damage, photosynthetic traits, metabolites, water status, and antioxidant enzymes were among the main response groups represented. To improve interpretability, each cell in the evidence map was annotated with both the number of extracted effects and the predominant biological direction of the response. Upward arrows indicate predominantly beneficial or stress-mitigating effects, downward arrows indicate

predominantly detrimental or stress-exacerbating effects, combined arrows indicate mixed or inconsistent responses, and gray symbols indicate descriptive or response-only evidence with uncertain direction. Overall, the map indicates that most extracted effects were beneficial, although multiple-stress responses were more heterogeneous. This distribution supports interpreting the quantitative synthesis as exploratory rather than confirmatory.

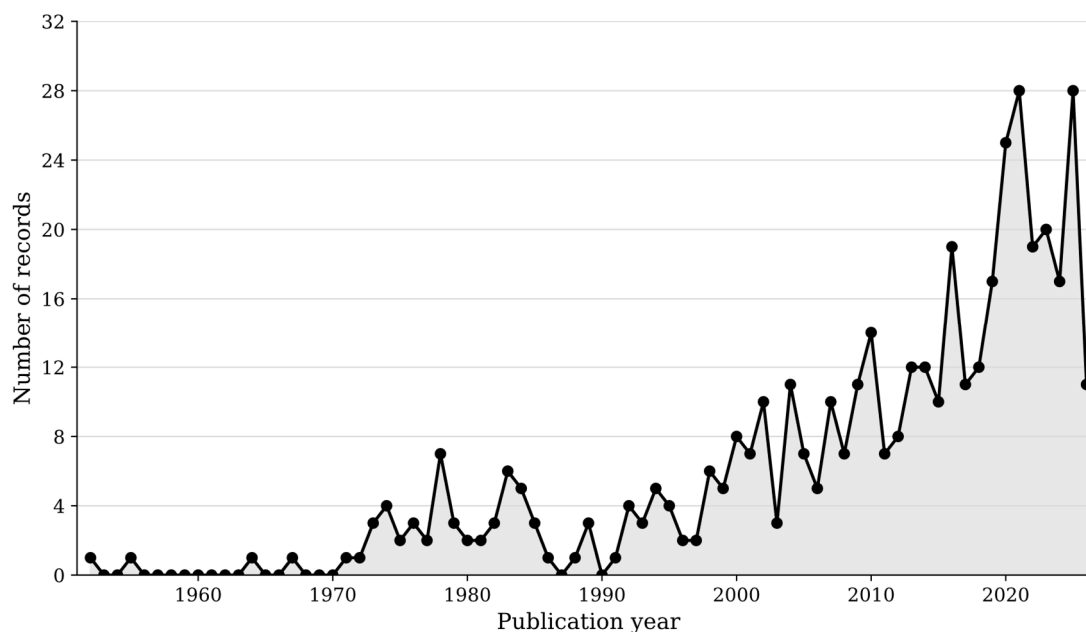


Figure 2. Temporal distribution of cadaverine-related records retrieved after deduplication from Web of Science and Scopus. The line shows the annual number of unique records included in the broad bibliographic corpus used for the systematic review, evidence mapping, and scientometric characterization.

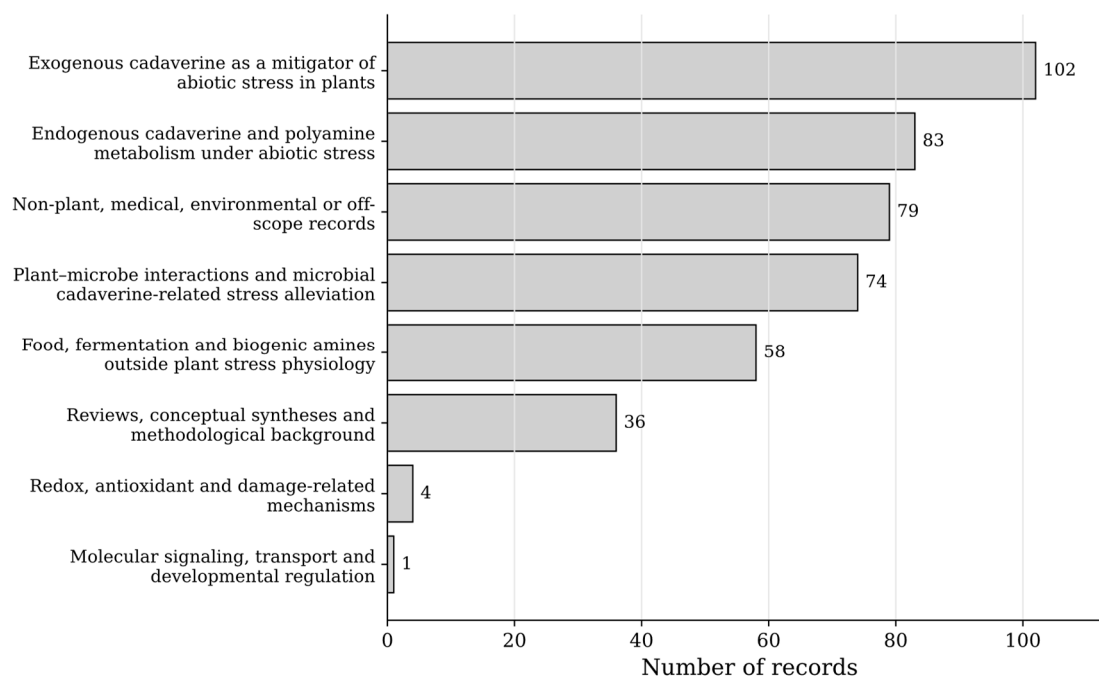


Figure 3. Thematic grouping of the 437 unique records identified during corpus curation. Bars indicate the number of records assigned to each thematic or eligibility-related category, separating plant abiotic-stress evidence from off-scope, microbial, food/fermentation, conceptual, and mechanistic background records.

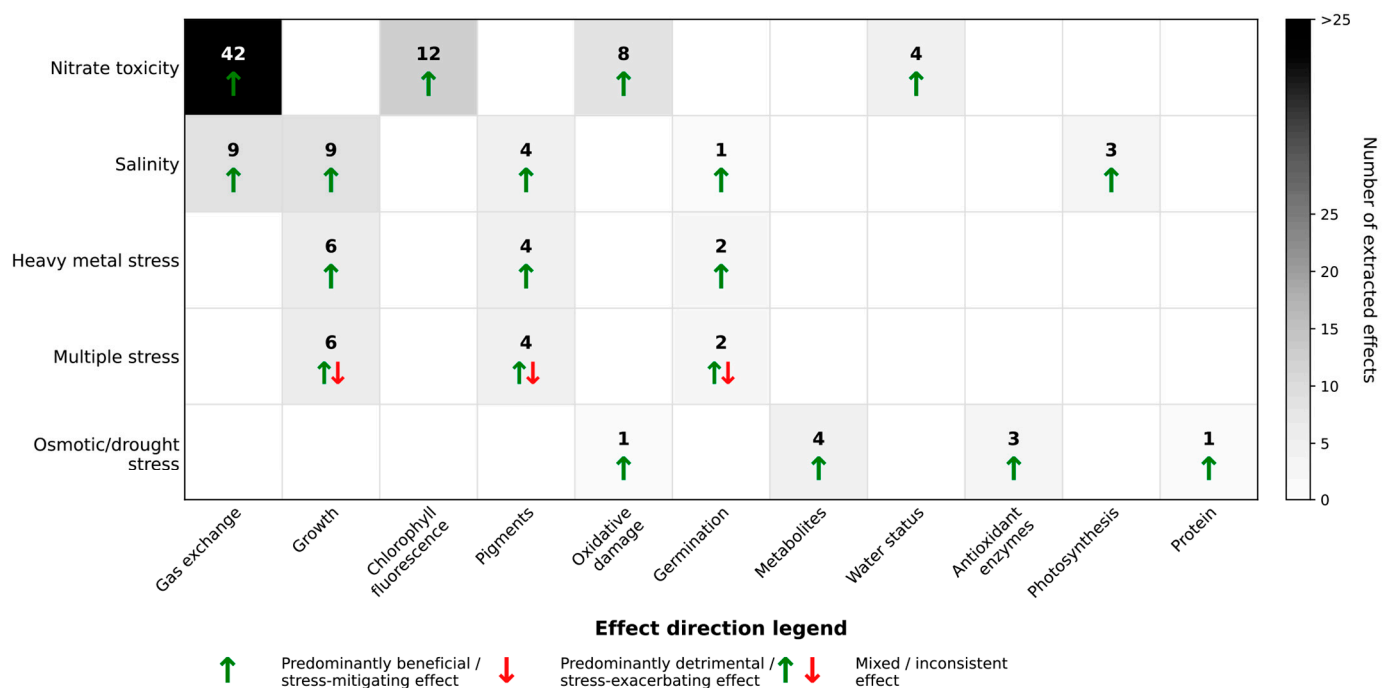


Figure 4. Evidence map of quantitative effects of cadaverine across abiotic stress categories and plant response groups. Cell shading indicates the number of extracted effects, and symbols indicate the predominant biological direction of the response. Green upward arrows indicate predominantly beneficial or stress-mitigating effects, red downward arrows indicate predominantly detrimental or stress-exacerbating effects, and combined arrows indicate mixed or inconsistent responses.

3.4. Quantitative Dataset and Exploratory Synthesis

The exploratory quantitative dataset comprised 125 effect sizes extracted from seven independent studies. These studies covered lettuce under salinity stress; barley under polyethylene glycol (PEG)-induced osmotic stress; wheat under nitrate toxicity; *Brassica juncea* under NaCl, Cd, and Pb exposure; rice under osmotic stress; and two studies on wheat under harmful heating or hyperthermia. The combined exploratory synthesis is summarized in Figure 5. At the study level (Figure 5a), cadaverine generally showed a positive beneficial effect, although confidence intervals were wide in some cases. Heterogeneity was high, confirming the exploratory nature of the synthesis. Cochran's Q-test was significant ($Q = 104.37$, $df = 6$, $p < 0.001$), and the inconsistency index was high ($I^2 = 94.25\%$), with an estimated between-study variance of $\tau^2 = 0.0359$. These results indicate that the magnitude of cadaverine-associated responses varied substantially among studies. Therefore, the overall estimate should not be interpreted as a universal average effect of cadaverine across all biological contexts, but as a broad, hypothesis-generating indicator of the direction of responses reported in the available literature. More homogeneous subsets, such as exogenous application of cadaverine under salinity conditions, were considered conceptually. However, the number of independent studies within these subsets was too small to support a reliable separate meta-analysis. When grouped by stress category (Figure 5b), the magnitude of the beneficial effect varied numerically across stressors such as heat stress, nitrate toxicity, heavy metal stress, osmotic or drought stress, and salinity. However, these patterns should be interpreted as exploratory numerical trends rather than statistically confirmed subgroup differences, because only one or two independent studies represented several stress categories. Therefore, the stress type synthesis was used to describe possible context dependence rather than to infer formal differences among abiotic stress categories. When grouped by response category (Figure 5c), the strongest beneficial patterns were observed for gas exchange, hormonal or stress response, oxidative damage,

photosynthesis, pigments, and survival. In contrast, growth-related responses were weaker, and protein responses were nearly neutral. The sensitivity analysis (Figure 5d) showed that the overall beneficial direction was retained across alternative analytical scenarios, supporting the robustness of the exploratory interpretation while still indicating that the synthesis should not be treated as confirmatory.

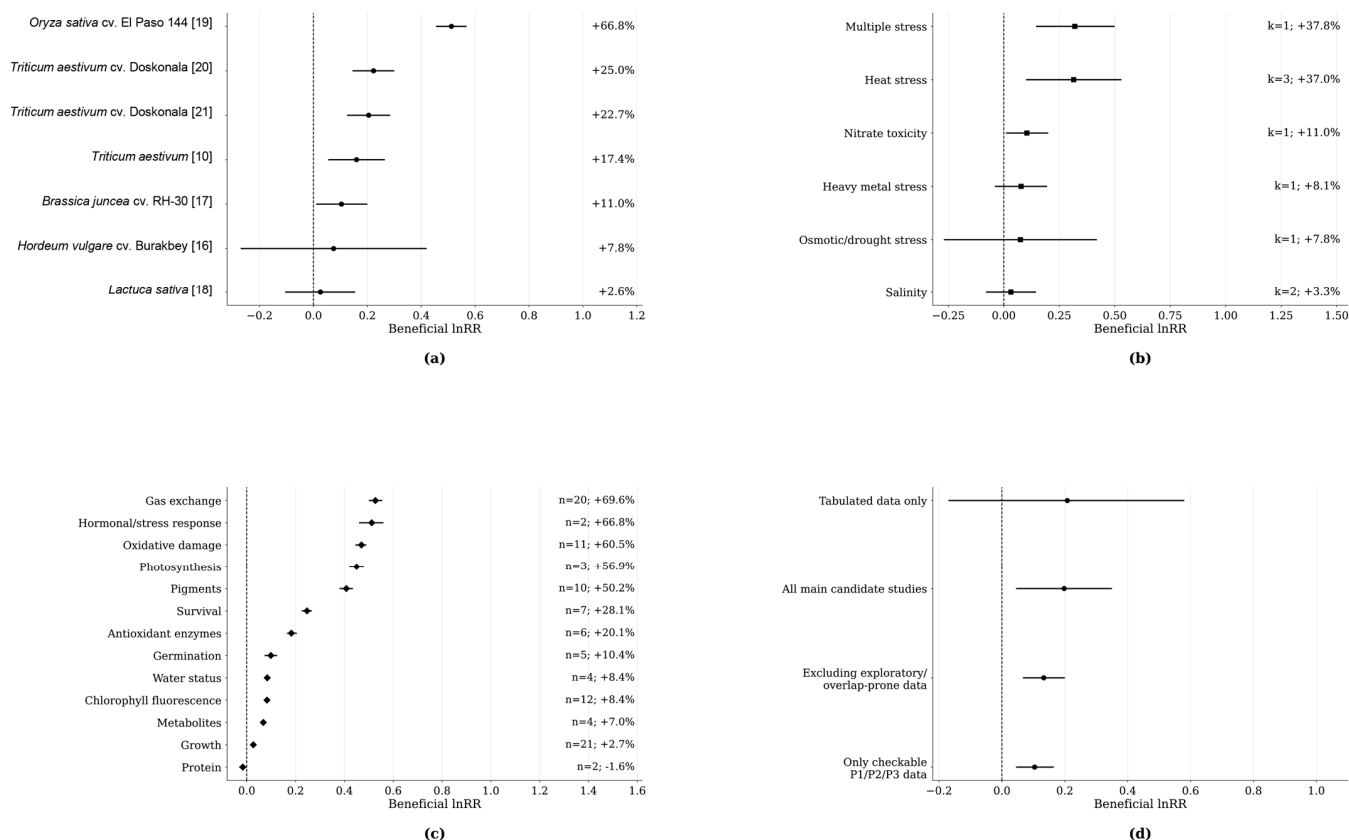


Figure 5. Exploratory quantitative synthesis of cadaverine effects in plants under abiotic stress. (a) Study-level synthesis expressed as beneficial lnRR. (b) Synthesis by abiotic-stress category. (c) Synthesis by plant response group. (d) Sensitivity analysis comparing alternative analytical scenarios. Effect sizes were harmonized so that positive values indicate a biologically beneficial or stress-mitigating direction. For the study-level synthesis, heterogeneity was high ($Q = 104.37$, $df = 6$, $p < 0.001$; $I^2 = 94.25\%$; $\tau^2 = 0.0359$), supporting the exploratory interpretation of the meta-analysis. Stress-type and response-group panels should be interpreted as exploratory numerical trends rather than formal subgroup comparisons [10,16–21].

3.5. Main Studies of the Quantitative Dataset

The studies that comprised the quantitative dataset differed substantially in species, stress type, cadaverine dose, and variables evaluated. Zhou et al. [18] investigated *Lactuca sativa* under salinity, focusing on biomass, SPAD, and gas exchange. Ozmen et al. [16] evaluated *Hordeum vulgare* under osmotic stress, with an emphasis on malondialdehyde (MDA), superoxide dismutase (SOD), catalase (CAT), ascorbate peroxidase (APX), proteins, and polyamines. Balci et al. [17] studied *Triticum aestivum* under nitrate toxicity, including RWC, fluorescence, photosynthesis, H_2O_2 , and TBARS. Tomar et al. [10] evaluated *Brassica juncea* under NaCl, Cd, Pb, and combinations, with germination, growth, and pigment responses. Cassan et al. [19] provided evidence associated with *Azospirillum*-produced cadaverine, rice growth promotion and osmotic stress mitigation. Kokorev et al. [20,21] conducted studies on wheat subjected to harmful heating (hyperthermia), examining survival, lipid peroxidation (LPO), antioxidant enzymes, and MDA.

3.6. Physiological and Biochemical Patterns

Studies on salinity and heavy metals have indicated that cadaverine helps maintain photosynthetic pigments, improves growth, and reduces ionic or metallic toxicity (Table 1). In lettuce, Zhou et al. [18] observed positive responses in growth, pigmentation, and photosynthesis under salinity. In *Brassica juncea*, Tomar et al. [10] showed that the molecule attenuated deleterious effects of NaCl, Cd, and Pb on germination, growth, and pigments. In the study by Ozmen et al. [16] conducted with barley under PEG, cadaverine was associated with reductions in MDA and modulation of SOD, CAT, and APX, suggesting an effect on redox balance. In wheat under nitrate toxicity, Balci et al. [17] observed improvements in RWC, gas exchange, and fluorescence, as well as reductions in H₂O₂ and TBARS. The studies by Kokorev et al. [20,21] reinforce the hypothesis that cadaverine participates in protection against thermal damage, contributing to greater survival and lower lipid peroxidation.

Table 1. Main studies included in the exploratory quantitative synthesis.

Study	Species/System	Stress	Response Axes	Use in Synthesis
Ozmen et al. [16]	<i>Hordeum vulgare</i>	PEG/osmotic stress	MDA, SOD, CAT, APX, proteins, polyamines	Exploratory meta-analysis
Balci et al. [17]	<i>Triticum aestivum</i>	Nitrate toxicity	RWC, fluorescence, photosynthesis, H ₂ O ₂ , TBARS	Exploratory meta-analysis
Zhou et al. [18]	<i>Lactuca sativa</i>	Salinity	Biomass, SPAD, gas exchange	Exploratory meta-analysis
Tomar et al. [10]	<i>Brassica juncea</i>	NaCl, Cd, Pb and combinations	Germination, growth, pigments	Exploratory meta-analysis
Cassan et al. [19]	<i>Oryza sativa</i>	Osmotic stress	<i>Azospirillum</i> -produced cadaverine, rice growth promotion, osmotic stress mitigation	Exploratory/supporting evidence
Kokorev et al. [20]	<i>Triticum aestivum</i>	Harmful heating	Survival, LPO, antioxidant enzymes	Exploratory/sensitivity
Kokorev et al. [21]	<i>Triticum aestivum</i>	Hyperthermia	Survival and MDA	Exploratory/sensitivity

4. Discussion

4.1. General Synthesis: Cadaverine as a Neglected Regulator of the Growth-Stress Interface

The synthesis of the corpus positions cadaverine as a regulatory candidate at the interface between plant growth and responses to abiotic stress. The body of evidence suggests that its contribution is not limited to a single physiological process but arises from the integration of redox regulation, photosynthetic protection, water status, ionic homeostasis, polyamine metabolism, and stress-associated signaling. From a physiological standpoint, the strongest and most recurrent evidence concerns attenuation of oxidative damage. Reductions in H₂O₂, MDA, TBARS, and LPO across different systems, together with increased antioxidant enzyme activity, indicate that cadaverine-associated responses are closely linked to redox protection networks.

It is important to distinguish between two types of evidence with different interpretative boundaries. Most quantitative evidence in this review comes from studies in which cadaverine was supplied exogenously under abiotic stress, allowing direct comparison between stressed plants treated with cadaverine and those not treated. Therefore, conclusions regarding growth maintenance, photosynthetic protection, antioxidant activity, oxidative damage reduction, water status, ion homeostasis, and survival are primarily supported by

exogenous cadaverine application. In contrast, evidence involving endogenous cadaverine accumulation or cadaverine-related polyamine metabolism reflects associations within the plant stress response. It should be interpreted as mechanistic or regulatory plausibility rather than direct proof of causal mitigation.

A critical point in interpreting cadaverine is its relationship with the better-studied polyamines putrescine, spermidine, and spermine. These compounds are widely recognized as components of plant stress responses because they contribute to membrane stabilization, redox regulation, osmotic adjustment, ion interactions, and signaling processes associated with ROS and nitric oxide. Cadaverine shares part of this polycationic behavior, which may explain why several cadaverine-associated responses resemble broader polyamine-mediated protection. However, cadaverine differs from the canonical polyamine pathway in that it is derived from lysine decarboxylation. In contrast, putrescine is primarily derived from the metabolism of ornithine or arginine and serves as a precursor to spermidine and spermine. This biochemical distinction suggests that cadaverine may occupy a different position in nitrogen metabolism and stress-associated metabolic adjustment.

The available evidence, therefore, supports a cautious mechanistic hypothesis rather than a definitive claim of cadaverine specificity. Cadaverine may overlap functionally with other cationic polyamines in membrane protection, oxidative damage mitigation, photosynthetic maintenance, and osmotic adjustment. Its potential distinctiveness may lie in three interconnected aspects: its lysine-derived origin, its possible dependence on organic cation transport and genotype-dependent sensitivity, and its context-dependent association with ion balance and redox regulation. Thus, cadaverine should not be interpreted as a simple substitute for putrescine, spermidine, or spermine. Instead, it should be considered a regulatory candidate whose role may depend on the species, stress type, dose, route of application, and transport capacity. Direct comparative experiments with cadaverine, putrescine, spermidine, and spermine under identical stress conditions are still needed to determine whether cadaverine has a unique physiological signature or whether its effects largely reflect shared properties of cationic polyamines.

The preservation of photosynthetic function constitutes another central axis of interpretation. In lettuce and wheat studies, cadaverine was associated with the maintenance of pigments, gas exchange, and chlorophyll fluorescence parameters, suggesting a potential role in protecting the photosynthetic apparatus under stress. This pattern links oxidative damage, membrane integrity, stomatal regulation, and photochemical efficiency as interconnected physiological responses. However, the proposed mechanisms do not have the same level of experimental support. Evidence for antioxidant defense, photosynthetic protection, ion homeostasis, growth maintenance, water status, survival, and stress tolerance is directly supported by the reviewed plant studies. In contrast, the involvement of nitric oxide, ethylene signaling, biotin metabolism, and broader polyamine-related regulatory pathways should be interpreted as mechanistic hypotheses requiring further validation. Figure 6 summarizes these relationships in an evidence-graded conceptual model, presenting cadaverine as a regulatory node that may connect redox protection, photosynthetic performance, ion balance, growth, and abiotic stress tolerance.

Figure 7 summarizes an integrative conceptual model of cadaverine-associated responses under abiotic stress in plants. The model positions cadaverine as a regulatory node connecting different sources, including endogenous biosynthesis from lysine, exogenous application, and microbial- or rhizosphere-derived production, and the physiological processes involved in stress tolerance. Exposure to salinity, water or osmotic deficit, high temperature, heavy metals, nitrate toxicity, and oxidative stress may trigger metabolic and physiological changes that converge on cadaverine-associated responses related to redox

regulation, photosynthetic protection, ion homeostasis, water status, growth maintenance, and survival.

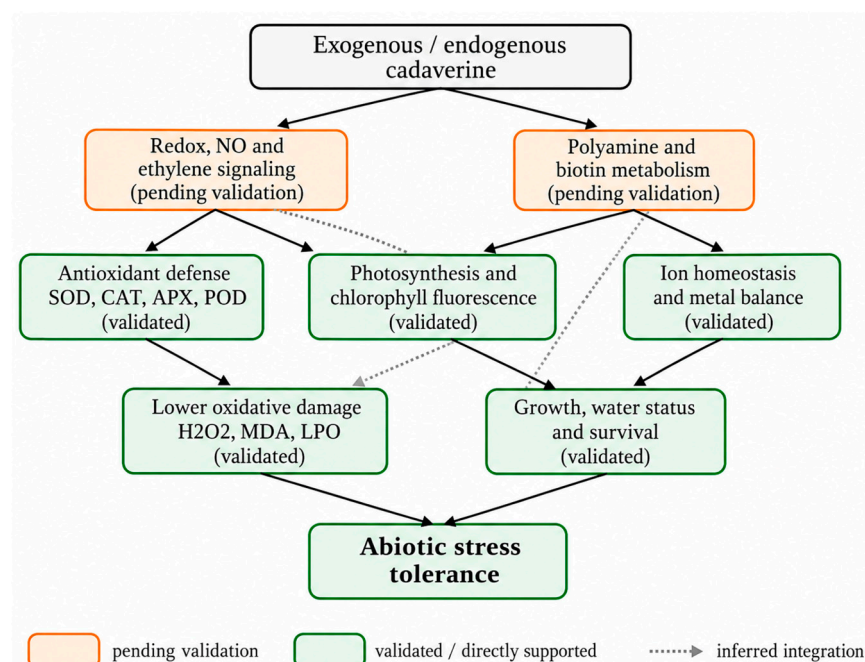


Figure 6. Evidence-graded conceptual model of cadaverine action under abiotic stress. Orange boxes indicate mechanisms that remain pending validation, whereas green boxes indicate modules and outcomes directly supported by the reviewed plant studies. Solid arrows represent the main proposed relationships among cadaverine-associated pathways, and dotted arrows indicate inferred integration or mechanistic cross-talk.

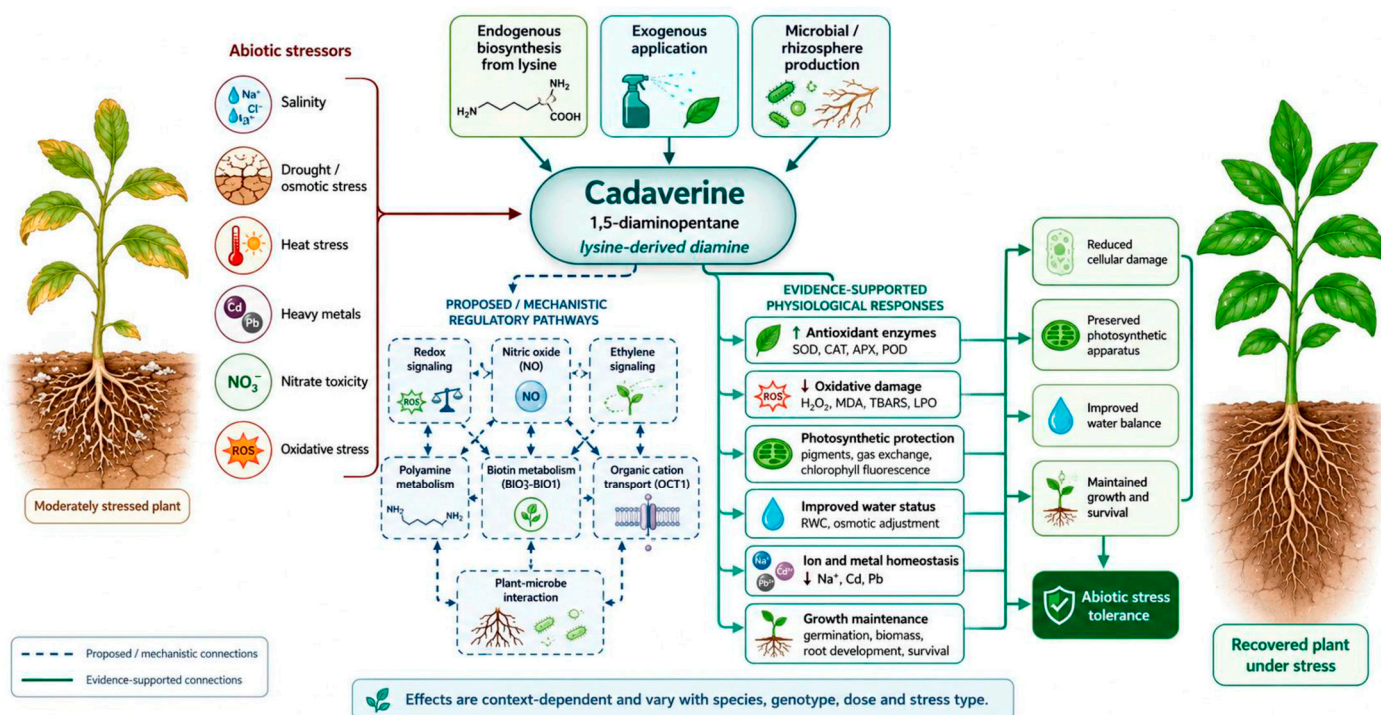


Figure 7. Integrative conceptual model of cadaverine-associated responses under abiotic stress in plants. Dashed blue lines indicate proposed or mechanistic connections requiring further validation, whereas solid green lines indicate evidence-supported physiological responses. Biological interpretations were manually checked against the reviewed literature. Assisted by ChatGPT-5.5 (<https://chatgpt.com>, accessed on 1 July 2026).

The proposed connections in the model indicate that cadaverine may participate in redox signaling, nitric oxide signaling, ethylene signaling, polyamine metabolism, biotin metabolism, organic cation transport, and plant-microbe interactions. These pathways still require further experimental validation, but they help explain the multifactorial nature of the responses observed across different species and stress conditions. In parallel, the physiological responses with stronger support in the literature include increased activity of antioxidant enzymes, such as SOD, CAT, APX, and POD, reduced oxidative damage, indicated by lower levels of H₂O₂, MDA, TBARS, and LPO, preservation of photosynthesis, improved water status, regulation of ionic and metal homeostasis, and maintenance of growth, germination, root development, and survival.

Taken together, these responses suggest that cadaverine should not be interpreted merely as a secondary diamine derived from lysine metabolism, but rather as a potential regulatory component integrated into cellular protection networks and physiological performance under stress. However, the effects of cadaverine are context-dependent and vary according to the experimental conditions, species, genotype, applied dose, application method, and type of stress.

4.2. Mechanistic Basis of Cadaverine Action

4.2.1. Perception, Transport and Root Growth

The cellular uptake of cadaverine should be interpreted in the light of its nature as a protonatable aliphatic diamine, whose positive charge at physiological pH limits purely passive transmembrane diffusion and makes plausible the participation of transport systems for organic cations, polyamines, and charged nitrogenous metabolites. Unlike neutral or weakly lipophilic molecules, cadaverine encounters a selective electrochemical barrier in the plasma membrane: its access to the cytosol probably depends on gradients of membrane potential, energy status, apoplastic pH, competition with other polyamines, and availability of transporters with affinity for organic cations [4,13]. This characteristic is particularly relevant under abiotic stress conditions, in which salinity, drought, nitrate excess, metals, and hyperthermia alter membrane polarization, H⁺ flux, H⁺-ATPase activity, cell wall composition, and apoplastic permeability. Thus, the efficacy of exogenous cadaverine cannot be reduced to the concentration applied to the growth medium or leaf surface; it depends on the plant's ability to internalize, redistribute, compartmentalize, and metabolize diamine.

The evidence regarding OCT1 should be interpreted with caution. In *Arabidopsis thaliana*, natural variation in OCT1 expression was associated with differences in the primary root length response to cadaverine. However, this association does not by itself demonstrate causal transport-mediated control or define a universal magnitude of effect [13]. In the present synthesis, this evidence is therefore used not to repeat the introductory description of the study, but to support a mechanistic hypothesis: genotype-dependent variation in organic cation transport may influence cadaverine entry, accumulation, distribution, or cellular sensitivity. Under abiotic stress, this hypothesis is relevant because cadaverine is a polycationic molecule whose intracellular distribution may be functionally connected with ion balance, membrane stability, and redox regulation. Direct experimental tests are still needed to determine whether OCT1 or related transporters causally link cadaverine transport with stress tolerance.

In root development, cadaverine appears to act at an intersection zone between growth, primary metabolism, and stress signaling. The root is simultaneously an organ of absorption, an environmental sensor, and an acclimatization platform, and the modulation of its growth by cadaverine may affect cell division in the meristem, elongation in the elongation zone, cell wall organization, local redox balance, polyamine metabolism, and hormonal communication. The proposed link between cadaverine and the biotin pathway in *Arabidopsis*

adds a particularly sophisticated mechanistic layer: by interfering with biotin biosynthesis, cadaverine can affect biotin-dependent carboxylase enzymes, fatty acid metabolism, carbon homeostasis, and cell expansion processes necessary for primary root growth [14]. This interaction suggests that the root response to cadaverine is not only osmoprotective or antioxidant, but can also reprogram key points of developmental metabolism.

4.2.2. Crosstalk with Nitric Oxide and Ethylene

Cadaverine should be interpreted as a regulatory node at the intersection of polyamine metabolism, redox state, nitrogen metabolism, and gas messengers, particularly nitric oxide (NO). In this review, the term regulatory node refers to a molecule positioned at the convergence of multiple stress-related processes, without implying that cadaverine has been fully validated as a canonical signaling molecule. Its relevance lies not only in its potential ability to stabilize membranes or attenuate oxidative damage, but also in its possible role in modulating nitrosative and redox-associated responses in stressed tissues. In plants exposed to salinity, hyperthermia, nitrate excess, metals, or water deficit, NO acts as a second messenger, regulating stomatal closure, antioxidant enzyme activity, post-translational protein modifications, Ca^{2+} homeostasis, gene expression, and metabolic adjustment [11,21]. Cadaverine may influence this network in multiple ways: by altering the cellular redox state, it may affect NO-associated pathways, including nitrate reductase-dependent and oxidative routes, although this relationship remains context-dependent; by modulating polyamine metabolism, it may affect amino catabolism fluxes associated with H_2O_2 production; and, by interacting with membranes and cations, it may modify cellular microdomains where Ca^{2+} , reactive oxygen species (ROS), and NO functionally converge.

The functional interaction between cadaverine and NO seems to assume special importance in rapid stress responses, in which the cell needs to convert environmental disturbances into coordinated changes in metabolism, defense, and survival. Under hyperthermia, cadaverine-associated protection has been linked to the involvement of NO and other mediators, suggesting that the diamine may induce a form of nitrosative signaling-dependent cellular priming [21]. In this scenario, cadaverine could promote a transient, spatially controlled elevation of NO, which in turn would activate or modulate target proteins via S-nitrosylation, thereby affecting antioxidant enzymes, Ca^{2+} signaling components, heat shock proteins, transcription factors, and cellular repair elements. NO can also interact with ROS derived from NADPH oxidases, mitochondria, and peroxisomes, generating redox-nitrosative pulses that serve as alarm signals rather than merely toxic byproducts.

The relationship between cadaverine and ethylene adds a layer of complexity because polyamine metabolism and ethylene biosynthesis share common metabolic and physiological pathways. Although cadaverine is derived directly from lysine by LDC and is not similarly dependent on the aminopropylated network that connects S-adenosylmethionine metabolism with spermidine/spermine biosynthesis and ethylene production, its accumulation may influence the polyamine-ethylene network by effects on redox status, senescence, root growth, nitrogen metabolism, and expression of ACS/ACO-associated genes. Evidence of NaCl and ethylene-dependent cadaverine accumulation in *Mesembryanthemum crystallinum* suggests that diamine may not act simply against the ethylene pathway, but within a feedback loop in which ethylene contributes to cadaverine induction or redistribution. In contrast, cadaverine modulates the intensity of ethylene effects on growth, senescence, and defense [9].

4.2.3. Redox Protection and Stabilization of Membranes

The redox protection conferred by cadaverine should be understood as a bifunctional process, in which the molecule can act both by immediate physicochemical mechanisms and by metabolic and transcriptional reprogramming of longer duration. Due to its diamine nature and protonatability at physiological pH, cadaverine behaves as a cationic species capable of electrostatically interacting with negatively charged cell and subcellular surfaces, including anionic phospholipids, cell wall carboxylic groups, nucleic acids, acid proteins, and membrane domains enriched in negative charges [1,4]. This property is particularly relevant in chloroplasts, where abiotic stress promotes over-reduction of the electron transport chain, excessive formation of reactive oxygen species, and peroxidation of the thylakoid membrane lipids. By associating with anionic surfaces and oxidation-sensitive lipid microdomains, cadaverine can help reduce the spread of peroxyl radicals, limit bilayer disorganization, preserve the controlled fluidity of membranes, and stabilize the spatial arrangement of thylakoid-associated photosynthetic complexes.

This physicochemical component, however, does not exhaust the redox function of the cadaverine. The molecule also appears to participate in priming processes, in which prior or concomitant exposure to diamine primes the cell to respond more efficiently to stress-induced ROS production. Rather than acting as a direct scavenger alone, cadaverine can modulate the expression and/or activity of antioxidant enzymes, including SOD, CAT, APX, guaiacol peroxidases, glutathione reductase, and components of the ascorbate-glutathione cycle [16,17,21]. SOD converts $O_2^{\bullet-}$ to H_2O_2 , reducing the immediate toxicity of the superoxide; CAT and APX remove H_2O_2 in distinct compartments, preventing its sustained accumulation from leading to protein oxidation, lipid peroxidation, and chloroplast dysfunction.

The duality between physical protection and transcriptional priming makes cadaverine especially interesting as a regulator of redox homeostasis under abiotic stress. On the one hand, its positive charge allows for rapid interactions with membranes and macromolecules, stabilizing critical structures before lipid peroxidation becomes irreversible; on the other hand, its integration into polyamine metabolism can activate more complex redox circuits, including changes in Ca^{2+} , NO, H_2O_2 , amine oxidase activities, signaling by MAPKs, and expression of antioxidant genes. Oxidation of diamines by amine oxidases can generate H_2O_2 , aldehydes, and ammonia, suggesting that cadaverine may also contribute to controlled redox signals, provided sufficient antioxidant capacity is present to prevent toxicity [3,6]. Thus, cadaverine should not be described solely as a chemical antioxidant; it acts as a modulator of cellular redox architecture, combining membrane stabilization, peroxidation limitation, the generation or modulation of transient oxidative signals, and the activation of ROS-removal enzyme systems.

4.2.4. Osmotic Adjustment and Overall Resilience

Osmotic adjustment is one of the most plausible mechanisms explaining cadaverine's contribution to plant resilience under water deficit, salinity, excess solutes, or stressors that disrupt cellular water potential. Under adverse conditions, turgor loss, reduced cell expansion, protein dehydration, and membrane instability result from progressive inability to maintain the balance between water absorption, retention, and redistribution. Cadaverine, due to its cationic nature and its insertion in nitrogen metabolism, can contribute to this balance by direct and indirect mechanisms. Directly, it can interact with negatively charged cell wall surfaces, phospholipids, and membrane proteins, thereby favoring the structural stability of cellular interfaces subject to osmotic compression and dehydration. Indirectly, it can modulate responses associated with water status, including the maintenance of relative

water content, the preservation of membrane integrity, the reduction in electrolyte leakage, and the sustained photosynthetic activity under water limitation [16,17].

The accumulation of proline is one of the most recurrent mechanisms of osmotic adjustment in plants under stress, and cadaverine can interact with this response at the metabolic and signaling level. Proline is primarily synthesized from glutamate by the sequential action of Delta1-pyrroline-5-carboxylate synthetase (P5CS) and P5C reductase. At the same time, its degradation involves proline dehydrogenase and P5C dehydrogenase, forming a cycle closely associated with redox balance, nitrogen metabolism, and NADP(H) availability. Cadaverine may favor proline accumulation by stimulating redox priming pathways and modulating the relationship among ROS, NO, and the expression of genes associated with osmoprotection. In functional terms, proline not only acts as a compatible osmolyte but also stabilizes proteins and membranes, protects photosynthetic complexes, contributes to ROS removal, preserves macromolecular structures, and serves as a reversible reservoir of carbon and nitrogen during post-stress recovery. Thus, when cadaverine studies report higher relative water content, reduced oxidative damage, or improved physiological performance, such responses should be interpreted as part of an integrated circuit of water conservation, macromolecular protection, and energy maintenance.

In addition to proline, cadaverine may be related to the accumulation of soluble carbohydrates, reducing sugars, sucrose, and other compatible solutes that contribute to cellular osmotic potential and membrane protection under stress. The preservation of photosynthesis by cadaverine, by maintaining pigments, photochemical efficiency, and thylacoidal integrity, can sustain the supply of carbonaceous skeletons necessary for osmolyte synthesis and respiratory maintenance. At the same time, membrane stabilization and the reduction in lipid peroxidation can preserve transporters, channels, and pumps needed to regulate water and ion fluxes, including H⁺-ATPases, K⁺ channels, and transport systems associated with solute compartmentalization. This interplay among carbon, nitrogen, and water status is essential for understanding the extent of cadaverine's action: the diamine does not act in isolation as the main osmolyte, but as a modulator of a metabolic environment in which proline, sugars, antioxidants, membranes, and transporters become functionally coordinated.

Taken together, the mechanisms discussed support the interpretation that the beneficial effects observed in the exploratory meta-analysis result from a physiological protection network rather than an isolated response. Cadaverine may be transported by organic cation transporters, including OCT1 and functionally related transporters, thereby linking cellular transport to genotype-dependent sensitivity, ionic homeostasis, and redox regulation. In parallel, cadaverine-associated responses may involve interactions with biotin-related pathways and primary metabolism, NO and ethylene circuits, membrane stabilization, reduced lipid peroxidation, induction of SOD, CAT, and APX, preservation of the photosynthetic apparatus, and osmotic adjustment through proline and compatible solutes. This mechanistic convergence helps explain why, despite the small number of independent studies and the high experimental heterogeneity, the quantitative synthesis showed a generally favorable trend. Cadaverine, therefore, emerges as a neglected regulatory candidate whose action may involve the integration of transport, root growth, redox-nitrosative signaling, membrane protection, osmotic metabolism, and the maintenance of physiological performance under abiotic stress.

4.3. Limitations, Quality of Evidence and Interpretative Implications

The interpretation of the meta-analysis should be approached with caution. The average positive effect observed at the study level is biologically coherent and reinforces the regulatory potential of cadaverine, but does not eliminate relevant limitations: a small

number of independent studies, predominance of controlled conditions, low uniformity of doses and treatments, concentration on short-term physiological responses, scarcity of data on productivity or performance in the field, absence of a prospectively registered protocol, and inability to formally assess publication bias. The absence of protocol registration may increase the risk of selective reporting or post hoc analytical decisions. This limitation was partly mitigated by explicit reporting of the search strategy, eligibility criteria, screening procedures, data extraction rules, synthesis decisions, analytical structure, PRISMA flow diagram, and completed PRISMA 2020 checklist. Publication bias and small-study effects could not be reliably tested because the quantitative synthesis included only seven independent studies. Although 125 effect sizes were extracted, many outcomes originated from the same studies and therefore could not be treated as independent observations for funnel-plot or regression-based publication bias analyses. Thus, quantitative results should be understood as an indication of general patterns and not as a definitive agronomic recommendation.

The observed heterogeneity also has biological significance. Differences in species, application routes, developmental stage, stress severity, and response group can profoundly alter the relationships among cadaverine, redox, NO, ethylene, root growth, and osmotic adjustment. The scarcity of direct comparative studies among cadaverine, putrescine, spermidine, and spermine still makes it impossible to determine whether the observed effects are cadaverine-specific or reflect general properties of cationic polyamines. The field, therefore, needs mechanistically designed studies with dose–response, field validation, productivity measurements, and the integration of physiology, transcriptomics, metabolomics, and transport analysis.

4.4. Scientific Gaps and Future Research Agenda

The literature reveals consistent gaps that limit mechanistic and translational interpretations of cadaverine in plant responses to abiotic stress. To strengthen the structural coherence of the research agenda, Table 2 organizes future priorities into two functionally distinct research routes. The first route addresses the specificity for cadaverine and aims to determine whether its effects can be distinguished from those of other cationic polyamines, such as putrescine, spermidine, and spermine. The second route addresses transport-dependent stress regulation and aims to test whether cadaverine uptake, compartmentalization, and organic cation transporters, such as OCT1 or functionally related transporters, link ion homeostasis, redox regulation, and stress tolerance. Together, these routes move from comparative biochemical specificity to mechanistic validation of transport-linked physiological protection.

Table 2. Priority research routes for cadaverine studies in plant abiotic stress resilience.

Core Scientific Question	Current Knowledge Gap	Recommended Research Route	Key Measurements and Expected Outputs
Is cadaverine-specific activity distinguishable from the general effects of cationic polyamines?	Current evidence does not clearly separate cadaverine-specific effects from broader responses shared with putrescine, spermidine, and spermine.	Conduct comparative dose–response experiments using cadaverine, putrescine, spermidine, and spermine under the same stress conditions, with standardized doses, application routes, developmental stages, and response variables.	Quantify growth, photosynthesis, oxidative damage, antioxidant enzymes, osmotic adjustment, ion accumulation, and recovery after stress. Expected outputs include identification of cadaverine-specific versus polyamine-shared effects, optimal dose ranges, and clearer criteria for defining cadaverine as a distinct regulator of stress responses.

Table 2. Cont.

Core Scientific Question	Current Knowledge Gap	Recommended Research Route	Key Measurements and Expected Outputs
Does cadaverine transport regulate stress tolerance through ion homeostasis and redox control?	The involvement of OCT1 and functionally related organic cation transporters suggests a possible link among cadaverine uptake, intracellular distribution, ionic balance, membrane stability, and oxidative stress mitigation, but direct causal evidence remains limited.	Use transporter mutants, contrasting genotypes, transporter expression analysis, tracer-based cadaverine uptake assays, and controlled salinity, metal, osmotic, or nitrate-stress experiments. Promising combinations should subsequently be validated in greenhouse and field conditions.	Measure cadaverine uptake and compartmentalization, OCT1 or transporter-related expression, Na ⁺ , K ⁺ , heavy-metal accumulation, ROS, MDA, electrolyte leakage, NO, SOD, CAT, APX, chlorophyll fluorescence, gas exchange, biomass, yield, and stress recovery. Expected outputs include validation of transport-dependent mechanisms and clarification of whether cadaverine-mediated protection is linked to ion balance and redox regulation.

5. Conclusions

The available literature supports the interpretation that cadaverine participates in plant responses to abiotic stress and may act as a regulatory molecule at the interface among growth, redox metabolism, photosynthesis, water status, and ionic homeostasis. The main response axes associated with cadaverine include mitigation of oxidative damage, preservation of the photosynthetic apparatus, maintenance of water status, modulation of growth, and adjustment of ionic homeostasis. These responses should not be interpreted in isolation, but as components of an integrated network involving metabolism, redox regulation, transport, and physiological protection.

The scientometric component showed that the field is undergoing conceptual expansion, although it remains limited in volume and dispersed across multiple subthemes. The exploratory meta-analysis indicated a positive average beneficial effect, but with high heterogeneity, reinforcing the need for interpretative caution. Taken together, the evidence suggests that cadaverine is more than a stress-associated metabolic byproduct and represents a promising regulatory candidate for fundamental research on plant responses to abiotic stress. However, its agronomic application potential remains preliminary. Most available studies were conducted under controlled conditions, focused on short-term physiological responses, and rarely evaluated yield, crop quality, field performance, or economic feasibility. Therefore, cadaverine should not yet be considered a ready-to-use agronomic recommendation. Its advancement as a translational tool will depend on standardized dose–response assays, comparative studies with other polyamines, crop- and stress-specific validation, and greenhouse and field trials designed to test productivity, quality, and stress-recovery outcomes under realistic agronomic conditions.

Supplementary Materials: The following supporting information can be downloaded at <https://www.mdpi.com/article/10.3390/stresses6030046/s1>: Supplementary File S1: PRISMA 2020 checklist (DOI: 10.5281/zenodo.210145344).

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