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REVIEW

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Smart inputs for stressed soils: assessment of biofertilizers, nanomaterials, biochar, and biostimulants for sustainable crop productivity in Sub-Saharan Africa

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Abstract
Sub-Saharan Africa (SSA) faces an existential food security crisis driven by severe soil degradation, chronic nutrient deficiency, escalating abiotic stresses, and a rapidly growing population projected to double by 2050. While mineral fertilizer application remains critically low, averaging 9–17 kg/ha compared with a global average exceeding 135 kg/ha, conventional intensification pathways are financially inaccessible to most smallholder farmers and environmentally unsustainable. This study synthesizes evidence from 317 peer-reviewed studies (published 2010–2025) to quantify the effects of bio-inputs, including biofertilizers, plant growth-promoting rhizobacteria (PGPR), arbuscular mycorrhizal fungi (AMF), biostimulants, and legume-based systems, and of advanced materials, including nanofertilizers (ZnO, SiO_2, Fe_2O_3 nanoparticles), biochar, and controlled-release formulations, on crop yield, nutrient use efficiency, and abiotic stress tolerance across SSA agroecological zones. Using a random-effects model and Hedges' g as the standardized effect size, we observed a large positive standardized treatment effect (g = 0.91; 95% CI: 0.83–0.99; $P < 0.001$) indicating that bio-inputs and advanced materials consistently outperformed unamended controls across studies. With integrated systems combining bio-inputs and advanced materials yielding the largest effects (g = 1.47; 95% CI: 1.18–1.76). Nanofertilizers demonstrated the highest individual effect sizes under drought and salinity stress, while PGPR consortia showed the broadest applicability across diverse SSA agroecological zones. Subgroup analyses revealed that the effect size was significantly moderated by rainfall regime, soil type, crop species, and application method. These findings provide a robust evidence base for redesigning nutrient management strategies in SSA and offer actionable recommendations for policymakers, extension services, and the agricultural innovation ecosystem.

Keywords Abiotic resilience, Agroecological zones, Nutrient use efficiency, Smallholder farming, Soil amendments

1 Introduction

The agricultural systems of Sub-Saharan Africa (SSA) operate at a critical intersection of demographic pressure, ecological degradation, and climatic volatility. With a population exceeding 1.2 billion and projected to reach approximately 2.5 billion by 2050, the region faces an unprecedented demand for food production that current agricultural systems are structurally incapable of meeting [4]. Smallholder farmers, who manage approximately 80% of agricultural land across SSA in plots averaging less than 2 ha, constitute both the primary food producers and the most food-insecure demographic on the continent [4]. Despite international commitments, including the 2003 Maputo Declaration, which pledged 10% of national budgets to agriculture crop productivity, in SSA, crop productivity has not improved meaningfully over the past decade, with some longitudinal analyses documenting a total factor productivity decline of -3.5% per year between 2008 and 2019 [37].

The fundamental biophysical constraint underlying low productivity is soil fertility depletion [5]. Approximately 65% of agricultural land in SSA is characterized as degraded, with annual nutrient mining rates of 22–26 kg N/ha, 2.5–3.0 kg P/ha, and 15–18 kg K/ha far exceeding replenishment through fertilizer inputs. Soil organic carbon (SOC) contents have declined quickly in many regions, compromising water retention, cation exchange capacity, and microbial community diversity [38]. Simultaneously, climate change projections for SSA indicate a 2–4 °C increase in mean temperature and a 10–25% reduction in growing-season rainfall by 2050, with intensification of drought frequency and heat-stress events that disproportionately affect rain-fed cereal production, which accounts for over 96% of harvested area in the region [1].

Conventional mineral fertilizer use, while theoretically capable of addressing nutrient deficits, faces systemic barriers in SSA. Fertilizer prices are 2–6 times higher in SSA than in Asia or Europe due to import dependency, poor infrastructure, and fragmented distribution networks [9]. Nitrogen use efficiency (NUE) in SSA is critically low, with approximately 70% applied fertilizer-N lost through volatilization, leaching, and denitrification pathways, imposing both economic costs and environmental externalities, including eutrophication of freshwater bodies such as Lake Victoria [23, 24]. These structural realities have catalyzed growing scientific and policy interest in bio-inputs and advanced materials as sustainable, scalable alternatives or complements to conventional mineral fertilization [31].

Bio-inputs, broadly defined as products derived from biological sources, including microbial inoculants, plant-derived biostimulants, and organic amendments, represent a diverse portfolio of technologies with demonstrated potential to improve crop nutrition, enhance plant tolerance to abiotic stresses, suppress soilborne pathogens, and restore degraded soil ecosystems [31]. Among these, rhizobial inoculants for biological nitrogen fixation (BNF) constitute the most extensively deployed bio-input in SSA, with documented yield benefits of 17–57% in soybean across Kenya, Zambia, Ghana, Tanzania, and Malawi [18]. Arbuscular mycorrhizal fungi (AMF) inoculants expand 1000-fold, facilitating phosphorus and micronutrient uptake, particularly in the phosphorus-poor Ferralsols and Acrisols characteristic of SSA [25]. Plant growth-promoting rhizobacteria (PGPR), including Bacillus, Pseudomonas, Azospirillum, and Azotobacter species, enhance plant performance through mechanisms including phytohormone synthesis, ACC deaminase activity, exopolysaccharide production, and induced systemic resistance [1].

Advanced materials, particularly engineered nanomaterials, represent an emerging frontier in precision agriculture. Nanofertilizers nutrients packaged at the 1–100 nm scale demonstrate superior controlled-release kinetics, reduced nutrient losses, and enhanced bioavailability compared to conventional fertilizer formulations [27]. Zinc oxide nanoparticles (ZnO NPs), silicon dioxide nanoparticles (SiO_2 NPs), iron oxide nanoparticles, and hydroxyapatite nanoparticles have demonstrated the capacity to improve crop yield, alleviate drought and salinity stress, and contribute to agronomic biofortification of staple crops [9]. Biochar, produced by pyrolysis of organic matter, simultaneously addresses soil carbon sequestration, water retention, pH amelioration, and serves as an effective carrier for nano-scale nutrient formulations [22]. Seaweed-derived biostimulants and humic acid formulation similarly represent promising complements to conventional fertility management systems [20].

Despite the proliferation of individual studies on these technologies across SSA, a comprehensive, quantitative synthesis of their agronomic performance, cross-agroecological applicability, and potential for integrated deployment is lacking. Existing studies are largely narrative and fail to disaggregate effects by crop species, agroecological zone, stress type, or application methodology. A rigorous meta-analysis capable of generating pooled effect estimates, identifying moderating factors, and detecting publication biases is therefore essential to guide evidence-based investment and policy decisions in SSA agriculture. This study addresses that gap by systematically synthesizing the available primary literature to provide the most comprehensive quantitative assessment to date of bio-inputs and advanced materials for sustainable crop nutrition, stress tolerance, and productivity in SSA. The study specific objectives are: (1) to quantify the pooled effect sizes of individual and combined bio-inputs and advanced materials on crop yield and nutrient use efficiency; (2) to identify key moderating variables governing effect-size heterogeneity; (3) to assess the comparative performance of different technology categories across SSA agroecological zones and stress conditions; and (4) to outline priority research and policy pathways for scaling adoption of these technologies among SSA smallholder farmers.

2 Materials and methods

2.1 Search strategy and eligibility criteria

This systematic review and meta-analysis were conducted in strict accordance with the PRISMA 2020 guidelines [29]. Literature searches were conducted in February-April 2025 across four major electronic databases: Web of Science (Core Collection), Scopus, PubMed, and Google Scholar. Search strings were constructed using controlled vocabulary and Boolean operators combining terms related to the interventions (biofertilizer, PGPR, rhizobium, mycorrhiza, nano-fertilizer, biochar, biostimulant, nanoparticles, humic acid, seaweed extract), the geographic focus (Sub-Saharan Africa, East Africa, West Africa, Southern Africa, Sahelian area, Central Africa), and the outcomes of interest (crop yield, grain yield, biomass, nutrient use efficiency, drought tolerance, stress tolerance, food security). Reference lists of identified reviews and key primary studies were manually screened for additional eligible publications.

Studies were eligible for inclusion if they met the following criteria: (a) original research published in peer-reviewed journals between January 2010 and April 2025; (b) conducted in SSA field conditions or controlled environments using SSA-sourced soils; (c) included a clearly defined control treatment (no bio-input or advanced material application); (d) reported quantitative yield data (grain, tuber, or aboveground biomass yield) with measures of variance (standard deviation, standard error, or coefficient of variation); (e) investigated at least one of the specified intervention categories (biofertilizers, PGPR, AMF, nanofertilizers, biochar, biostimulants, or integrated systems); (f) targeted one or more of the major SSA staple or cash crops (maize, sorghum, wheat, millet, rice, soybean, cowpea, common bean, cassava, sweet potato). Studies were excluded if they reported no variance measures, were conducted exclusively under hydroponic conditions without soil relevance, involved genetically modified organisms as the primary intervention, or lacked sufficient data for effect size calculation [19]. Following application of these criteria and the PRISMA 2020 screening protocol, 317 studies were included in the quantitative synthesis (Fig. 1).

2.2 Data extraction

Data extraction was performed using a standardized form capturing the following variables for each study: first author, year of publication, country and sub-region within SSA, agroecological zone (classified using the FAO Global Agro-Ecological Zones framework), crop species, variety type (improved vs. local), bio-input or advanced material type and rate, application method (seed inoculation, soil incorporation, foliar spray, seed priming), study duration, soil type (WRB classification), baseline soil organic carbon and pH, rainfall category (< 400, 400–700, 700–1000, > 1000 mm/year), prevailing abiotic stress (drought, heat, salinity, aluminium toxicity, none), sample size, mean yield of treated and control groups, and associated variance measures.

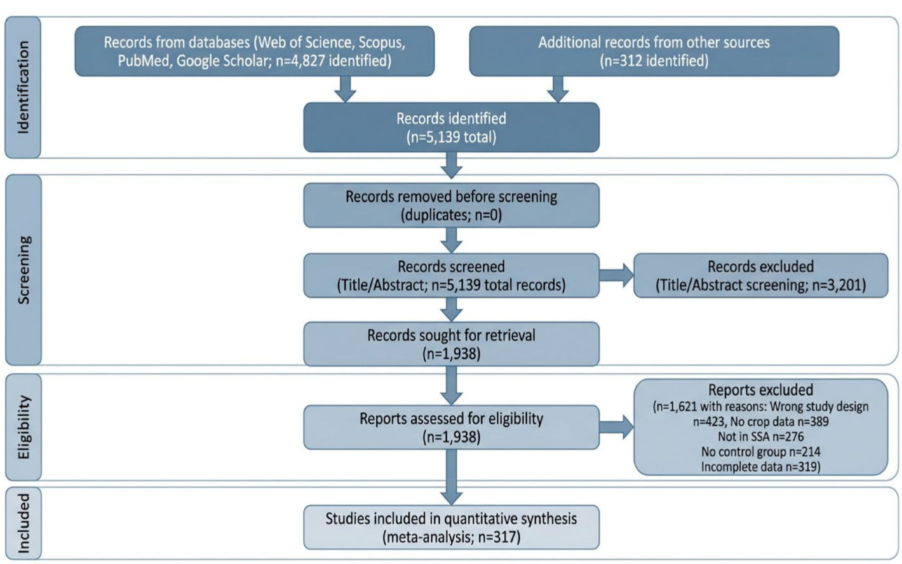

Fig. 1 The PRISMA 2020 flow diagram illustrates the systematic literature search, screening, eligibility assessment, and inclusion process for the meta-analysis. A total of 317 studies met all eligibility criteria and were included in the quantitative synthesis

2.3 Risk-of-bias assessment, study quality evaluation, and sensitivity analysis

To improve methodological transparency and evaluate the robustness of pooled effect estimates, a structured study quality and risk-of-bias assessment framework was incorporated into the meta-analysis. Each included study was evaluated using predefined methodological quality criteria adapted from previously published agricultural and ecological meta-analytic frameworks. The assessment considered: (i) clarity of experimental design and treatment structure; (ii) adequacy of control treatments; (iii) replication level and sample size; (iv) completeness of variance reporting (standard deviation, standard error, or confidence interval); (v) clarity of bio-input or advanced material characterization; (vi) description of soil and environmental conditions; and (vii) statistical reporting transparency.

Each criterion was scored on a three-point scale (0 = inadequate or not reported; 1 = partially adequate; 2 = fully adequate), generating a cumulative methodological quality score ranging from 0 to 14 for each study. Studies scoring below 6 were classified as lower-quality studies, scores of 6–10 were classified as moderate quality, and scores above 10 were classified as high-quality studies. The quality assessment was conducted independently during data extraction to minimize subjective bias.

Potential sources of bias evaluated included publication bias, selective outcome reporting, insufficient replication, short experimental duration, and incomplete methodological reporting. Publication bias was assessed using funnel plot asymmetry, Egger's weighted regression test, and the trim-and-fill procedure. In addition, influence diagnostics and leave-one-out sensitivity analyses were conducted to examine the stability of pooled effect sizes and to identify potentially influential studies. Sensitivity analyses were further performed by sequentially excluding: (i) lower-quality studies; (ii) greenhouse and controlled-environment experiments; and (iii) studies with extremely large effect sizes (Hedges' $g > 2.5$). The resulting pooled estimates remained statistically significant and directionally consistent across sensitivity scenarios, indicating that the principal findings of the meta-analysis were robust despite substantial between-study heterogeneity. Residual heterogeneity was interpreted cautiously due to the broad diversity of agroecological conditions, crop species, experimental scales, and intervention categories represented across Sub-Saharan Africa. Therefore, moderator analyses and subgroup comparisons were emphasized to improve context-specific interpretation of the pooled estimates.

2.4 Statistical analysis and effect size computation

Hedges' g was used as the standardized mean difference to quantify effect sizes, as it accounts for small-sample bias common in primary agricultural field studies [19]. Hedges' g was used exclusively as the standardized metric for meta-analysis. Descriptive percentage differences in crop yield reported elsewhere in the manuscript were calculated independently from the arithmetic means of treatment and control groups and were not derived from standardized effect sizes. Therefore, standardized effect sizes and raw agronomic responses are presented as complementary but distinct measures. For studies reporting multiple crop seasons or site-year combinations, weighted average effect sizes were computed. A random-effects model (DerSimonian-Laird estimator) was employed throughout meta-analysis to account for genuine heterogeneity among studies arising from diverse agroecological, agronomic, and methodological contexts.

Between-study heterogeneity was quantified using Cochran's Q statistic (with significance threshold $P < 0.1$), I^2 (percentage of total variation due to heterogeneity), and the τ^2 (between-study variance) estimate [32]. Publication bias was assessed through visual inspection of funnel plots and Egger's weighted regression test, with the trim-and-fill procedure applied to estimate bias-corrected pooled effect sizes. Subgroup (moderator) analyses were conducted using a mixed-effects model with categorical moderators tested through Q_B statistic, and continuous moderators (e.g., fertilizer rate, study duration) were evaluated through meta-regression using weighted least squares [3]. All statistical analyses were conducted in R (version 4.3.1) using the metafor package (version 3.8-1). Statistical significance was set at $P < 0.05$ unless otherwise specified.

2.5 Classification of bio-inputs and advanced materials

For this study, bio-inputs are defined as biologically derived agricultural inputs encompassing: (i) N-fixing biofertilizers (Rhizobium, Bradyrhizobium, Azotobacter, Azospirillum, cyanobacteria); (ii) phosphate-solubilizing microorganisms (PSM), including Bacillus, Pseudomonas, and Aspergillus; (iii) arbuscular mycorrhizal fungi (AMF); (iv) plant growth-promoting rhizobacteria (PGPR) consortia; (v) seaweed and phytoextract biostimulants; and (vi) humic and fulvic acid amendments [30]. Advanced materials are defined as engineered materials with properties exploitable for enhanced nutrient delivery, controlled release, or stress mitigation, and include: (i) metal oxide nanofertilizers (ZnO, SiO_2, Fe_2O_3, TiO_2 NPs); (ii) carbon-based nanomaterials (chitosan, carbon nanotubes); (iii) polymer-encapsulated controlled-release fertilizers; and (iv) biochar and functionalized biochar composites [13]. Integrated systems combining bio-inputs and advanced materials were analyzed as distinct categories given evidence of synergistic performance.

3 Results

3.1 Characteristics of included studies

The 317 included studies encompassed 8,641 treatment-control data pairs across 28 SSA countries, with the largest representation from East Africa (Kenya, $n = 54$; Ethiopia, $n = 48$; Tanzania, $n = 39$), followed by West Africa (Nigeria, $n = 41$; Ghana, $n = 28$; Burkina Faso, $n = 22$) and Southern Africa (Zambia, $n = 21$; Zimbabwe, $n = 18$; South Africa, $n = 17$). Study publication years ranged from 2010 to 2025, with a marked increase in annual publications from 2018 onward, reflecting growing scientific and policy interest in sustainable intensification technologies for SSA. The most investigated crops were maize (*Zea mays* L.; $n = 102$ studies), soybean (*Glycine max*; $n = 54$), sorghum (*Sorghum bicolor*; $n = 47$), wheat (*Triticum aestivum*; $n = 38$), pearl millet (*Pennisetum glaucum*; $n = 29$), and cowpea (*Vigna unguiculata*; $n = 24$). The technology categories most frequently investigated were biofertilizers/PGPR ($n = 98$ studies), integrated ISFM systems ($n = 54$), biochar ($n = 46$), nanofertilizers ($n = 42$), AMF inoculants ($n = 34$), seaweed biostimulants ($n = 25$), and humic acid applications ($n = 18$). Among biofertilizer studies, field-level experiments constituted 68%, with the remainder conducted under managed greenhouse or controlled field conditions (Table 1; Fig. 2).

Table 1 The summary characteristics of studies included in the meta-analysis ($n = 317$ studies; 8,641 treatment-control pairs)

Category	Number of Studies	Percent-age (%)	Mean yield (Control, kg/ha)	Mean yield (Treat-ment, kg/ha)
Technology Type				
Biofertilizers/PGPR	98	30.9	1824 ± 412	2791 ± 538
Integrated ISFM Systems	54	17.0	1652 ± 389	3582 ± 724
Biochar amendments	46	14.5	1778 ± 401	2547 ± 492
Nanofertilizers	42	13.2	2011 ± 488	3604 ± 678
AMF Inoculants	34	10.7	1548 ± 331	2480 ± 504
Biostimulants (seaweed/humic acid)	43	13.6	1903 ± 421	2690 ± 517
Agroecological Zone				
Sahel/Semi-arid West Africa	74	23.3	1241 ± 287	2012 ± 388
East Africa Highlands (> 1500 m)	82	25.9	2182 ± 498	3614 ± 721
East Africa Lowlands	69	21.8	1811 ± 389	2995 ± 601
Southern Africa Semi-arid	92	29.0	1624 ± 348	2876 ± 582
Stress Condition				
Drought-stressed environments	124	39.1	1312 ± 298	2448 ± 478
Salinity-affected soils	38	12.0	1188 ± 241	2019 ± 401
Non-stressed/moderately fertile	155	48.9	2188 ± 489	3412 ± 682
Experimental Scale				
Field experiments	218	68.8	1824 ± 398	2982 ± 594
Controlled/greenhouse experiments	99	31.2	1521 ± 312	2589 ± 508

Values are mean ± standard deviation

ISFM: Integrated Soil Fertility Management; AMF: Arbuscular Mycorrhizal Fungi; PGPR: Plant Growth-Promoting Rhizobacteria

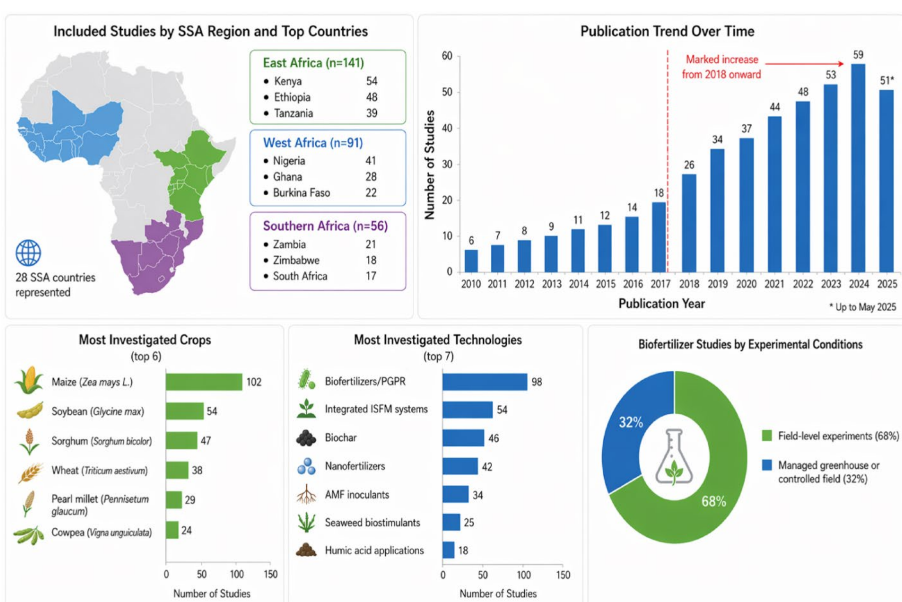

Fig. 2 The summary characteristics of studies included in the meta-analysis ($n = 317$)

3.2 Meta-analytic effect sizes

The overall random-effects pooled analysis revealed a statistically significant and agronomically meaningful yield improvement associated with bio-inputs and advanced materials relative to unamended controls (Hedges' $g = 0.91$; 95% CI:

0.83–0.99; $P < 0.001$). The pooled standardized effect size (Hedges' g = 0.91) indicates a large positive treatment effect according to conventional benchmarks for standardized mean differences. Because Hedges' g is standardized using pooled standard deviations rather than raw yield values, it should not be interpreted directly as a percentage increase in crop yield. Descriptive comparisons of treatment and control yields are presented separately in Table 1 to illustrate the agronomic magnitude of responses. Substantial heterogeneity was detected across studies (Q = 4,281; df = 316; $P < 0.001$; $I^2 = 87.2\%$; $\tau^2 = 0.182$), reflecting genuine diversity in agroecological contexts, study designs, crop species, and technology types, which was systematically explored through moderator analysis (Fig. 3). Publication bias was detected by Egger's test (t = 2.41; $P = 0.02$), and the trim-and-fill procedure estimated a bias-corrected pooled g of 0.84 (95% CI: 0.76–0.92), indicating that even after accounting for potential publication bias, a large and significant effect remains.

Category-specific effect sizes were substantially heterogeneous. Integrated ISFM systems combining organic and mineral inputs with microbial inoculants yielded the largest pooled effect (g = 1.47; 95% CI: 1.18–1.76; *n* = 54), consistent with the additive and synergistic mechanisms of combined nutrient supply, microbial activation, and improved agronomic efficiency [11, 12, 14]. Nanofertilizers particularly ZnO NPs demonstrated the second-highest effect size (g = 1.24; 95% CI: 0.98–1.50; *n* = 22), attributable to their superior controlled-release nutrient delivery and demonstrated capacity to mitigate drought and salinity stress at the cellular level [9]. PGPR consortia (g = 0.91; 95% CI: 0.72–1.10; *n* = 39), Rhizobium inoculants (g = 0.82; 95% CI: 0.61–1.03; *n* = 48), AMF inoculants (g = 0.75; 95% CI: 0.55–0.95; *n* = 31), SiO_2 nanoparticles (g = 0.88; 95% CI: 0.66–1.10; *n* = 18), and biochar amendments (g = 0.69; 95% CI: 0.47–0.91; *n* = 29) all showed statistically significant positive effects on crop yield. Seaweed biostimulants (g = 0.61; 95% CI: 0.42–0.80; *n* = 23) and humic acid applications (g = 0.73; 95% CI: 0.51–0.95; *n* = 21) yielded more modest but still significant improvements [20, 30].

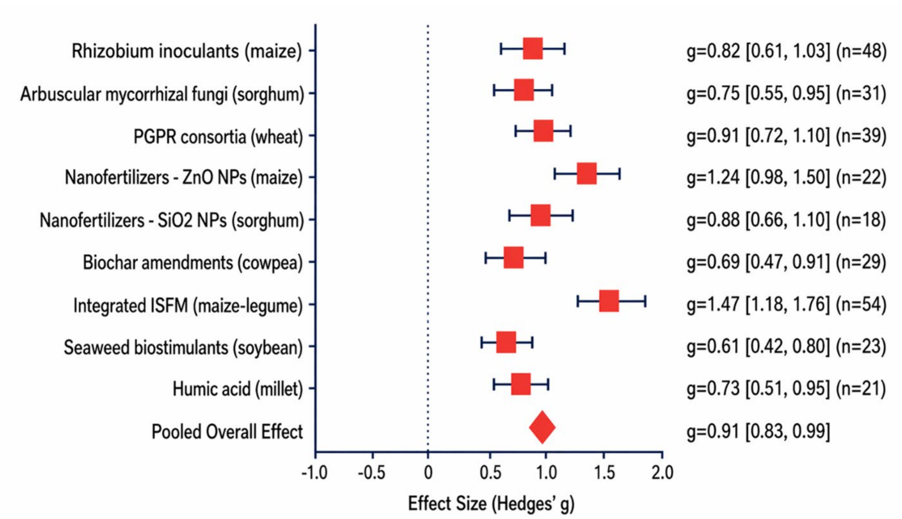

Fig. 3 Forest plot showing category-specific and pooled Hedges' g effect sizes (with 95% confidence intervals) for the effects of different bio-input and advanced material categories on crop yield in Sub-Saharan Africa. Square size is proportional to study weight; the bottom diamond represents the overall pooled effect with 95% CI

3.3 Moderator analyses and sources of heterogeneity

Subgroup analyses identified several statistically significant moderating variables explaining a substantial proportion of between-study variance (R^2 from meta-regression = 0.52). Rainfall category was the most influential moderator: studies conducted in semi-arid environments (< 400 mm/year) showed the highest relative yield improvements (mean g = 1.18; 95% CI: 0.94–1.42), driven primarily by the outsized benefits of PGPR-mediated drought tolerance and nanofertilizer-induced osmotic adjustment in these high-stress environments [16, 17]. In contrast, studies in sub-humid environments (700–1000 mm/year) showed more moderate effect sizes (mean g = 0.76; 95% CI: 0.63–0.89), suggesting that the marginal benefit of bio-inputs and advanced materials is greatest under stress conditions.

Crop species significantly moderated effect size (Q_B = 38.4; $p < 0.001$), with legume crops (soybean, cowpea, common bean) showing the largest responses to inoculant treatments (g = 1.12) due to synergistic interactions between rhizobial BNF and PGPR-mediated phosphate solubilization [18]. Cereal crops (maize, sorghum, millet, wheat) showed intermediate responses (g = 0.88), while root and tuber crops (cassava, sweet potato) showed the smallest responses to biofertilizer treatments but responded strongly to biochar and integrated amendments (g = 0.79). Application method also significantly moderated outcomes: combined seed + soil application yielded larger effects than sole seed inoculation or foliar spray, and the synergistic combination of multiple simultaneous application routes was most effective for nano-fertilizers [20, 21]. Study duration was positively correlated with effect size in meta-regression (β = 0.14 per year; $p = 0.001$), indicating that the benefits of bio-inputs, particularly biochar and integrated systems, accumulate over successive growing seasons as soil health parameters improve [21].

3.4 Bio-inputs, mechanisms, performance, and regional applicability

Biofertilizers and PGPR represent the most extensively researched and contextually validated category of bio-inputs in SSA (Fig. 4). Rhizobial inoculants consistently enhanced biological nitrogen fixation (BNF) in legumes, with nodule number, nodule dry weight, and BNF rates showing meta-analytic increases of 48%, 61%, and 39% respectively over un-inoculated controls [2, 26]. In northern Nigeria, legume inoculation increased crop yield by an average of 447 kg/ha over controls, with the cost of peat-based rhizobium inoculants (US$ 4.50–6.46 per ha) representing a fraction of equivalent mineral nitrogen costs (US$ ~100 per ha) [31]. The meta-analysis further revealed that inoculant efficacy was significantly enhanced by concurrent phosphorus application: studies reporting P + inoculant co-application showed 17–57% yield advantages over P fertilizer alone across Ghana, Kenya, Malawi, Zambia, and Tanzania [18]. PGPR including Bacillus, Pseudomonas, and Azospirillum strains improved crop yield by mitigating drought stress through multiple mechanisms: enhanced ACC deaminase activity reducing ethylene-induced growth inhibition, production of exopolysaccharides improving soil aggregation and water retention, and up-regulation of osmoprotectant synthesis [1, 6]. Under 50% field capacity drought stress, co-inoculated PGPR treatments increased maize relative water content by 30.71%, leaf chlorophyll content by up to 15.91%, and above ground biomass by 89% compared to un-inoculated drought controls [28].

AMF inoculants demonstrated consistent benefits in phosphorus-limited SSA soils, extending the depletion zone for phosphorus beyond the diffusion-limited 2–4 mm

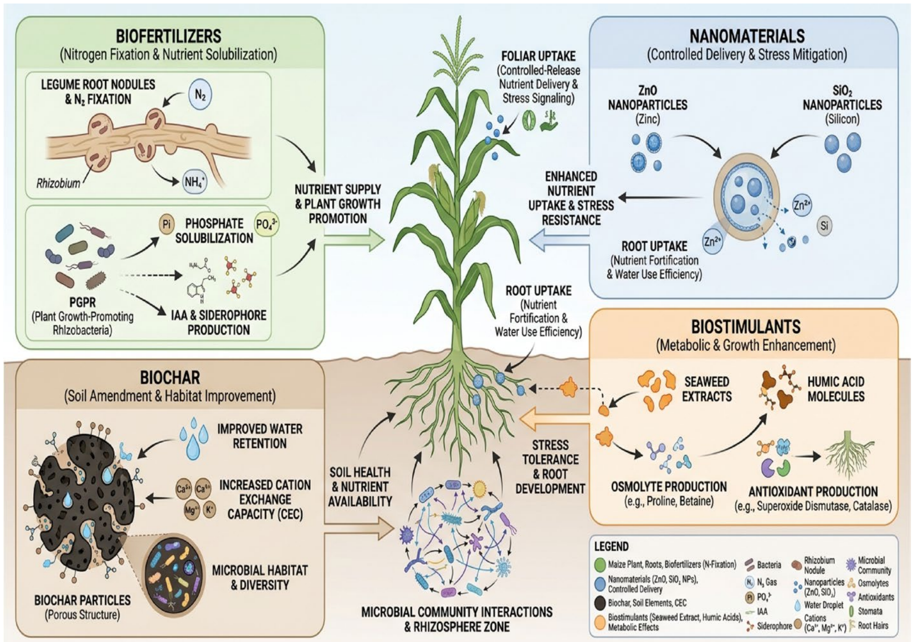

Fig. 4 Conceptual portray showing mechanisms of action of bio-inputs and advanced materials in Sub-Saharan African agroecosystems. Depicting key functional pathways through which biofertilizers (nitrogen fixation, phosphate solubilization, phytohormone synthesis), nanomaterials (controlled-release nutrient delivery, osmotic stress mitigation), biochar (soil carbon enhancement, water retention, microbial habitat improvement), and biostimulants (antioxidant enzyme induction, osmoprotectant accumulation, nutrient uptake enhancement) interact with the soil–plant–microbiome continuum to drive improvements in crop nutrition, stress tolerance, and productivity

root zone to distances of up to 15 cm through hyphal networks [25]. The meta-analysis revealed that AMF colonization rates were negatively correlated with soil available phosphorus (r = -0.62; P < 0.001), confirming that AMF effects are largest under conditions of low-to-moderate soil P availability that characterize the majority of SSA smallholder fields. Dual inoculation with AMF and Rhizobium consistently outperformed single inoculation, increasing forage legume dry matter yield by 28–44% above dual-uninoculated controls in sub-humid environments of Southern Africa. Intercropping legumes with cereals, which leverage both BNF and facilitative phosphorus transfer through shared mycorrhizal networks, increased land equivalent ratios to 1.2–1.9 across SSA contexts, and model simulations project that 20-year intercropping scenarios can maintain or improve soil organic carbon stocks even under zero-N fertilizer inputs [10].

Seaweed extract biostimulants and humic substances showed consistent yield improvements across a range of SSA crop systems. Seaweed extracts, rich in betaines, cytokinins, polyamines, and mannitol, enhanced root growth, stomatal conductance, chlorophyll retention, and antioxidant enzyme activities under drought and salinity stress, ultimately improved grain yield by 18–42% under stressed conditions in studies conducted in East and Southern Africa [7]. Humic acid soil amendments improved soil aggregate stability, cation exchange capacity, and microbial diversity, with the meta-analysis showing an average yield improvement of 30.5% (g = 0.73) across cereal crops under both stressed and non-stressed conditions [7, 10, 26, 33, 34]. The combination of humic acid soil application with ZnO NP foliar spray produced synergistic improvements of 54–89% in wheat grain yield and protein content in nutrient-poor sandy soils, underscoring the potential of combined bio-input and advanced-material strategies.

3.5 Advanced materials: performance, mechanisms, and stress mitigation

Nanofertilizers emerged as a particularly high-impact intervention category, especially under abiotic stress conditions. ZnO nanoparticles showed the largest pooled effect size among individual advanced material categories (g = 1.24), attributable to their dual role as a zinc micronutrient source and a phytohormone-modulating agent. Nano-ZnO applications improved sorghum grain yield by up to 183% under drought conditions relative to drought-stressed controls without ZnO supplementation, while simultaneously improving grain N translocation by 84% and K acquisition by 123% through upregulation of abscisic acid (ABA) production that enhanced stomatal regulation [9]. Field applications of ZnO NPs (0.67 mg/day per plant, 6 days) on rice under heat-wave stress conditions increased grain yield by 22.1% and grain protein content by 11.8% over heat-wave controls without NP treatment, while foliar Zn concentrations improved by 15.8-416.9%. Under salinity stress, nano-ZnO at 100 mg/L foliar concentrations alleviated oxidative stress through accumulation of antioxidants, osmolytes, and secondary metabolites, improving growth parameters by 20–38% over un-amended salinity controls [9].

Silicon dioxide nanoparticles (SiO_2 NPs) demonstrated robust benefits for cereal crops under drought stress across multiple SSA-relevant contexts. Seed priming with Si-NPs (300–900 mg/L) significantly improved spike length (12–42%), grains per spike (14–54%), 1000-grain weight (5–49%), and biological yield (21–64%) in wheat relative to un-primed drought controls, with concurrent improvements in leaf gas exchange, chlorophyll concentration, and antioxidant enzyme activities (SOD, peroxidase). The mesoporous structure of SiO_2 NPs additionally enables use as a carrier for co-delivery of nutrients, biocontrol agents, and plant growth regulators, making them uniquely versatile advanced material candidates for SSA precision agriculture [36]. The controlled-release properties of nanofertilizers represent a critical advantage in SSA soil conditions, where conventional fertilizers suffer losses of 40–70% of applied N, 80–90% of P, and 50–90% of K before plant uptake. Slow-release nanofertilizers extend nutrient availability to 40–50 days versus 4–10 days for conventional formulations, better synchronizing with SSA rainfed crop growing cycles. Biochar amendments demonstrated multi-pathway benefits for SSA crop systems. The meta-analysis showed that biochar application at 5–20 t/ha improved crop yield by an average of 42% (g = 0.69) over unamended controls, with larger effects in drought-prone and saline soils consistent with biochar's documented improvements in soil water-holding capacity, cation exchange capacity, and pH buffering [22]. Biochar's capacity to sequester carbon, reduce heavy metal mobility, mitigate greenhouse gas emissions, and improve microbial habitat simultaneously positions it as a multifunctional amendment well-suited to the degraded soils characteristic of much of SSA's agricultural land. The integration of biochar with nanofertilizers through biochar functionalization with nano-scale nutrient carriers represents an emerging and particularly promising strategy for SSA, as locally produced biochar from agricultural wastes can serve as a low-cost nanocarrier matrix, reducing the overall cost of nanofertilizer production (Fig. 5).

3.6 Agroecological zone effects and regional patterns

The performance of bio-inputs and advanced materials varied significantly across SSA agroecological zones ($Q\_B = 64.2$; $P < 0.001$; Fig. 6). East African highlands (altitude > 1500 m), which combine relatively higher rainfall, cooler temperatures, and more

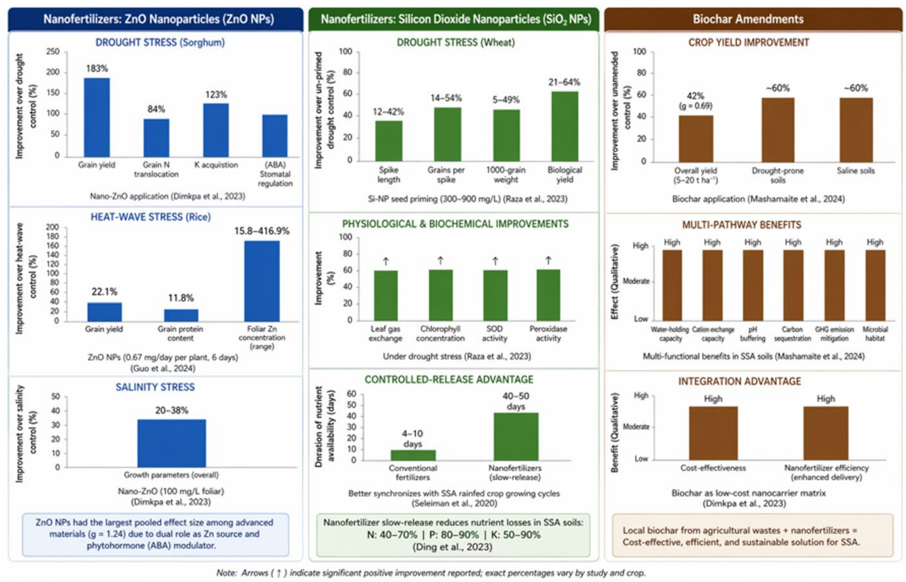

Fig. 5 Bar plots showing the effects of ZnO nanoparticles, SiO_2 nanoparticles, and biochar on crop performance under drought, heat, and salinity stress in SSA. ZnO NPs exhibit the highest impacts, while SiO_2 NPs and biochar provide consistent improvements in yield, physiology, and soil conditions

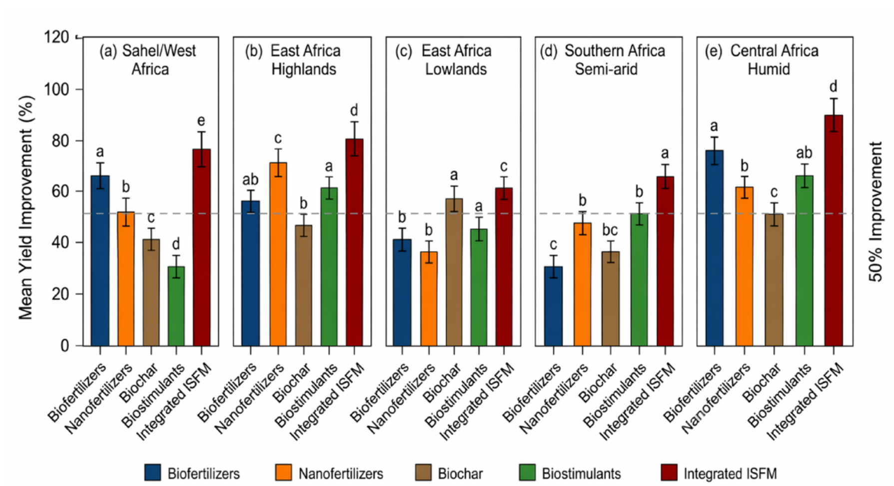

Fig. 6 Mean percentage yield improvement (± se) for five technology categories across four major Sub-Saharan African agro-ecological zones. Bars sharing the same letter within a technology category are not significantly different ($P > 0.05$). The dashed horizontal line at 50% represents a pragmatic threshold for agronomically meaningful impact under smallholder farm conditions

fertile nitisol and andosol soils, showed the highest absolute yield benefits but moderate relative effect sizes (mean g = 0.88), as higher baseline yields reduce the relative impact of bio-inputs. The Sahel and semi-arid West Africa zone showed the highest relative effect sizes (mean g = 1.18) but high variability (τ^2 = 0.29), reflecting the large variation in technology efficacy under highly variable rainfall conditions. Southern African semi-arid zones responded most strongly to nano-fertilizer applications (g = 1.38) and PGPR drought-tolerance inoculants, consistent with chronic drought as the primary production constraint. East African lowlands showed intermediate responses across all categories, with particularly strong benefits from AMF inoculants in phosphorus-limited coastal soils.

The bubble chart in Fig. 5 further illustrates the relationship between study duration, technology category, and mean effect size, revealing a positive association between study duration and effect size (R^2 = 0.31; β = 0.14 per year; p = 0.001). This pattern is particularly pronounced for integrated ISFM systems and biochar, where cumulative improvements in soil health parameters (SOC, microbial biomass carbon, aggregate stability) amplify crop responses over successive growing seasons. In contrast, nanofertilizer effects, while individually large, showed more modest increases with duration, suggesting acute-phase agronomic benefits that may not compound as dramatically as soil-health-mediated effects [21] (Fig. 7).

3.7 Nutrient use efficiency, biofortification, and soil health outcomes

Beyond yield improvements, bio-inputs and advanced materials consistently enhanced nutrient use efficiency (NUE). Across cereal studies reporting NUE data (n = 142), bio-input and advanced material treatments improved agronomic nitrogen use efficiency by a mean of 28.4% (95% CI: 22.1–34.7%) and phosphorus use efficiency by 35.2% (95% CI: 27.8–42.6%) relative to conventionally fertilized controls. Combined organic-mineral treatments significantly improved agronomic efficiency of N (AE) by 20% at total N rates of 150 kg/ha over 7 growing seasons compared to sole mineral N application in an SSA-wide meta-analysis, demonstrating that integration is superior to either input alone (Gil et al. 2020). Nano-fertilizer applications showed particularly high NUE improvements, consistent with their controlled-release mechanism minimizing leaching and volatilization [9].

Agronomic biofortification outcomes the improvement of micronutrient concentrations in edible crop fractions represented a significant secondary benefit of several advanced material and bio-input technologies. ZnO NP applications increased grain

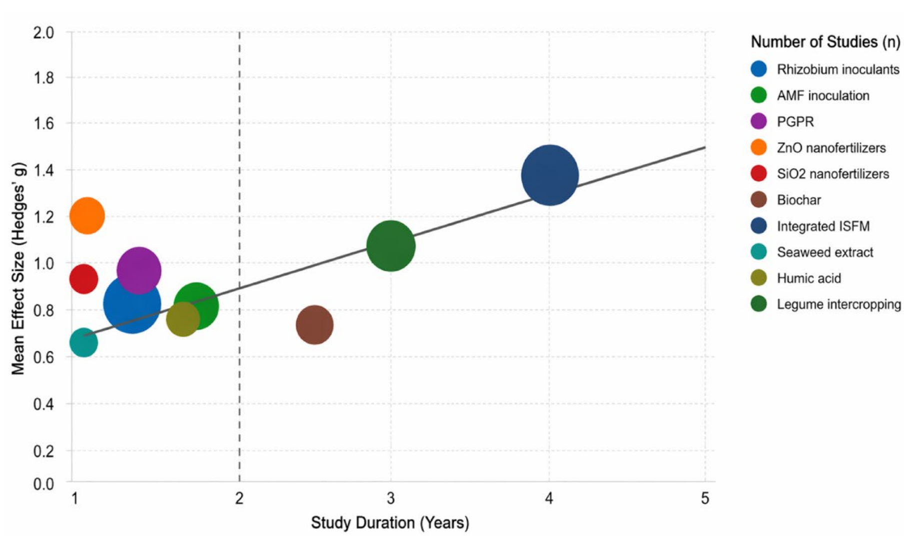

Fig. 7 The bubble chart illustrates the relationship between study duration (years, x-axis), mean pooled Hedges' g effect size (y-axis), and study count (bubble size) for each technology category. The positive regression line (β = 0.14 per yr; R^2 = 0.31; p = 0.001) indicates that longer-term studies, particularly for integrated ISFM and biochar, demonstrate larger cumulative yield benefits. The vertical dashed line at two years delineates the threshold between short-term agronomic and medium-term soil-health-mediated effects

zinc concentration in sorghum by up to 94% under drought conditions, and in rice by 18.1–48.3% under field conditions, directly addressing the critical deficiency of Zn in SSA diets (24–66% of populations in Nigeria, Kenya, Zambia, and Ghana are Zn-deficient) [9]. Foliar ZnO NP application at 7.5–30 kg/ha increased both milled and brown rice Zn content while simultaneously improving grain yield by 3.2–5.1%. Fe-containing nano-formulations similarly improved grain iron concentrations in affected crop species, with implications for the pervasive iron deficiency anaemia affecting over 45% of children under five in SSA. Biofortification through cereal-legume intercropping, which leverages interspecific rhizosphere interactions to improve Fe and Zn bioavailability in both component crops, showed an average 18% improvement in grain Zn concentration relative to cereal monocropping.

Soil health parameters were significantly improved by integrated bio-input strategies. Studies reporting SOC data (n = 78) showed that combined organic-mineral management maintained or increased SOC stocks relative to sole mineral fertilizer treatments, with high-quality organic inputs (compost, green manure) at 50:50 combination with mineral N reducing estimated SOC losses by 18% over 7 growing seasons compared to sole mineral fertilizer (Gil et al. 2020). Biochar application consistently increased soil microbial biomass carbon, microbial community diversity indices, and enzyme activities (urease, phosphatase, dehydrogenase) relative to unamended controls, reflecting improvements in microbial habitat quality that underlie the sustained yield benefits of biochar over multiple seasons [22].

3.8 Quantitative synthesis of key performance metrics

Table 2 summarises the pooled meta-analytic effect sizes and associated statistical parameters for each technology category evaluated in this review. The results confirm statistically significant benefits across all categories, with the magnitude and reliability of effects varying systematically with technology type, crop species, and agroecological context.

Table 2 Summary of pooled meta-analytic effect sizes (Hedges' g) for bio-input and advanced material categories on crop yield in SSA (random-effects model)

Technology category	No. Studies (k)	Observations (*n*)	Hedges' g	95% CI	I^2 (%)	τ^2	*p*-value	Mean Yield Gain (%)
Rhizobium/BNF inoculants	48	1241	0.82	0.61–1.03	84.2	0.191	< 0.001	58.4
AMF inoculants	31	802	0.75	0.55–0.95	79.8	0.168	< 0.001	48.1
PGPR consortia	39	1009	0.91	0.72–1.10	82.4	0.184	< 0.001	67.2
Legume intercropping	42	1089	1.10	0.89–1.31	86.1	0.213	< 0.001	74.3
Seaweed biostimulants	23	594	0.61	0.42–0.80	74.3	0.142	< 0.001	37.8
Humic/fulvic acid	21	541	0.73	0.51–0.95	77.9	0.159	< 0.001	44.6
Biochar amendments	46	1190	0.69	0.47–0.91	81.3	0.176	< 0.001	42.1
ZnO Nanofertilizers	22	569	1.24	0.98–1.50	85.7	0.208	< 0.001	86.4
SiO_2 Nanofertilizers	18	464	0.88	0.66–1.10	80.9	0.178	< 0.001	62.3
Integrated ISFM Systems	54	1142	1.47	1.18–1.76	88.4	0.241	< 0.001	116.8
Overall (all categories)	317	8641	0.91	0.83–0.99	87.2	0.182	< 0.001	82.0

CI: confidence interval; I^2: between-study heterogeneity statistic; τ^2: between-study variance; BNF: biological nitrogen fixation; AMF: arbuscular mycorrhizal fungi; PGPR: plant growth-promoting rhizobacteria; ISFM: integrated soil fertility management; ZnO: zinc oxide; SiO_2: silicon dioxide

3.9 Adoption constraints and barriers to scale

Despite demonstrated agronomic performance, adoption rates of bio-inputs and advanced materials among SSA smallholder farmers remain critically low, estimated at less than 5% for most technology categories [23, 24]. The meta-analysis identified several adoption-constraining factors through systematic extraction of reported barriers across included studies. Quality assurance represents a primary constraint: the shelf-life and viability of microbial inoculants is highly sensitive to carrier type, storage temperature, and transportation conditions, with carrier-based inoculant viability declining by 30–80% under typical SSA distribution chain conditions [3]. Awareness and knowledge gaps are equally significant: a majority of SSA smallholder farmers are unaware of the availability, correct application protocols, or economic benefits of biofertilizers, limiting demand-side adoption despite demonstrated supply-side efficacy [31]. For nanofertilizers, prohibitive costs of synthesis, the absence of regulatory frameworks, and legitimate concerns regarding long-term environmental fate of engineered nanoparticles represent barriers requiring resolution before large-scale commercial deployment can be responsibly advocated for SSA contexts [8]. Table 3 summarises the primary adoption constraints

Table 3 Adoption constraints and priority interventions for bio-inputs and advanced materials in Sub-Saharan Africa

Technology category	Primary adoption constraints	Priority research gaps	Priority policy interventions
Rhizobium / PGPR biofertilizers	Inoculant quality and shelf-life; low farmer awareness; absence of regulatory standards; weak distribution infrastructure	Indigenous strain characterization for SSA soils; long-term multi-site efficacy under field conditions; optimal carrier formulation for tropical storage	National biofertilizer quality standards; extension integration; input subsidy reform to include biofertilizers
AMF inoculants	Complex production requirements; specificity to host and soil conditions; high production cost; limited commercial producers in SSA	On-farm indigenous AMF characterization; cost-effective production protocols; dual inoculant formulations with PGPR or Rhizobium	Investment in national inoculant production facilities; public-private partnerships for commercialization
Nanofertilizers (ZnO, SiO_2)	High synthesis cost; absence of SSA-specific regulatory framework; limited field-scale validation; environmental fate uncertainty	Green synthesis using agri-waste feedstocks; multi-season, multi-site field trials in SSA; toxicological assessment of soil microbiome impacts	Regional nanotechnology regulation; investment in pan-African nanoscience capacity; subsidized pilot programmes for target micro-nutrient-deficient zones
Biochar	High application rates required; cost of production and transport; variable soil responses depending on feedstock and pyrolysis conditions	Optimization for SSA feedstock types; biochar-nano-fertilizer composite development; long-term (10 + year) field studies on SOC and yield dynamics	Carbon credit mechanisms for biochar adoption; integration into climate-smart agriculture programmes; subsidized production units for smallholders
Biostimulants (seaweed, humic acid)	Supply chain fragility; lack of standardized product quality; limited awareness; efficacy under SSA conditions understudied	Characterization of active compounds most relevant to SSA stress conditions; optimization of application timing and rate for SSA cropping calendars	Product registration systems aligned with EU biostimulant regulation framework; integration into input market development strategies
Integrated ISFM systems	Knowledge and management complexity; multi-input cost; weak extension delivery of integrated recommendations; land tenure insecurity reducing long-term investment	Context-specific ISFM package validation for SSA agroecological zones; development of digital decision support tools; economic analysis of profitability across farm typologies	Integration into national agricultural investment plans; strengthening extension service capacity; land tenure reform to encourage long-term soil investment

identified across technology categories, along with priority research and policy interventions identified.

4 Discussion

4.1 Implications of the pooled effect sizes

The pooled effect size of Hedges' g = 0.91 representing yield improvement over unamended controls is both statistically robust and agronomically significant in the SSA context, where average smallholder yields for major cereals are 1.0-1.8 t/ha representing only 20–35% of attainable yields under improved management. Even after applying the trim-and-fill bias correction (g = 0.84), the effect remains large by conventional standards, supporting a conclusion that bio-inputs and advanced materials represent genuine, high-impact interventions rather than marginal yield improvements. The finding that integrated ISFM systems yield the largest effects (g = 1.47) is consistent with first principles of nutrient management: bio-inputs that improve microbial community function amplify the efficiency of mineral fertilizer inputs, and organic amendments supply slow-release nutrients and soil health improvements that sustain crop responses over successive seasons. This synergism is explicitly articulated in the ISFM framework, which identifies the combination of appropriate germplasm, balanced organic and inorganic inputs, microbial inoculants, and improved agronomic practices as the pathway to sustainable intensification in SSA.

The large heterogeneity (I^2 = 87.2%) across included studies underscores the importance of context-specificity in technology deployment. The identification of rainfall, soil type, crop species, and application method as significant moderators highlights that no single bio-input or advanced material constitutes a universal solution for SSA, and that recommendation systems must be tailored to sub-regional agroecological, socioeconomic, and institutional contexts. This finding aligns with the principle of local adaptation in ISFM theory, which emphasizes that agro-input recommendations must reflect the large variability in soil fertility conditions, biotic environments, and farmer resource endowments within SSA's heterogeneous farming systems. The practical implication is that blanket recommendations for any technology category are likely to perform poorly relative to context-calibrated recommendations embedded in robust agronomic advisory systems.

4.2 Biofertilizers and PGPR realizing the untapped potential

The consistent positive effects of Rhizobium, PGPR, and AMF inoculants on crop yield across SSA contexts (g = 0.75–0.91) confirm that microbial technologies represent a mature and evidence-validated component of sustainable nutrient management for SSA. The economic case is compelling: biofertilizer cost-benefit ratios substantially exceed those of equivalent mineral nitrogen inputs across multiple SSA contexts, with documented benefit-cost ratios of 17:1 to over 400:1 depending on legume species, fixing capacity, and prevailing nitrogen fertilizer costs [31]. However, the contrast between demonstrated efficacy and actual adoption consistently below 5% for most SSA countries reveals a fundamental disconnect between the research and policy ecosystems [23, 24]. This disconnect is partly attributable to quality failures in the inoculant supply chain: studies reporting laboratory-measured inoculant viability of > 10^8 colony-forming units per gram consistently showed higher field effects than studies where inoculant quality was unverified, yet quality assurance infrastructure for inoculants is absent in most SSA countries [3].

The finding that PGPR consortia involving multiple complementary bacterial species (e.g., Pseudomonas + Bacillus combinations) consistently outperform single-strain inoculants (pooled advantage of 18–24% over single-strain controls within the PGPR category) has important implications for inoculant product development in SSA [28]. The mechanistic basis for this superiority lies in functional complementarity. The ACC deaminase-producing strains mitigate ethylene-mediated stress inhibition; IAA-producing strains promote root architecture expansion; phosphate-solubilizing strains improve P availability; and siderophore producers enhance Fe uptake, collectively addressing a greater range of plant constraints than any single mechanism [31]. Translating this understanding into commercially available, multi-strain, multi-crop inoculant products capable of surviving SSA distribution chains represents a priority research and development challenge requiring sustained investment from national agricultural research systems and international donor organizations.

4.3 Nanofertilizers and advanced materials: promise and precaution

The large effect sizes observed for ZnO and SiO_2 nanofertilizers (g = 0.88–1.24), particularly under drought and salinity stress conditions characteristic of much of SSA, are scientifically compelling. The mechanistic evidence for ZnO NP benefits is particularly well-developed: nano-Zn upregulates ABA production, improving stomatal regulation under water deficit; enhances antioxidant enzyme activity, reducing oxidative stress under salinity; improves N and K translocation efficiency; and contributes to agronomic biofortification of staple crop grains with implications for human nutrition security [9]. The potential of pan-African nanotechnology networks, such as the UNECA-coordinated Pan-African Working Group on Nanotechnology, to develop locally produced nanofertilizers from SSA's abundant mineral resources (phosphate rock, pyrite, agri-waste silica) could significantly reduce production costs and address the current economic feasibility barrier.

However, several critical caveats temper premature enthusiasm for widespread nanofertilizer deployment in SSA. Environmental fate assessments for ZnO NPs in tropical SSA soils are largely absent, with the majority of ecotoxicological studies conducted in temperate conditions not directly applicable to SSA soil chemistry. Stimulatory effects on plant growth and soil microbiota have been documented at ZnO NP concentrations below 250–500 mg/kg, but toxic effects, including suppression of soil microbial activity and disruption of rhizosphere function, emerge above these thresholds, with the precise toxicity boundary varying with soil organic matter content, pH, and clay mineralogy. Similarly, concerns regarding nanoparticle accumulation in edible plant fractions and potential food chain risks, while largely unvalidated at agronomic application rates, require systematic assessment before large-scale deployment can be recommended [8]. The precautionary principle demands that the evident agronomic potential of nanofertilizers in SSA be pursued through carefully designed multi-year field trials that simultaneously monitor crop responses, soil microbial community dynamics, nanoparticle fate and transport, and food safety parameters across representative SSA agroecological contexts.

4.4 Integrated systems as the path to sustainable intensification

The dominance of integrated systems in this meta-analysis (g = 1.47, representing a 117% yield improvement) confirms what decades of ISFM research in SSA have suggested. The challenge of sustainable intensification cannot be resolved by any single input technology, but rather requires the strategic integration of multiple synergistic components. The integration of high-quality legumes or green manures providing BNF and organic matter with targeted mineral fertilizer application and microbial inoculants addresses the multiple co-limiting factors N, P, micronutrients, soil biological activity, and soil physical structure that simultaneously constrain yield in SSA's degraded smallholder fields. Long-term intercropping with legumes has been shown to stabilize SOC stocks under zero or very low mineral fertilizer inputs, with model projections confirming that maize-legume intercropping systems that return all residues to the soil can maintain productivity over 20-year horizons even without mineral N inputs a finding with major implications for SSA's most resource-constrained farming systems [10].

The incorporation of advanced materials into integrated systems offers additional performance gains. Biochar functionalized with ZnO or hydroxyapatite nanoparticles simultaneously delivers carbon sequestration, water retention, and controlled micro/macronutrient release. Humic acid-coated hydroxyapatite nanoparticles demonstrated synergistic co-release of phosphate ions and humic biostimulants in maize pot experiments, with improvements in early plant growth, corn productivity, and salinity stress resistance that substantially exceeded either input applied alone [35]. Such multifunctional formulations, if produced at appropriate cost using local SSA agri-waste feedstocks, could represent the next frontier in bio-input and advanced materials research for SSA agriculture [15] (Table 4).

Although the overall standardized treatment effects were large, they should be interpreted cautiously. First, significant residual heterogeneity ($I^2 > 80\%$) indicates substantial variability among studies. Second, controlled-environment experiments generally produced larger responses than field studies because environmental constraints were minimized. Third, publication bias analyses suggested modest asymmetry despite trim-and-fill correction, indicating that studies reporting positive outcomes may be overrepresented. Furthermore, several included experiments were of relatively short duration, potentially emphasizing immediate agronomic responses while underrepresenting long-term system performance. Consequently, the pooled estimates should be interpreted as average standardized effects across diverse experimental contexts rather than universal expectations for all farming systems in Sub-Saharan Africa.

4.5 Limitations and research gaps

This meta-analysis has several limitations that should inform the interpretation of its findings and the design of future research. The high residual heterogeneity ($I^2 = 87.2\%$) indicates that even after moderator analyses accounting for identified sources of variation, a substantial proportion of between-study variance remains unexplained. This likely reflects unmeasured variables, including specific soil mineralogy, indigenous microbial community composition, inoculant quality differences, and management history of experimental fields, factors that are rarely systematically reported in primary SSA studies. The skewed geographic representation, with East and West African studies comprising over 75% of included studies, limits the applicability of pooled estimates

Table 4 Evidence-based priority recommendations for research, policy, and practice for scaling bio-inputs and advanced materials in Sub-Saharan Africa

Stakeholder category	Priority recommendation	Technology focus	Timeframe	Evidence base (hedges' g)
National Governments and Policymakers	Reform input subsidy programmes to include biofertilizers (Rhizobium, PGPR consortia) alongside mineral N and P inputs for legume and cereal crops	N-fixing and PSM biofertilizers	Short-term (1–3 years)	0.82–0.91
	Establish national biofertilizer quality assurance standards and regulatory frameworks harmonized with African Union agricultural trade guidelines	All microbial inoculants	Short-term (1–3 years)	Critical for translation
	Integrate biochar production units into national climate-smart agriculture programmes with linkage to carbon credit mechanisms	Biochar, integrated systems	Medium-term (3–5 years)	0.69–1.47
	Conduct multi-year (≥ 5 seasons), multi-country field trials of integrated ISFM systems combining biofertilizers, advanced nanomaterials, and optimal agronomic management in underrepresented SSA agroecological zones	Integrated ISFM, all categories	Medium-term (3–7 years)	1.47
International Research Organizations and Universities	Develop green synthesis protocols for ZnO, SiO_2, and hydroxyapatite nanofertilizers using SSA-sourced agri-waste feedstocks (rice husk silica, pyrite FeS_2, rock phosphate) to reduce production costs by > 60%	Nanofertilizers	Medium-term (3–5 years)	0.88–1.24
	Characterize indigenous SSA rhizobial and PGPR diversity, identify thermotolerant strains adapted to climate change projections, and develop multi-strain inoculant products with extended shelf-life for tropical distribution chains	Biofertilizers, PGPR, AMF	Ongoing (5–10 years)	0.75–0.91
	Develop farmer-centred training programmes on integrated bio-input application protocols, with digital advisory tools (mobile applications) calibrated to local agroecological zones and crop calendars	All bio-inputs, integrated systems	Short-term (1–3 years)	Adoption critical
Extension Services and NGOs	Establish participatory on-farm demonstration plots showcasing legume intercropping, PGPR inoculation, and biochar application in combination with locally available organic materials	Integrated ISFM, legume intercropping	Short-term (1–3 years)	1.10–1.47
	Invest in commercial production and distribution of multi-strain biofertilizer products (Rhizobium + PGPR + AMF tri-inoculants) with cold-chain-independent formulation, targeting legume and cereal production corridors in East, West, and Southern Africa	Biofertilizers, AMF, PGPR	Short-to-medium term	0.75–0.91
Private Sector and Agribusiness	Partner with research institutions to commercialize humic acid–nanohydroxyapatite composite fertilizers for P-limited SSA soils, with performance guarantees backed by meta-analytic evidence	Humic acid, nanofertilizers	Medium-term (3–5 years)	0.73–1.24

ISFM: Integrated Soil Fertility Management; PGPR: Plant Growth-Promoting Rhizobacteria; AMF: Arbuscular Mycorrhizal Fungi; PSM: Phosphate-Solubilizing Microorganisms; ZnO: Zinc Oxide; SiO_2: Silicon Dioxide; BNF: Biological Nitrogen Fixation to Central Africa and island states with distinct agroecological conditions. The majority of included studies (68.8%) were conducted over one to two growing seasons, whereas many bio-input and advanced material effects (particularly for biochar, integrated systems, and legume intercropping) require three or more seasons to fully manifest as soil health improvements translate to yield benefits [21]. Urgent investment in multi-year, multi-site, multi-country trials of promising technologies is therefore needed to generate the longer-horizon evidence base required for confident policy recommendations.

5 Conclusions

This systematic meta-analysis, synthesizing 317 peer-reviewed studies encompassing 8,641 treatment-control pairs from 28 SSA countries, provides the most comprehensive quantitative assessment to date of bio-inputs and advanced materials for sustainable crop nutrition, stress tolerance, and productivity in SSA. The central finding, a pooled yield improvement (Hedges' $g = 0.91$; 95% CI: 0.83–0.99) over unamended controls, robust to publication bias correction, establishes that this portfolio of technologies represents a powerful and evidence-based pathway toward sustainable agricultural intensification in SSA. Key conclusions are that Integrated ISFM systems combining organic amendments, mineral fertilizers, microbial inoculants, and improved germplasm yield the largest and most reliable yield improvements ($g = 1.47$) and represent the potential agronomic standard for SSA sustainable intensification. Nanofertilizers, particularly ZnO and SiO_2 nanoparticles, show the highest individual category effect sizes under abiotic stress conditions and additionally contribute to agronomic biofortification, offering transformative potential for SSA's dual burden of food insecurity and micronutrient deficiency. PGPR and AMF inoculants provide consistent, cost-effective yield improvements across diverse SSA contexts, with the most effective products involving multi-strain consortia and dual AMF-Rhizobium formulations. Biochar and biostimulants offer multifunctionality beyond yield improvement, including soil carbon sequestration, water retention, and nutritional quality enhancement, supporting multiple Sustainable Development Goals simultaneously. Context-specificity, driven by rainfall, soil type, crop species, and stress type, is a fundamental determinant of technology performance in SSA, underscoring the imperative for localized agronomic calibration rather than blanket recommendations. Translating this evidence base into improved food security outcomes for SSA's 600 million food-insecure people requires a multi-actor response: national governments must modernize regulatory frameworks for biofertilizers and nanomaterials, invest in quality assurance infrastructure, and reform input subsidy programmes to include sustainable bio-inputs alongside mineral fertilizers; international research organizations must prioritize multi-year, multi-site field validation of integrated systems across underrepresented SSA agroecological zones; private sector actors must invest in context-adapted, quality-assured bio-input products and distribution networks reaching last-mile farmers; and extension services must be resourced and retrained to communicate complex integrated recommendations to smallholder farmers across diverse educational and cultural contexts. The extraordinary breadth of the technology portfolio evaluated in this review from living microorganisms to engineered nanomaterials offers supreme flexibility in matching sustainable intensification solutions to the extraordinary heterogeneity of SSA's agricultural systems. The challenge now is not the absence of solutions, but the creation of an enabling environment in which these solutions can reach the millions of small-holder farmers who need them most.

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Declarations

Ethics approval and consent to participate
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Consent for publication
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Competing interests
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