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Livelihood impact of alternative crop adoption under climate stress: a meta-analysis

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Climate change is depressing yields of major staple crops, heightening pressure on farming systems and accelerating crop transitions in marginal environments. In response, farmers are increasingly adopting stress-tolerant alternative crops as an adaptation strategy. However, evidence on the livelihood associations of such adoption remains fragmented. To address this gap, this meta-analysis quantifies the associations between stress-tolerant alternative crop adoption and livelihood outcomes (income, food security, resilience and adaptive capacity). Meta-regression is used to assess spatiotemporal heterogeneity and examine whether estimated associations vary across key explanatory factors, crop types and regional contexts. Based on 56 empirical studies published between 2000 and 2025, 247 percentage-change effect-size estimates were extracted across the broader evidence base. Results suggest that drought-tolerant crops are positively associated with food security-related outcomes ($\beta = 0.175$; $p < 0.05$), heat-tolerant crops with resilience-related outcomes ($\beta = 0.549$; $p < 0.01$), and salt-tolerant crops with positive associations across income ($\beta = 0.195$; $p < 0.10$), food security ($\beta = 0.225$; $p < 0.10$), resilience ($\beta = 0.395$; $p < 0.01$) and adaptive capacity ($\beta = 0.683$; $p < 0.01$). Adoption-related associations are consistently linked to institutional support, credit access and market linkages, although the relative importance of these factors varies by climate stressor. Overall, the findings suggest that stress-tolerant alternative crop adoption is more consistently associated with food security and resilience than with short-term income-related outcomes, and that policy design may benefit from greater attention to stressor-specific adoption conditions.

KEYWORDS

abiotic stress, adaptive capacity, climate change adaptation, food security, livelihood resilience, stress-tolerant crops

1 Introduction

Climate change, driven by rising temperatures and the increasing frequency of extreme weather events, is exerting pressure on agricultural systems worldwide (Fróna et al., 2021). A prominent consequence is the decline in yields of major staple crops, including rice, maize, and wheat, threatening global food security (Lesk et al., 2016; Zhao et al., 2017). Droughts and extreme heat have been linked to wheat yield losses and crop failures even in advanced agricultural systems in developed countries (Asseng et al., 2015; Hultgren et al., 2025). These risks are especially acute in developing tropical regions, where lower adaptive capacity heightens vulnerability—notably in Sub-Saharan Africa, Southeast Asia, and Western Asia (Knox et al., 2012; FAO, 2017). Given these conditions, adjustments in cropping systems has become increasingly essential for farmers to cope with rising climate risks.

Against this backdrop, shifting from traditional staples to alternative crops has emerged as an important adaptation strategy, particularly in marginal environments (Elouafi et al., 2020). Building on existing definitions of alternative crops (Elouafi et al., 2020), climate-change resilient crops (Mampholo et al., 2024), and stress-tolerant crops (González Guzmán et al., 2022), we distinguish in this study between "alternative crops"—defined as crops and varieties introduced or promoted as alternatives to dominant staple systems—and their stress-tolerant or climate-resilient attributes. We focus specifically on alternative crops that the empirical literature documents as drought-, heat-, or salinity-tolerant options relative to existing staples and, for brevity, we refer to these as stress-tolerant alternative crops, which form the core analytical focus of this study. While crop transitions are part of broader adaptive practices, our empirical analysis is restricted to crop-based adaptation and excludes non-crop practices (e.g., irrigation, input management, or livestock-related adjustments). In practice, these transitions may involve both crop switching (replacing existing staple crops) and diversification (adding stress-tolerant alternative crops alongside existing crops). This category encompasses newly introduced species as well as indigenous, underutilized, and previously neglected crops selected for their documented suitability under adverse climatic conditions (Isleib, 2012; Mabhaudhi et al., 2019).

Evidence of this transition has been documented across diverse regions. In arid and semi-arid areas of Iran and India, farmers have shifted from rice toward drought-tolerant cereals and legumes that require less water (Davis et al., 2018; Yazdanpanah et al., 2022). In Taiwan, parts of rice and tea cultivation areas have been converted to sweet potato and soybean to reduce irrigation demand (Lin and Chiang, 2025). In the Mediterranean Basin, crops such as quinoa, teff, camelina, and chia have been promoted as well-adapted to hot and arid conditions (Hermuth et al., 2016). Studies also indicate that salt-tolerant species—such as quinoa and *Salicornia bigelovii*—can be cultivated in saline conditions where conventional crops struggle to survive (Ismail et al., 2019). Across climate-vulnerable regions of Africa, renewed interest in underutilized crops reflects their suitability for adverse climatic environments (Mampholo et al., 2024). Taken together, these cases illustrate an ongoing adjustment in cropping systems, whereby farmers switch or diversify away from traditional staple crops toward stress-tolerant alternative crops in response to climate stress. Recent research highlights the environmental co-benefits of shifting to stress-tolerant alternative crops. Across multiple settings, crop switching has been found to reduce agricultural water demand and enhance ecosystem performance. In China, for example, crop transitions are reported to cut green water by approximately 10% and blue water use by nearly 19% (Xie et al., 2023). On the Loess Plateau, adopting drought-tolerant crops lowers gray water footprints by up to 27% (Han et al., 2023). A case study from Taiwan shows that converting 30% of rice and tea areas to sweet potato reduces both irrigation- and rainfall-derived components by 30% (Lin and Chiang, 2025). In the U.S. Southwest, a review of more than 70 climate-resilient species indicates that replacing water-intensive crops with drought-tolerant alternatives eases peak-season hydrologic stress while cutting on-farm water requirements (Silber-Coats et al., 2025). Studies also report higher nitrogen-use efficiency and lower soil erosion, reinforcing the environmental sustainability potential of these transitions.

Beyond environmental considerations, the economic implications of adopting stress-tolerant alternative crops have been widely examined, yet key questions remain. Evidence from China indicates that crop conversion, when paired with appropriate policy support and technical guidance, is associated with improvements in production efficiency and household income (Xie et al., 2023; Guan et al., 2024). In several case studies, shifting toward specialty or underutilized crops has been reported to help farmers access niche markets and diversify livelihood strategies, as illustrated by the development of Andean grains in Bolivia and Peru (Padulosi et al., 2014). However, adoption at scale faces persistent constraints, including niche market demand, limited policy support, and limited availability of quality seed and planting material, all of which may impede wider diffusion (Pradhan et al., 2021). Several value-chain bottlenecks hinder the expansion of stress-tolerant alternative crops, including poor market access, weak aggregation and processing infrastructure, limited agronomic knowledge and extension services, and yield variability (Kakabouki et al., 2021). These contrasting findings underscore ongoing debates regarding the potential and limits of adopting stress-tolerant alternative crops in practice.

Although a growing body of empirical research has examined the adoption of stress-tolerant alternative crops under diverse socioecological conditions, the evidence remains fragmented. Most of the existing literature consists of isolated case studies that vary in their objectives, indicators, and methodological approaches, limiting cross-study comparability and the ability to draw general conclusions across settings. To date, few studies have undertaken a comprehensive quantitative synthesis to evaluate the associations between stress-tolerant alternative crop adoption and food security, household income, and climate resilience across broader spatial and temporal scales. This lack of integrated evidence limits a coherent understanding of the role that stress-tolerant alternative crops may play in relation to livelihood outcomes and constrains the development of evidence-based climate change strategies and agricultural management interventions.

To address this gap, this study synthesizes empirical evidence on the livelihood outcomes associated with stress-tolerant alternative crop adoption across diverse contexts. It pursues two objectives. First, it quantifies associations between adoption and key livelihood outcomes—income, food security, resilience, and adaptive capacity—using percentage-change effect sizes within a meta-regression framework and examines how these associations vary by crop type, region, and study period. Second, it synthesizes the socio-economic, institutional, environmental, and spatiotemporal factors reported to be associated with farmers' adoption of drought-, heat-, and salt-tolerant crops. Accordingly, two research questions were specified:

1. How is the adoption of stress-tolerant alternative crops associated with key livelihood outcomes, including income, food security, resilience, and adaptive capacity?
2. Which socio-economic, institutional, environmental, and spatiotemporal factors are associated with farmers' adoption of stress-tolerant alternative crops?

2 Materials and methods

2.1 Literature search

We conducted a systematic keyword search across the Web of Science Core Collection, Scopus, CAB Abstracts, AGRIS, the FAO publications database, and Google Scholar to identify English-language studies published between 2000 and 2025. Searches were performed in titles, abstracts, and author keywords.

Search strings comprised three conceptual blocks linked via Boolean operators:

i Stress-tolerant alternative crops (e.g., "alternative crop*", "stress-tolerant crop*", "climate-resilient crop*", "drought tolerant", "heat tolerant", "salt tolerant").

ii Adoption-related terms and determinants, which were operationalized into six predefined domains: access to land, credit, markets, institutions, social networks, and environmental conditions (e.g., "adopt*", "crop switching", "crop diversification", "access to land", "credit", "market access", "institution*", "social network*", and "environmental condition*").

iii Livelihood outcomes (e.g., "household income", "food security", "resilience", "adaptive capacity").

Within each block, terms were combined using OR, and the three blocks were then intersected using AND. Comprehensive database-specific search strings, applied filters, and supplementary search procedures (including reference-list screening and citation tracking) are detailed in the Supplementary material.

Subsequently, the retrieved records were imported into a reference-management tool. In addition, the reference lists of relevant articles identified during the search process, as well as those of all included studies, were examined to identify any additional publications.

2.2 Study selection and eligibility criteria

The inclusion and exclusion criteria are detailed in Table 1. Records retrieved from all databases were exported to Zotero for automated deduplication, followed by a manual check. Screening was conducted in two stages. First, two reviewers independently screened titles and abstracts against the eligibility criteria to exclude clearly irrelevant studies and those outside the agricultural domain. Second, the full texts of potentially eligible reports—including those where eligibility remained uncertain at the title and abstract screening stage—were retrieved and assessed.

During the full-text stage, the two reviewers independently applied all criteria using a structured screening form, focusing on publication type, empirical design, and the availability of quantitative data required for effect-size calculation. Discrepancies were resolved through consensus or, if necessary, consultation with a third reviewer. To prevent double counting, when multiple publications reported analyses based on the same underlying dataset, only the most comprehensive and most recent peer-reviewed article was retained. A PRISMA flow diagram (Figure 1) shows the outcomes of the search process and provides an overview of the number of studies that were included and excluded at each screening stage.

2.3 Evaluation

To minimize bias, two independent reviewers screened records and full texts. Following Mabhaudhi et al. (2025), we also rated the topical relevance of each included study on a 5-point Likert scale (1 = least aligned with the review objective, 5 = most aligned), based on how directly it examined the adoption of stress-tolerant alternative crops and their associations with livelihood outcomes. Disagreements during the screening and scoring stages were resolved through discussion, with a third reviewer adjudicating when necessary (Page et al., 2021). The relevance scores were used descriptively to characterize the evidence base and were not used as weights in the main meta-regressions.

To estimate weighted meta-regression models, each percentage-change effect-size estimate was assigned a corresponding standard error, which was incorporated through inverse-variance weighting to reflect differences in precision across observations (Meemken, 2020). Potential explanatory variables (moderators) were selected based on their frequency of discussion and reported relevance in the reviewed literature. Their associations with effect-size estimates were subsequently examined in the meta-regression analysis (Neves et al., 2024).

TABLE 1 Inclusion/exclusion criteria applied in this study.

Inclusion	Exclusion
Articles published in English.	Articles not printed in English.
Articles published 2000–2025 on adoption of stress-tolerant alternative crops and livelihood outcomes.	Studies outside agriculture (e.g., forestry, urban systems) or published before 2000.
Peer-reviewed journal articles.	Conference abstracts, theses, book chapters, and other grey literature without a clearly documented peer-review process.
Empirical, quantitative studies including a comparison group (adopters vs. non-adopters, conventional crops, or before–after adoption).	Qualitative or review papers without empirical data.
Report at least one measurable outcome: income, food security, resilience, or adaptive capacity.	Laboratory-only experiments with unrealistic conditions and limited field relevance.
Provide sufficient quantitative information for effect-size estimation (e.g., means, sample sizes, percentages, or other extractable comparative statistics).	Studies lacking essential statistics needed for effect-size estimation.
No geographic restrictions; studies from all regions considered.	

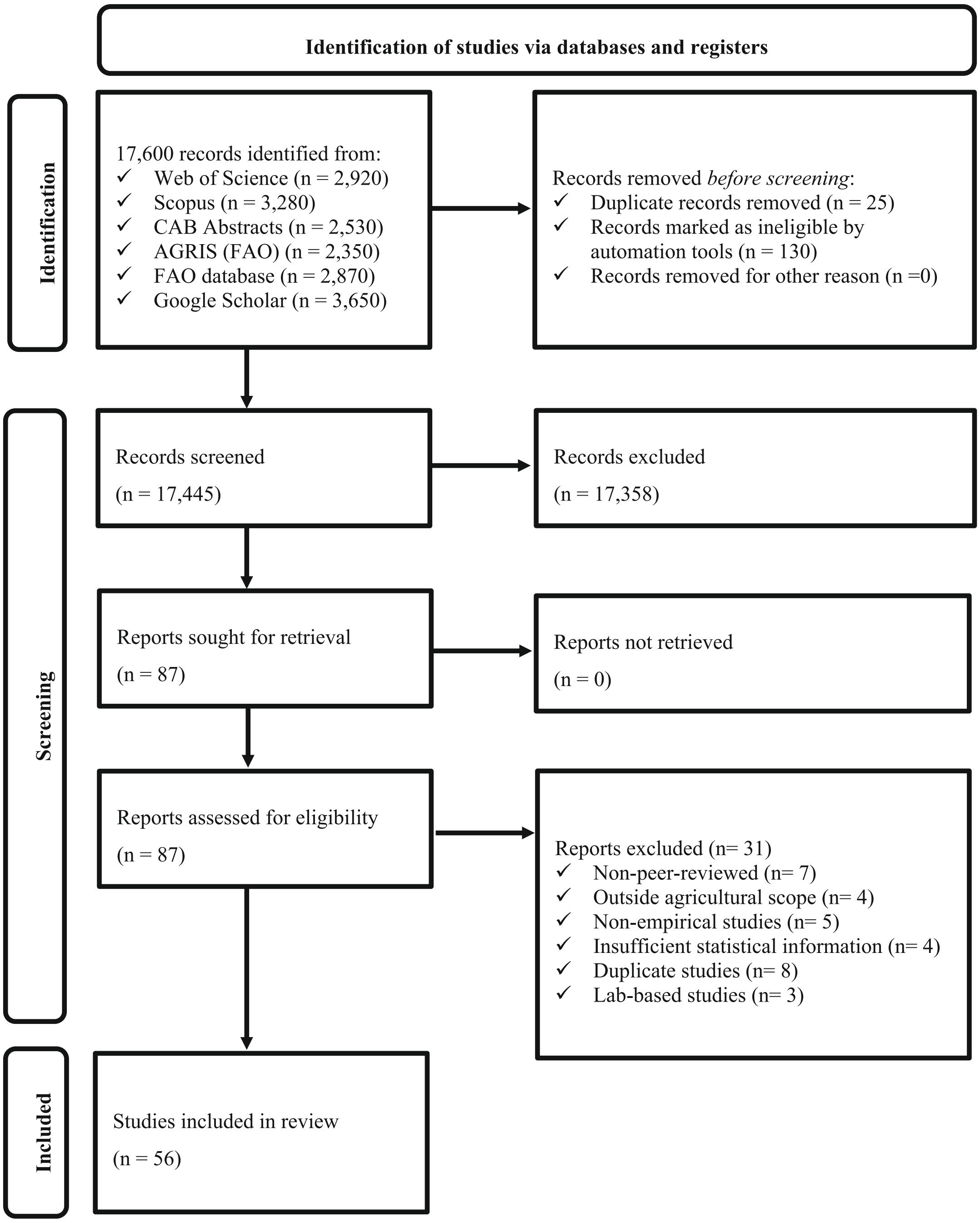

FIGURE 1
PRISMA diagram for literature selection. Source: study findings.

2.4 Data extraction

The quantity and quality of data reported in the original articles varied considerably, even when studies addressed the same issue. Clear decisions about which results to extract and how to extract them are essential, as they can influence meta-analytic findings. Therefore, the data extraction procedure should be explicitly described, and the extracted metrics should be consistent across articles (Pigott and Polanin, 2020; Vesco et al., 2020). In this study, data were extracted from 56 included articles.

Following Narayanan et al. (2020) and Pigott and Polanin (2020) we defined three coding domains (Table 2) to harmonize terms reported by each article: (i) main factors, (ii) alternative crops, and (iii) spatial and temporal scale. Data extraction proceeded in three stages. First, we recorded qualitative descriptors for each domain from the full text. Second, we classified variables as continuous or binary. Third, we assigned dummy indicators (1 if the article addressed a specific term; 0 otherwise). The resulting coding scheme and descriptive statistics for all variables used in the meta-analysis are presented in Table 2.

To provide a guiding framework for planning interventions across scales, the domains were operationalized as follows:

- Main factors: Contextual enabling conditions that may influence adoption of stress-tolerant alternative crops, including access to

TABLE 2 Descriptive statistics of variables used in the meta-analysis factor.

Factor	Description	Mean	Std. dev.	Min	Max
Livelihood outcome					
Income	The percentage change in income associated with alternative crops	0.076	0.462	−0.967	0.986
Food security	The percentage change in food security associated with alternative crops	0.123	0.466	−0.964	0.835
Resilience	The percentage change in resilience associated with alternative crops	0.039	0.491	−0.867	0.942
Adaptive capacity	The percentage change in adaptive capacity associated with alternative crops	0.046	0.457	−0.913	0.873
Main factor					
Access to land	Equal to one when access to land is analyzed	0.719	0.445	0	1
Credit	Equal to one when credit is analyzed	0.052	0.377	0	1
Markets	Equal to one when the market is analyzed	0.772	0.416	0	1
Institutions	Equal to one when the institution is analyzed	0.325	0.494	0	1
Social networks	Equal to one when the social network is analyzed	0.579	0.489	0	1
Environmental conditions	Equal to one when the environmental condition is analyzed	0.325	0.495	0	1
Stress-tolerant alternative crops					
Drought -tolerant crops	Equal to one when drought-tolerant crops are analyzed	0.059	0.520	0	1
Heat-tolerant crops	Equal to one when heat-tolerant crops are analyzed	0.045	0.461	0	1
Salt-tolerant crops	Equal to one when salt-tolerant crops are analyzed	0.049	0.475	0	1
Spatial and temporal scale					
Africa	Equal to one when the article position is located in Africa	0.438	0.492	0	1
Americas	Equal to one when the article position is located in the Americas	0.582	0.489	0	1
Asia	Equal to one when the article position is located in Asia	0.526	0.495	0	1
Europe	Equal to one when the article position is located in Europe	0.425	0.436	0	1
Oceania	Equal to one when the article position is located in Oceania	0.351	0.473	0	1
Period	Equal to one when the study was conducted after 2020	0.524	0.432	0	1

Source: Authors own work.

land, credit, markets, institutions, social networks, and environmental conditions. These variables capture farmers' adaptive capacity and socio-economic status rather than spatial or temporal scale.

- Stress-tolerant alternative crops: Crops and varieties that primary studies describe as suitable for climate-related constraints (e.g., limited water availability, high temperatures and soil salinity) and that are promoted as substitutes for dominant staple crops. At the effect-size level, this broad category was further disaggregated into three crop groups based on stressor type: drought-tolerant, heat-tolerant and salt-tolerant crops.
- Spatial and temporal scale: To capture potential variation in effect sizes across place and time, we coded the geographic region of the primary study (Africa, the Americas, Asia, Europe, and Oceania) and a period indicator (1 if the study was conducted after 2020; 0 otherwise). Geographic setting can shape estimates for both main factors and stress-tolerant alternative crops. The period indicator was included to assess whether effect-size estimates differed between more recent and earlier studies across livelihood outcome dimensions (income, food security, resilience, and adaptive capacity). Accounting for spatial and temporal scales allows assessment of whether reported associations vary across contexts (Table 2).

2.5 Effect size calculation

To obtain a comparable effect-size metric across studies, all dependent variables (income, food security, resilience, and adaptive capacity) were expressed as percentage changes between households adopting stress-tolerant alternative crops and the control group, following Meemken (2020). The effect size was calculated using Equation (1):

$$\text{Percentage change in outcome} = \left(\frac{\overline{Y_A} - \overline{Y_C}}{\overline{Y_C}}\right) \times 100 \qquad (1)$$

Where $\overline{Y_A}$ represents the mean value of the livelihood outcome for households adopting stress-tolerant alternative crops, $\overline{Y_C}$ represents the corresponding mean value for the control group, and Y refers to the livelihood outcome of interest (income, food security, resilience, or adaptive capacity). The control group consisted of non-adopters or farmers cultivating conventional staple crops.

Although percentage-change effect sizes do not incorporate study-level variance information in the same way as conventional meta-analytic effect sizes and may be sensitive to very small baseline values in the control group, they offer two practical advantages in our setting. First, they are straightforward to interpret. Second, they can be calculated without variance measures, which many of the included studies did not report. Conventional meta-analytic effect sizes, such as standardized mean differences or log response ratios, require means and variances for both groups and could therefore only be estimated for a subset of the included studies. Given the frequent absence of variance statistics in our sample, percentage-change effect sizes allowed us to retain a larger number of studies while presenting results in a form that is readily interpretable for policymakers and development practitioners.

Two meta-analytic model specifications were tested. The first model included only the main factors and alternative crops. The second model additionally included spatial and temporal scales.

Meta-regressions were run using Stata version 17 (Stata Corp, College Station, TX, United States).

2.6 Statistical analysis

Meta-regression can be implemented using either fixed- or random-effects models. Fixed-effects models assume a common underlying true effect size across studies, whereas random-effects models allow true effect sizes to vary due to between-study heterogeneity.

The general random-effects meta-regression specification is given in Equation (2):

$$M_{ij} = \alpha_0 + \sum \beta_k E_{ij,k} + \mu_j + \varepsilon_{ij} \quad (2)$$

where M_{ij} denotes the reported effect-size estimate from study j, $E_{ij,k}$ represents moderator k, β_k is the corresponding parameter estimate, α_0 is the intercept, μ_j captures the study-level random effect in random-effects specifications, and ε_{ij} is the error term. For fixed-effects specifications, the study-level random effect (μ_j) is omitted. Each effect-size estimate was weighted according to its precision using inverse-variance weighting. Residual heterogeneity in random-effects models is represented by the estimated between-study variance component (τ^2).

Our dataset included 247 effect-size estimates derived from 56 studies. Separate meta-regression models were estimated for each livelihood outcome. For the analyses presented in Table 3, models were further stratified by stressor type (drought, heat, and salinity), and random-effects specifications were applied to account for residual between-study heterogeneity. For the analyses presented in Table 4, stressor categories were included simultaneously as moderator variables within each livelihood outcome model rather than being estimated separately; these combined models were estimated using fixed-effects inverse-variance weighted meta-regression. Accordingly, Table 3 reports random-effects estimates, whereas Table 4 presents fixed-effects estimates. In the overall meta-analytic dataset, the unit of analysis was the individual effect-size estimate rather than the study. As a result, a single primary study could contribute multiple effect-size estimates across the broader evidence base when reporting different livelihood outcomes or climate stressor categories. For the reported meta-regression analyses, however, separate model-specific analytical datasets were constructed such that only one effect-size estimate from a given primary study was retained within any individual regression model. This analytical structure avoided within-model dependence arising from repeated effect-size contributions from the same study.

TABLE 3 Meta-regression results on the adoption of stress-tolerant alternative crops variables.

Variable	Drought -tolerant crops		Heat-tolerant crops		Salt-tolerant crops	
	Coefficient	Std. err.	Coefficient	Std. err.	Coefficient	Std. err.
Constant	−0.291	0.378	−0.044	0.232	−0.155	0.113
Main factor						
Access to land	0.130	0.095	−0.021	0.168	−0.102**	0.051
Credit	0.198*	0.108	−0.068	0.127	−0.146**	0.062
Markets	−0.110	0.366	0.335***	0.106	0.211***	0.056
Institutions	0.745***	0.089	−0.033	0.127	−0.027	0.071
Social networks	0.025	0.089	0.020	0.140	0.104	0.089
Environmental conditions	−0.027	0.079	0.152	0.106	0.199***	0.061
Spatial and temporal scale						
Africa	0.147*	0.084	−0.063	0.105	0.129**	0.064
Americas	−0.141*	0.079	−0.080	0.114	−0.004	0.062
Asia	−0.073	0.076	−0.061	0.107	−0.068	0.057
Europe	−0.118*	0.072	−0.251	0.194	−0.346***	0.120
Oceania	0.031	0.069	−0.194**	0.097	0.147***	0.056
Period	0.160**	0.080	0.023	0.120	0.097	0.062
R^2	93.69		20.46		83.12	
Wald chi^2	105.51		27.99		65.70	
tau^2	0.008		0.120		0.014	

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. Source: Study findings.

TABLE 4 Meta-regression results of the livelihood outcomes.

Variable	Livelihood outcome							
	Income		Food security		Resilience		Adaptive capacity	
	Coefficient	Std. err.	Coefficient	Std. err.	Coefficient	Std. err.	Coefficient	Std. err.
Constant	0.051	0.045	0.051	0.046	0.325**	0.138	0.075	0.048
Stress-tolerant alternative crops								
Drought-tolerant crops	0.028	0.053	0.175**	0.084	0.180	0.234	−0.099	0.095
Heat-tolerant crops	0.114	0.116	0.158	0.118	0.549***	0.172	0.107	0.106
Salt-tolerant crops	0.195*	0.110	0.225*	0.124	0.395***	0.136	0.683***	0.133
Spatial and temporal scale								
Africa	−0.074	0.054	0.039	0.060	−0.055	0.104	−0.072	0.078
Americas	−0.065	0.054	−0.047	0.058	0.132	0.089	0.010	0.069
Asia	0.066	0.049	0.013	0.049	−0.018	0.115	−0.065	0.054
Europe	0.031	0.091	−0.139	0.109	−0.013	0.151	0.009	0.125
Oceania	0.192***	0.054	0.247***	0.058	0.435***	0.085	0.196***	0.066
Period	0.181***	0.055	0.118*	0.065	−0.010	0.085	0.056	0.066
R^2	84.00		82.56		82.93		55.86	
Wald chi^2	44.85		44.32		47.69		37.04	

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. Source: Study findings.

3 Results

3.1 Study selection

The search identified 17,600 records from electronic databases (Figure 1). Before screening, 25 duplicate records were removed and 130 records were marked as ineligible by automation tools, leaving 17,445 records for title and abstract screening. Of these, 17,358 records were excluded, and 87 reports were retrieved and assessed for eligibility at the full-text stage. At full-text assessment, 31 reports were excluded because they were non-peer-reviewed ($n = 7$), outside the agricultural scope ($n = 4$), non-empirical ($n = 5$), lacked sufficient statistical information ($n = 4$), duplicate publications ($n = 8$), or lab-based studies ($n = 3$). Finally, 56 studies were included in the meta-analysis. The complete list of the original articles is in Supplementary Appendix A.

3.2 Descriptive statistics

The distribution of published studies on alternative stress-tolerant crops over the period 2000–2025 is shown in Figure 2. The annual number of such articles varied over time. The number of original articles per year reached a peak in 2024 within the study period. Generally, as shown in Figure 2, relatively few articles were published before 2004, whereas higher annual publication counts were observed from 2019 to 2025. The number of studies on stress-tolerant alternative crops increased notably after 2010; this pattern may reflect broader global attention to agricultural adaptation.

Figure 3 shows the continental distribution of studies on stress-tolerant alternative crop adoption. The highest proportion was observed in Asia, accounting for approximately 27% of all studies, followed by the Americas (23%) and Europe (20%). The lowest proportion of studies on the adoption of stress-tolerant alternative crops was observed in Oceania and Africa, which accounted for 16 and 14%, respectively.

Table 5 presents the categories of main factors associated with the adoption of stress-tolerant alternative crops included in the meta-analysis. Access to land accounted for the highest number of observations (57). This was followed by credit (51 observations) and social networks (48 observations). These factors therefore appear most frequently in the reviewed empirical literature.

Figure 4 shows variation in the distribution of livelihood outcomes examined in the reviewed studies, with some outcomes receiving greater attention than others. Income accounts for the highest proportion of original articles (32%), followed by food security (29%). Adaptive capacity represents 21% of the empirical studies, focusing on households' ability to adjust to climate change, while resilience accounts for the remaining 18%.

3.3 Factors associated with the adoption of stress-tolerant alternative crops

Table 3 presents the meta-regression results for three models corresponding to drought-tolerant, heat-tolerant, and salt-tolerant crop categories. These models synthesize heterogeneous estimates across main factors as well as spatial and temporal scales. The pseudo-R^2 for the drought-tolerant crop model is 93.69, suggesting that the included moderators explain a substantial proportion of the between-study heterogeneity in effect-size estimates for drought-tolerant crops. The corresponding pseudo-R^2 values for the heat-tolerant and salt-tolerant crop models are 20.46 and 83.12, respectively, indicating that the included moderators explain a substantially smaller proportion of between-study heterogeneity in the heat-tolerant model than in the other two models. The overall statistical significance of the models is indicated by the Wald χ^2 statistics reported in Table 3.

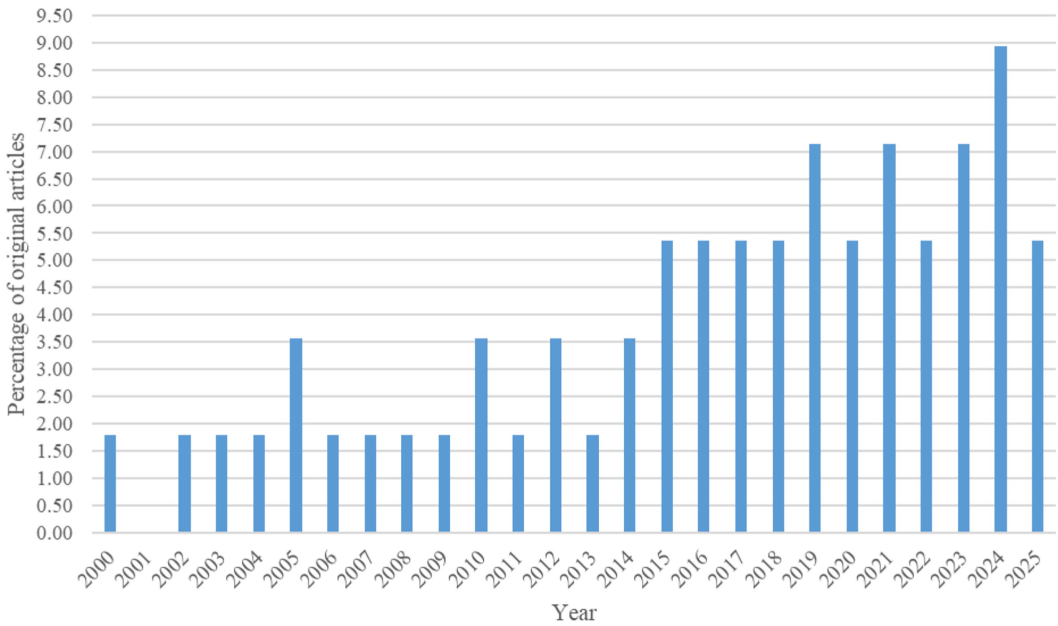

FIGURE 2
Distribution of original articles published between 2000 and 2025 on stress-tolerant alternative crop adoption and associated livelihood outcomes. Source: study findings.

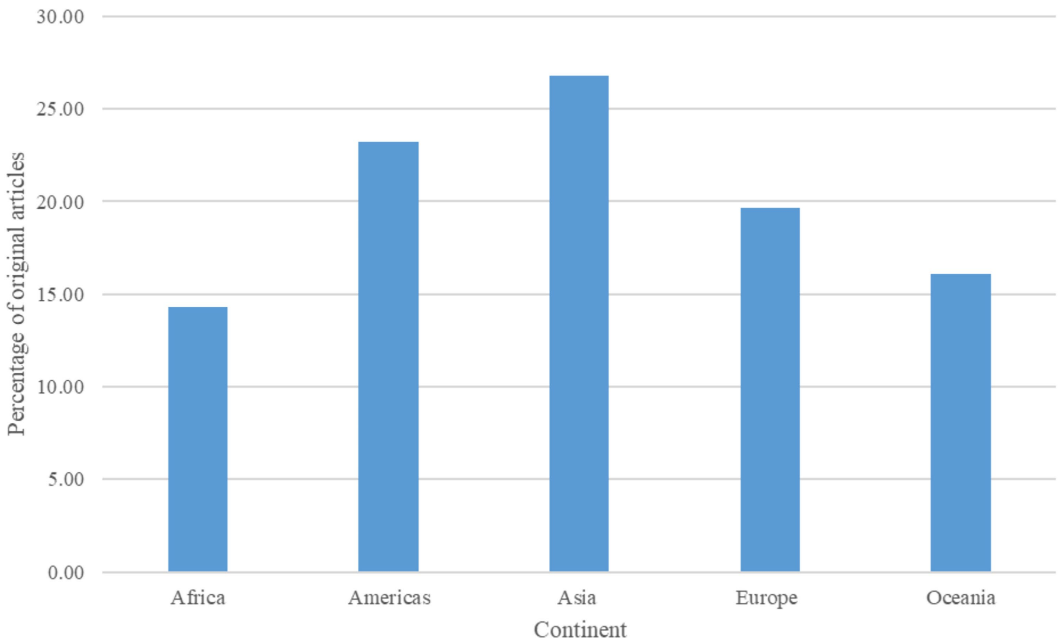

FIGURE 3
Continental distribution of studies on stress-tolerant alternative crop adoption. Source: study findings.

According to main factor terms, the results in Table 3 show that credit and institutions are positively and significantly associated with the estimated effect-size outcomes reported for drought tolerant crop adoption. Specifically, credit ($\beta = 0.198$; $p < 0.10$) and institutions ($\beta = 0.745$; $p < 0.01$) have significant positive associations with the estimated effect-size outcomes related to drought-tolerant crop adoption. Compared to credit, which has received the most attention in previous studies, institutions show a larger estimated association with the drought-tolerant crop model. The results of the heat-tolerance model show that markets ($\beta = 0.335$; $p < 0.01$) are positively and statistically significantly associated with the estimated effect-size outcomes related to heat tolerant crop adoption. This coefficient suggests that, in the underlying studies, higher market access is associated with larger estimated effect sizes related to heat-tolerant crop adoption. In the salt-tolerant crop model, access to land ($\beta = -0.102$; $p < 0.05$), credit ($\beta = -0.146$; $p < 0.05$), markets ($\beta = 0.211$; $p < 0.01$), and environmental conditions ($\beta = 0.199$; $p < 0.01$) are significantly associated with the estimated effect-size outcomes. While access to land and credit show negative associations with the estimated outcomes related to salt-tolerant crops, markets and environmental conditions show

TABLE 5 Main factors associated with stress-tolerant alternative crop adoption.

Term	Class	Number of observations
Main factor	Access to land	57
	Credit	51
	Markets	10
	Institutions	42
	Social networks	48
	Environmental conditions	39

Source: Study findings.

positive associations. Most of the primary articles focused on the main explanatory factors, whereas the results of this meta-analysis show that spatial and temporal scales, i.e., continents and period, are also associated with variation in the estimated associations related to stress-tolerant alternative crops.

The meta-regression results of the spatial and temporal moderators indicate that the dummy variable for Asia is not statistically significant in the models for drought-, heat-, or salt-tolerant crops. This suggests that, in our sample, estimates from Asian studies do not differ systematically from those in the reference category. In contrast, Africa ($\beta = 0.147$; $p < 0.10$), the Americas ($\beta = -0.141$; $p < 0.10$), and Europe ($\beta = -0.118$; $p < 0.10$) show statistically significant associations in the drought-tolerant crop model relative to the reference category. For the heat-tolerance model, the Oceania dummy is statistically significant ($\beta = -0.194$; $p < 0.05$). For salt-tolerant crops, Africa ($\beta = 0.129$; $p < 0.05$), Europe ($\beta = -0.346$; $p < 0.10$), and Oceania ($\beta = 0.147$; $p < 0.01$) show significant associations relative to the reference category. These results suggest that the estimated associations between stress-tolerant alternative crop adoption and livelihood outcomes vary across continents in our sample. However, because the meta-analysis relies on study-level summaries and a limited set of coded moderators, it cannot directly identify the drivers underlying these regional differences. The period effect indicates that articles published after 2020 report higher estimated effect-size associations related to drought-tolerant crop adoption ($\beta = 0.160$; $p < 0.05$), suggesting stronger reported associations in more recent studies.

3.4 Livelihood outcomes associated with stress-tolerant alternative crop adoption

Meta-regression results for four models of livelihood outcomes, namely income, food security, resilience, and adaptive capacity, are shown in Table 4. These models examine variation in effect-size estimates associated with stress-tolerant alternative crops across studies. The R^2 for the income model is 84.00, indicating that the included moderators explain a substantial proportion of the variation in effect-size estimates for income outcomes. The R^2 for the food security model is 82.56, suggesting that the included moderators explain a substantial proportion of the variation in effect-size estimates for food security outcomes. Similarly, the R^2 for the resilience model is 82.93, indicating strong explanatory power with respect to variation in effect-size estimates related to resilience outcomes. Finally, the R^2 for the adaptive capacity model is 55.86, indicating comparatively more moderate explanatory power for variation in effect-size estimates related to adaptive capacity outcomes.

To examine crop-type heterogeneity, drought-, heat-, and salt-tolerant crops were evaluated separately. The results in Table 4 show that drought-tolerant crops ($\beta = 0.175$; $p < 0.05$) are significantly positively associated with food security outcomes. Accordingly, drought-tolerant crop categories are positively associated with food security-related effect-size estimates. In addition, heat-tolerant crops ($\beta = 0.549$; $p < 0.01$) have a statistically significant positive association with resilience-related effect-size estimates. This coefficient indicates that resilience-related effect-size estimates tend to be higher in studies including heat-tolerant crops, with a coefficient of $\beta = 0.549$. For salt-tolerant crops, positive and statistically significant associations are observed across multiple livelihood outcome models, including income ($\beta = 0.195$; $p < 0.10$), food security ($\beta = 0.225$; $p < 0.10$), resilience ($\beta = 0.395$; $p < 0.01$), and adaptive capacity ($\beta = 0.683$; $p < 0.01$). These coefficients suggest that studies including salt-tolerant crop categories tend to report higher effect-size estimates across these livelihood outcome dimensions.

The spatial moderator captures study location at the continental level, although the number of primary studies varies across regions and estimates may not be fully comparable across contexts. The results show that coefficient estimates for Africa, the Americas, Asia, and Europe are not statistically significantly different from the reference category. This suggests that, within these continents and in our sample, livelihood-related effect-size estimates associated with stress-tolerant alternative crops do not systematically differ from the baseline regional group. However, the Oceania coefficient is positive and statistically significant across all four livelihood outcome models. Specifically, studies from Oceania report significantly higher effect-size estimates for income ($\beta = 0.192$; $p < 0.01$), food security ($\beta = 0.247$; $p < 0.01$), resilience ($\beta = 0.435$; $p < 0.01$), and adaptive capacity ($\beta = 0.196$; $p < 0.01$) compared with the omitted reference group. These positive and statistically significant coefficients indicate that studies from Oceania tend to report larger effect-size estimates across these livelihood outcome dimensions in studies including stress-tolerant alternative crops, although the study-level data do not allow the underlying contextual drivers of these regional patterns to be identified directly. In addition, the period variable is statistically significant for income ($\beta = 0.181$; $p < 0.01$) and food security ($\beta = 0.118$; $p < 0.10$), suggesting that studies published after 2020 tend to report higher effect-size estimates for these outcomes. This temporal pattern may reflect changes in study contexts, reporting patterns, or intervention environments over time, although this cannot be directly established from the available study-level data. However, these patterns should be interpreted with caution given the observational and heterogeneous nature of the underlying studies.

Figure 5 indicates that median effect-size estimates associated with stress-tolerant alternative crops are statistically significant for studies from Oceania across several livelihood outcomes. Specifically, drought-tolerant crops show a statistically significant median food security-related effect-size estimate of 0.15 in Oceania. Heat-tolerant crops show a statistically significant median resilience-related effect-size estimate of 0.15. Salt-tolerant crops in Oceania show statistically significant median effect-size estimates for income, food security, resilience, and adaptive capacity, with corresponding values of 0.16, 0.14, 0.17, and 0.15, respectively.

Additionally, Supplementary Appendix B indicates that funnel plots are approximately symmetric for all livelihood outcomes when pooling results across the original articles. Accordingly, publication

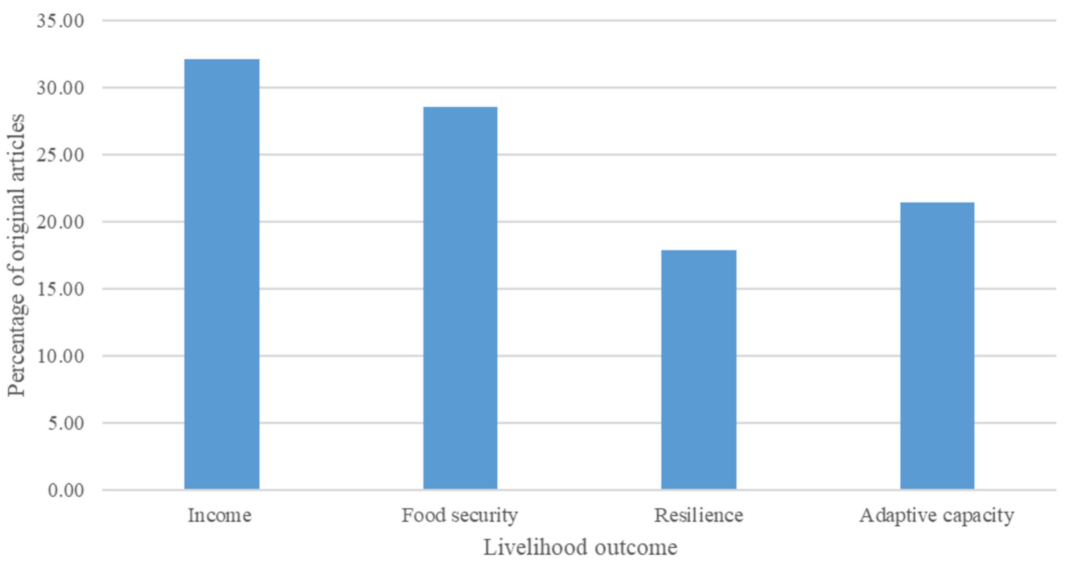

FIGURE 4
The proportion of original articles noting the four bases of the livelihood outcome. Source: study findings.

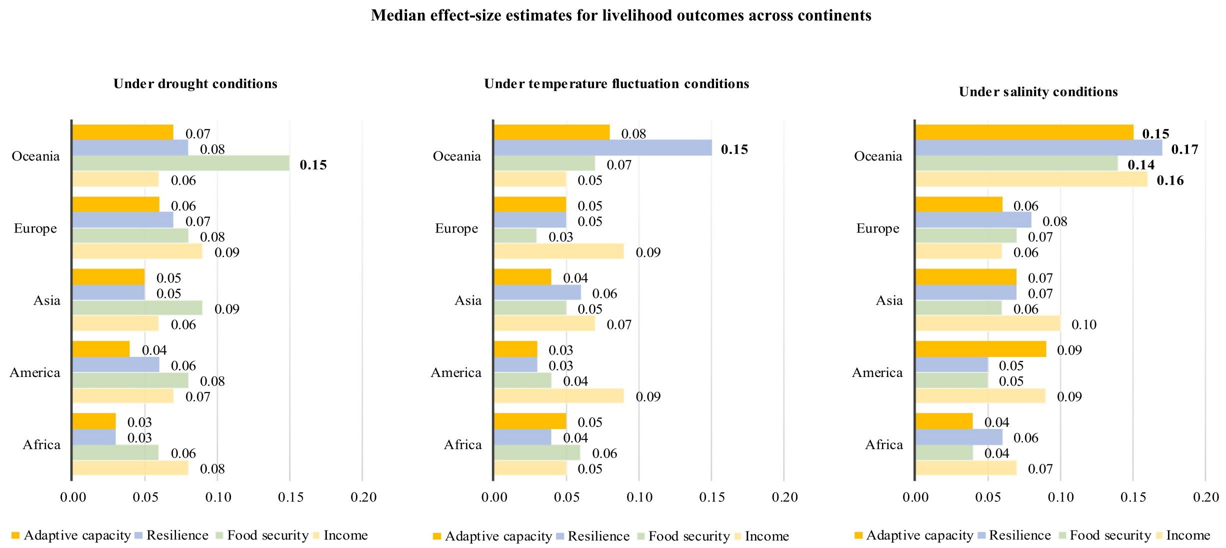

FIGURE 5
Median effect-size estimates for livelihood outcomes across continents. Bold labels indicate significant median effects. Source: study findings.

bias tests did not indicate strong evidence of substantial publication bias in the pooled study-level estimates. However, funnel plots alone cannot definitively establish the absence of publication bias or other reporting biases. Therefore, these results should be interpreted cautiously and should not be considered conclusive evidence of the overall validity of the meta-analysis.

4 Discussion

4.1 Drivers of stress-tolerant alternative crop adoption

The meta-analysis suggests that study-level associations related to stress-tolerant alternative crop adoption are linked to three main factors: (i) institutional support, (ii) access to credit, and (iii) market access. However, the strength of these associations varies across stressor types, suggesting that the reported associations vary across specific environmental conditions.

4.1.1 Institutional support

Consistent with prior empirical evidence, institutional support shows one of the strongest estimated associations in studies examining farmers' adoption of stress-tolerant alternative crops in drought-prone areas. Because shifting to drought-tolerant crops entail considerable production risk, farmers tend to adopt and invest more cautiously. In this context, institutional support may function as a substitute for insurance: it may reduce perceived risk and encourage uptake, as illustrated by drought-tolerant maize adoption in Zimbabwe (Makate and Makate, 2019).

Institutions, particularly technical training and extension services, not only disseminate information but also clarify the underlying technical complexities associated with stress-tolerant alternative crops, thereby potentially facilitating adoption decisions. Evidence from the Indo-Gangetic Plains shows that stress-tolerant varieties tend to be adopted more widely when farmers have access to institutional support (Aryal et al., 2018). Institutional interventions may help mitigate disparities in access to technical knowledge, especially for resource-constrained farmers. Aryal et al. (2018) also report that training and organizational linkages may enable poorer farmers to attain knowledge levels comparable to better-resourced groups, which in turn is likely to facilitate the adoption of stress-tolerant varieties and adaptive farming practices.

In short, institutional support appears to play an important role in supporting farmers to adopt stress-tolerant alternative crops. Strengthening extension services, technical training, and organizational linkages is therefore likely to be important for reducing information gaps and supporting adoption decisions, especially in drought-prone areas.

4.1.2 Access to credit

A notable finding of this study is that the association between credit access and stress-tolerant alternative crop adoption varies by stressor type. Specifically, while access to credit is positively associated with adoption-related effect-size estimates under drought conditions, the estimated coefficient becomes negative in salinity-affected environments.

In drought-sensitive contexts, uncertainty about yields can discourage investment in essential agricultural inputs. Access to credit may help mitigate this risk, enabling farmers to sustain input use and implement adaptive practices. Empirical evidence from Ethiopia, which has one of the most drought-prone agricultural systems in Africa, corroborates this point. Gebeyehu (2019) shows that both fertilizer-use intensity and agricultural productivity are higher among non-credit-constrained households than among those facing credit constraints. Limited financial access may therefore constrain farmers' capacity to maintain production and adopt appropriate practices during drought. Lemecha (2023) reports that approximately 54% of farming households face credit constraints, and this constraint has a negative, statistically significant effect on both the likelihood and intensity of adoption of adaptive interventions.

By contrast, accumulated evidence indicates that the association between credit and adoption may reverse in high-risk production environments. Giné and Yang (2009) demonstrate that when production risk is high, farmers are reluctant to take up credit for technology adoption due to repayment obligations. Under such conditions, the prospect of crop failure deters investment in input-intensive technologies, implying that credit alone may not create sufficient incentives for technology adoption. Their findings further suggest that credit demand may remain low even when access is formally available, as long as underlying production risk is unaddressed. Moreover, when farmers frequently experience income shocks, credit is often allocated to consumption rather than investment, weakening its role in supporting adoption (Regassa et al., 2023).

All in all, the relationship between credit access and adoption-related outcomes for stress-tolerant alternative crops appears to be shaped by the environmental stressors. These findings help to explain the inconsistent evidence in prior studies regarding the role of credit in climate-adaptive practices and suggest that credit programs should be tailored to specific stressors rather than applied through a single standardized approach. These results also caution against the uncritical use of credit-based interventions, as expanding credit in high-risk or low-return settings may not encourage the adoption of stress-tolerant alternative crops and could even heighten the financial vulnerability of farming households.

4.1.3 Market access

Market access emerges as an important factor associated with adoption in both tolerance models, namely heat tolerance and salt tolerance. Improved access to input and output markets may reduce perceived production risk and increase expected returns, thereby potentially being associated with a greater likelihood of adopting stress-tolerant alternative crops. Teshager Abeje et al. (2019) find that greater distance from major markets increases transaction costs and significantly reduces adoption of adaptive practices. Market access appears to shape not only the likelihood but also the intensity of adoption (Aryal et al., 2018). As noted by Kim (2016), the lack of reliable market information, weak value-chain development, and uncertain market outlets are significant barriers to transitioning toward stress-tolerant alternative crops. These patterns suggest the need for policy interventions that prioritize market information systems, value-chain development, and greater output-price stability for stress-tolerant alternative crops.

4.2 Livelihood implications of stress-tolerant alternative crop adoption

The meta-regression results indicate that the livelihood associations of stress-tolerant alternative crops are strongly dependent on the type of environmental stressor. In drought and temperature-fluctuation contexts, stress-tolerant alternative crops are primarily associated with higher food security and resilience, whereas salt-tolerant crops are associated with concurrent positive associations across income, food security, resilience, and adaptive capacity. Taken together, the meta-regression analysis underscores the moderating role of environmental stressors in shaping the estimated relationships between stress-tolerant alternative crop adoption and livelihood outcomes.

Although income has attracted the greatest research attention among livelihood outcomes, our results reveal no statistically significant associations between stress-tolerant alternative crops and income outcomes in both drought and temperature-fluctuation settings. This contrasts with several empirical studies reporting income gains from crop conversion. As droughts become more frequent and severe under climate change, traditional staples such as rice and other water-intensive crops become increasingly unsuitable under prolonged water scarcity. Production costs rise while the risk of crop failure intensifies. Under these conditions, drought-tolerant varieties and alternative crops may help farmers maintain a minimum level of production, lower production risks, and secure household food supplies. Prior literature on stress-tolerant alternative crop adoption consistently highlights their primary role in maintaining household food security and production stability in drought-prone settings (Davis et al., 2018; Yazdanpanah et al., 2022; Lin and Chiang, 2025). Income-related associations appear to remain limited because most additional output from stress-tolerant alternative crops is retained for household consumption rather than sold (Shiferaw et al., 2014; Makate and Makate, 2019).

By contrast, the multidimensional livelihood associations related to salt-tolerant crops may reflect the combination of their ecological adaptability and economic value. While conventional crops such as rice, maize, and many vegetables typically suffer severe yield losses under salinity stress, numerous salt-tolerant species can maintain growth and generate economic output in saline environments (Elouafi et al., 2020). Among these species, quinoa, amaranth, and teff are widely regarded as future candidate crops because they provide high levels of protein and micronutrients and can generate substantial economic value for farm households (Hirich et al., 2020). Effective adoption of stress-tolerant alternative crops may allow productive use of abandoned saline land and reduce pressure on freshwater resources, thereby potentially supporting the resilience of agricultural systems in coastal and salt-affected areas. Moreover, integrating salt-tolerant crops into diversified farming systems—including intercropping, forage-based systems, and saline agroforestry—may help reduce production risks and may enhance the resilience of livelihood systems to climate and environmental shocks (Elouafi et al., 2020). The development of such farming systems based on stress-tolerant alternative crops is closely linked to breeding programs, value-chain development, and technical training for farm households, which in turn may be associated with stronger adaptive capacity.

Overall, the findings suggest that stress-tolerant alternative crops tend to show the strongest positive livelihood associations in marginal environments, where substitution advantages may help offset climate-intensified constraints. At the same time, their livelihood associations differ not only in magnitude but also in the apparent pathways across stressors. Under drought conditions, stress-tolerant alternative crops appear to reflect a coping-type pattern, supporting food security and helping to reduce production risks without generating sustained income gains. Under temperature-fluctuation conditions, stress-tolerant alternative crops appear to reflect a buffering-type pattern that strengthens resilience but does not simultaneously improve other livelihood dimensions. By contrast, under saline conditions, stress-tolerant alternative crops appear to reflect an upgrading-type pattern, with concurrent positive associations across income, food security, resilience, and adaptive capacity. We use the terms "coping," "buffering," and "upgrading" as interpretive labels to describe recurring patterns in the estimated associations, rather than as constructs that are formally tested. Taken together, these context-specific livelihood responses suggest that crop transitions should be guided by local ecological conditions and production needs rather than generalized policy frameworks.

4.3 Regional heterogeneity

Beyond differences across climate stressors, the results indicate regional heterogeneity in the estimated associations between stress-tolerant alternative crop adoption and livelihood outcomes. In particular, larger positive estimated associations across multiple livelihood dimensions were observed in studies conducted in Oceania (Pagani, 2006; Chen et al., 2011). In this region, stress-tolerant alternative crops appear to be more frequently embedded in better-developed value chains, underpinned by robust infrastructure and high levels of commercialization, which may enhance the potential for crop transitions to be associated with stronger positive livelihood outcomes.

By contrast, in Africa, underdeveloped market systems, credit constraints, inadequate infrastructure, and weak support services are linked to more limited positive livelihood associations related to stress-tolerant alternative crop adoption, despite substantial ecological potential (Abdulai and Huffman, 2014; Makate and Makate, 2019). Meanwhile, Asia represents a context in which commercialized farming systems coexist with smallholder subsistence production, and the reported livelihood associations appear more moderate and heterogeneous. Overall, the meta-regression results suggest that regional contexts may play a moderating role, with market depth and institutional capacity being associated with both the magnitude and the pathways through which these associations are observed.

A paradox can be observed from these patterns: Sub-Saharan Africa, Southeast Asia, and West Asia—among the most climate-vulnerable regions—have attracted substantial research attention on alternative crop adoption, yet tend to more limited positive livelihood associations in the reported evidence base. This pattern suggests that adoption is likely to be more strongly associated with positive livelihood outcomes when accompanied by market development, targeted technical support, and stronger institutional capacity, rather than relying on broader policy frameworks.

4.4 Limitations and future directions

Although this meta-analysis provides essential quantitative evidence on the livelihood associations of stress-tolerant alternative crops under climate change, several limitations remain. First, it includes only studies that report quantitative effect sizes, thereby excluding a substantial body of qualitative and mixed-methods research. While this selection criterion supports a more consistent quantitative synthesis, it limits the capacity to capture institutional, behavioral, and social dimensions of the adoption process, which are better addressed through qualitative approaches (Reidsma et al., 2023), and may therefore result in an incomplete representation of the underlying adoption dynamics. Second, the analysis focuses on drought, temperature fluctuations, and salinity, whereas other major climate risks, such as flooding and extreme rainfall, are largely absent from the quantitative literature. In addition, the number of studies varies substantially across stressor categories, potentially influencing the relative magnitude of estimated associations across stressors. Third, regional differences, particularly between Oceania and Africa, suggest that positive associations observed under favorable market and institutional conditions may not be easily replicated across smallholder settings in most developing countries. This highlights potential limitations in the external validity and transferability of the findings across different socio-economic contexts. Fourth, the literature exhibits geographic and knowledge imbalances, with most studies centered on Africa and Asia and comparatively limited evidence from Oceania and Europe. The study is based on English-language publications, which may limit coverage of locally published evidence in some regions and may contribute to the uneven regional representation observed in the sample. Finally, effect sizes are constructed as percentage changes, which facilitates interpretation but does not fully account for the underlying variance structure and may be sensitive to near-zero or extreme control-group baseline values. Accordingly, the magnitude of the estimated associations should be interpreted with caution, particularly when control-group baselines are very small.

Overall, these limitations point to several priorities for future research. Quantitative datasets should be expanded to include additional climate risks, such as flooding and extreme rainfall, to enable more comprehensive assessments of stress-tolerant alternative crops across diverse climate contexts. At the same time, future studies should, where possible, prioritize panel data and long-term household-level analyses to better quantify the longer-term associations between adoption and livelihood outcomes such as income, resilience, and adaptive capacity.

5 Conclusion

This meta-analysis shows that adoption of stress-tolerant alternative crops is consistently associated with institutional support, credit availability, and market access, with these associations moderated by climate stressors. Under drought conditions, institutional support and credit exhibit some of the strongest estimated associations with adoption; under temperature fluctuations, market access emerges as the main factor associated with adoption. Under saline conditions, adoption tends to be higher where environmental conditions are more favorable and market access is stronger, whereas land constraints and limited credit are associated with lower uptake.

Livelihood associations likewise differ across stressors. In drought-prone contexts, stress-tolerant alternative crops are primarily associated with higher household food security, consistent with their role in stabilizing production and helping to manage production risk. Under temperature fluctuations, they appear to play a buffering role, with stronger links to resilience than to income gains. By contrast, salinity-tolerant crops are associated with an upgrading-type pattern, with concurrent estimated positive associations across income, food security, resilience, and adaptive capacity. From a regional perspective, no significant differences in livelihood associations are observed across Africa, the Americas, Asia, and Europe, while Oceania stands out with multidimensional positive associations in the available evidence base. This pattern may reflect stronger market integration and institutional capacity, but it should be interpreted cautiously.

Our findings suggest that policy design may be more effective when informed by stressor-specific contexts. In drought-affected areas, priorities may include improving the effectiveness of extension services, technical training, and access to credit to help households sustain investment and manage production risk. For temperature fluctuations and salinity, policies may benefit from emphasizing market development, price stabilization, and value-chain enhancement to support the adoption of stress-tolerant alternative crops. In climate-vulnerable regions, institutional support, appropriately designed credit schemes, and market development together appear to be important for realizing the potential livelihood associations linked to stress-tolerant alternative crops.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

TD: Conceptualization, Data curation, Methodology, Writing – original draft, Writing – review & editing. PL: Funding acquisition, Methodology, Supervision, Writing – review & editing. QT: Data curation, Supervision, Validation, Writing – review & editing. HH: Data curation, Validation, Writing – review & editing. PB: Methodology, Supervision, Writing – review & editing.

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Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

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Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2026.1843082/full#supplementary-material

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