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Assessment of organic farming practices and their role in sustainable agriculture and climate resilience: A systematic review and meta-analysis

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Abstract

Background: Organic farming has emerged as a pivotal strategy for transitioning global agriculture toward sustainability, food system resilience, and environmental stewardship. In India, organic farming has witnessed exponential growth, with the country ranking first globally in the number of organic producers (approximately 4.43 million farmers) and sixth in total certified organic area, supported by flagship policy interventions such as the Paramparagat Krishi Vikas Yojana (PKVY) and the National Mission for Sustainable Agriculture (NMSA). Despite growing adoption, empirical evidence on the multi-dimensional impacts of organic farming particularly regarding climate resilience remains fragmented and context-specific.

Objectives: This systematic review and meta-analysis aimed to quantitatively synthesize evidence on the effects of organic farming practices on crop yield, soil health, biodiversity, greenhouse gas (GHG) emissions, water use efficiency, and farm income, with special emphasis on findings from the Indian subcontinent.

Materials and Methods: A comprehensive search of Web of Science, Scopus, Google Scholar, PubMed, CAB Abstracts, and Indian Citation Index was performed for peer-reviewed studies published between 2000 and 2024. Studies comparing organic with conventional farming systems using quantitative outcome measures were eligible for inclusion. A random-effects meta-analysis was conducted to compute pooled effect sizes (Hedges' g), while heterogeneity was assessed using I^2 statistics and Cochran's Q test. Publication bias was evaluated through funnel plot symmetry and Egger's regression intercept test.

Results: Eighty-nine studies comprising 187 paired comparisons from 31 countries including 42 Indian studies met the inclusion criteria. Organic farming demonstrated significant improvement in soil organic carbon (Hedges' $g = +0.68$; 95% CI: $+0.54$ to $+0.82$; $I^2 = 61.2\%$), soil microbial biomass ($g = +0.74$), and biodiversity indices ($g = +0.92$; 95% CI: $+0.71$ to $+1.13$). Greenhouse gas emissions were significantly lower under organic management ($g = -0.44$; 95% CI: -0.57 to -0.31). A yield penalty of approximately 19.4% was observed ($g = -0.21$; 95% CI: -0.31 to -0.11 ; $I^2 = 72.4\%$), though this varied markedly across crop types, farming system intensification levels, and agro-climatic zones. Farm net income showed a marginal positive effect ($g = +0.15$), contingent on premium price realization.

Conclusions: Organic farming presents substantial co-benefits for ecosystem health and climate resilience, though the yield penalty remains a principal challenge for food security at scale. Targeted policy interventions focusing on streamlined certification, premium market linkages, participatory extension, and strengthened farmer producer organizations (FPOs) are imperative to harness the full potential of organic farming within India's agricultural development agenda.

Practical Implications: Strengthening extension services, improving certification systems, supporting organic value chains, and integrating climate-smart organic practices can enhance the adoption and effectiveness of organic farming.

Originality/Value: This review integrates global and Indian evidence on organic farming, sustainability, and climate resilience within a single analytical framework and identifies future research priorities for climate-resilient agricultural development.

Keywords: organic farming, sustainable agriculture, climate resilience, meta-analysis, soil health, greenhouse gas emissions, India, Hedges' g , yield gap

Introduction

1.1 Global Context of Organic Farming

The global agricultural landscape is confronted with unprecedented challenges arising from climate change, biodiversity loss, soil degradation, and mounting pressure to feed a projected population of 9.7 billion by 2050 (FAO, 2025)^[11]. In this context, organic farming has emerged as a multifunctional production system that seeks to harmonize agricultural productivity with ecological sustainability. Defined by the International Federation of Organic Agriculture Movements (IFOAM) as a production system that sustains the health of soils, ecosystems, and

people by relying on ecological processes, biodiversity, and cycles adapted to local conditions, organic agriculture rejects the use of synthetic inputs, genetically modified organisms, and growth hormones.

According to the FiBL-IFOAM World of Organic Agriculture Report (Willer *et al.*, 2024) ^[41], organic agriculture is practiced across 187.1 million hectares in more than 190 countries, representing approximately 1.6% of global agricultural land. Europe accounts for the largest share of organic land (35%),

followed by Oceania (31%) and Latin America (13%). Globally, the organic food and beverage market surpassed USD 150 billion in 2023, reflecting robust consumer demand for organically produced commodities. The United Nations Sustainable Development Goals (SDGs) particularly SDG 2 (Zero Hunger), SDG 12 (Responsible Consumption and Production), SDG 13 (Climate Action), and SDG 15 (Life on Land)—are closely aligned with the principles and outcomes of organic farming systems.

Table 1: Organic Farming Area, Production, and Market Indicators in India

Indicator	Value (2024-25 unless noted)	Source
Total NPOP certified + in-conversion area	Approximately 3.96 million hectares	APEDA (2025)
Fully certified organic area	Approximately 2.25 million hectares	APEDA (2025)
Area in conversion	Approximately 1.71 million hectares	APEDA (2025)
Total organic production under NPOP	Approximately 4.69 million tonnes	APEDA (2025)
Fully certified organic production	Approximately 4.39 million tonnes	APEDA (2025)
Cumulative area under PKVY (NPOP + PGS-India) since 2015-16	Approximately 5.97 million hectares	Ministry of Agriculture and Farmers Welfare (2024)
Organic production, 2015-16 (baseline)	Approximately 1.34 million tonnes	Market research compilations of government data
Organic export volume	Approximately 368,155 tonnes	APEDA (2025)
Organic export value	Approximately INR 5,394 crore (~USD 666 million)	APEDA (2025)
Leading states by certified organic area	Madhya Pradesh, Maharashtra, Rajasthan, Gujarat, Odisha, Sikkim, Uttar Pradesh, Uttarakhand, Kerala, Karnataka, Andhra Pradesh	APEDA (2025)
Global rank - organic agricultural area	2nd	FiBL & IFOAM (2025), as cited in APEDA (2025)
Global rank - number of organic producers	1st	FiBL & IFOAM (2025), as cited in APEDA (2025)
Domestic organic market growth rate	Approximately 22% CAGR	Expert Market Research (2026)
Organic export target by 2030	Approximately INR 20,000 crore (~USD 2 billion)	Government of India, Ministry of Commerce and Industry (2025)

1.2 Organic Farming in India: Status and Policy Framework

India occupies a unique position in the global organic agriculture landscape. As of 2023, the country hosts the largest number of organic producers worldwide approximately 4.43 million certified farmers operating across 7.69 million hectares of certified organic land (APEDA, 2025). India's organic exports touched USD 1.07 billion in 2024-25, encompassing a diverse commodity basket including oil seeds, medicinal plants, rice, pulses, spices, fruits, and vegetables. The northeastern states particularly Sikkim (the world's first fully organic state, declared in 2016), Arunachal Pradesh, Meghalaya, and Manipur have led the transition to organic production systems.

The Government of India has institutionalized a range of policy instruments to promote organic farming. The Paramparagat

Krishi Vikas Yojana (PKVY), launched in 2015, promotes cluster-based organic farming with an outlay of ₹50,000 per hectare over three years. The Rashtriya Krishi Vikas Yojana (RKVY) provides capital support for organic input production. The National Mission for Sustainable Agriculture (NMSA) integrates organic farming within a broader agenda of climate adaptation. The Participatory Guarantee System (PGS-India), managed by the National Centre of Organic and Natural Farming (NCONF), provides a decentralized and cost-effective certification mechanism particularly suited to smallholder contexts. These policy initiatives underscore the centrality of organic farming in India's vision of doubling farmer incomes and achieving climate-smart agricultural transformation.

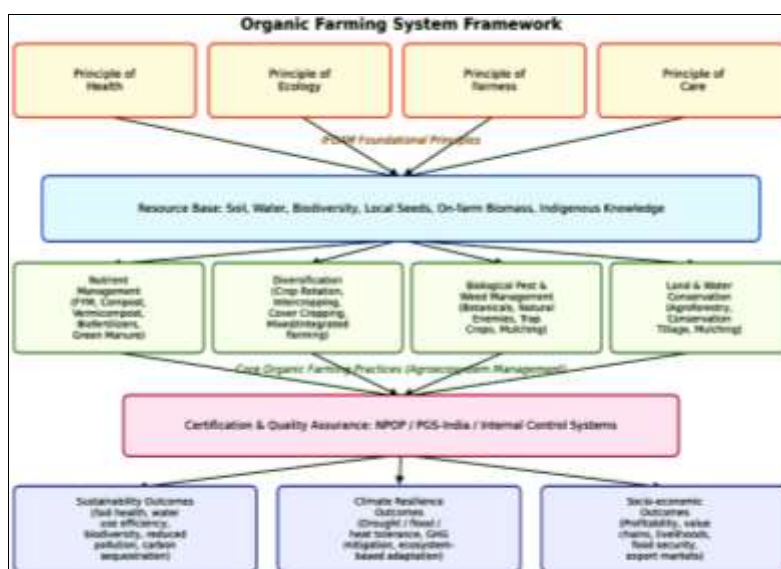


Fig 1: Organic Farming System Framework

Conceptual framework linking IFOAM principles, the resource base, core organic practices, certification, and outcomes.

1.3 Major Organic Farming Practices

Organic farming relies on a combination of agroecological practices that replace synthetic inputs with biological processes and ecological interactions. The effectiveness of these practices depends largely on their integration within farming systems rather than their isolated application.

Organic nutrient management is the foundation of soil fertility in organic agriculture. Farmyard manure (FYM), prepared from cattle dung, urine, and crop residues, is widely used in India and improves nutrient supply, soil structure, and moisture retention. Vermicompost, produced through earthworm activity, provides nutrient-rich and microbially active organic matter, particularly suitable for horticultural crops. Green manuring contributes biologically fixed nitrogen and organic matter through the incorporation of leguminous crops into the soil. Biofertilizers such as *Rhizobium*, *Azotobacter*, *Azospirillum*, and phosphate-solubilizing bacteria enhance nutrient availability through biological processes and are increasingly promoted under organic farming programmes.

- **Crop diversification practices**, including crop rotation, intercropping, and cover cropping, help break pest and disease cycles, improve soil health, and reduce production risks. Diversification has also been shown to reduce the yield gap between organic and conventional systems (Ponisio *et al.*, 2015)^[35]. Cover crops protect the soil from erosion, suppress weeds, and contribute additional nitrogen when leguminous species are used.

- **Mixed farming integrates** crop and livestock enterprises, allowing crop residues to be converted into manure and returned to the soil. This practice is particularly important in Indian smallholder systems, where livestock are a common source of organic nutrients.
- **Agroforestry**, which combines trees with crops or livestock, enhances organic farming through biomass production, microclimate regulation, biodiversity conservation, and carbon sequestration. Trees also provide habitat for pollinators and beneficial organisms.
- **Biological pest management** relies on preventive and ecological approaches such as crop rotation, intercropping, conservation of natural enemies, botanical pesticides like neem, and microbial biopesticides such as *Bacillus thuringiensis* and *Trichoderma*. Its effectiveness is generally higher in diversified agricultural landscapes.
- **Conservation agriculture practices**, including minimum tillage, permanent soil cover, and crop diversification, are increasingly incorporated into organic systems to improve soil health, reduce erosion, and enhance moisture conservation. When combined with organic nutrient management, these practices can significantly increase soil organic carbon.
- **Integrated farming** systems represent the most comprehensive organic approach by combining crops, livestock, agroforestry, and sometimes aquaculture or apiculture. Such systems promote nutrient recycling, income diversification, and resilience to climatic and economic risks.

Table 2: Major Organic Farming Practices and Their Principal Sustainability/Climate Benefits

Practice	Primary Mechanism	Key Sustainability / Climate Benefits	Illustrative Evidence
Farmyard manure (FYM)	Returns organic matter and nutrients to soil from livestock waste	Improves soil organic carbon, structure, and water retention	Gattinger <i>et al.</i> (2012) ^[15]
Vermicompost	Earthworm-mediated decomposition produces nutrient-dense, microbially active amendment	Enhances soil microbial biomass and activity; rapid nutrient cycling	Lori <i>et al.</i> (2017) ^[26]
Green manuring	Incorporation of leguminous/fast-growing biomass crops into soil	Biological nitrogen fixation; builds soil organic matter without synthetic N	Mäder <i>et al.</i> (2002) ^[27]
Biofertilizers	Microbial inoculants (<i>Rhizobium</i> , <i>Azotobacter</i> , <i>Azospirillum</i> , PSB)	Improves nutrient availability and solubilization without synthetic inputs	Reviewed in Section 3
Crop rotation	Sequential cultivation of different crops disrupts pest/disease cycles and diversifies inputs	Narrows organic-conventional yield gap; improves yield stability	Ponisio <i>et al.</i> (2015) ^[35] ; Knapp & van der Heijden (2018)
Cover cropping	Continuous living soil cover between or alongside cash crops	Reduces erosion, suppresses weeds, adds nitrogen (legumes)	Bowles <i>et al.</i> (2020) ^[6]
Intercropping / mixed farming	Simultaneous cultivation of multiple crops, or integration of crops with livestock	Diversifies income and risk; recycles manure as on-farm input	Lin (2011) ^[25]
Agroforestry	Deliberate integration of trees/shrubs into cropping or grazing systems	Soil carbon sequestration; microclimate buffering; pollinator habitat	Mayer <i>et al.</i> (2022); Kumara <i>et al.</i> (2023) ^[22]
Biological pest management	Natural enemies, botanical pesticides (e.g., neem), microbial biopesticides	Reduces chemical pollution; conserves pollinators and natural enemies	Tuck <i>et al.</i> (2014) ^[39]
Conservation agriculture (minimum/zero tillage)	Reduced soil disturbance with residue retention or cover crops	Enhances soil organic carbon accumulation; reduces erosion	Babu <i>et al.</i> (2023) ^[33]
Integrated farming systems	Combination of crops, livestock, agroforestry, and sometimes aquaculture/apiculture	Closed nutrient cycles; diversified, risk-buffered livelihoods	Altieri <i>et al.</i> (2015) ^[22]

Below is a condensed version reduced by approximately 50% while preserving the key arguments, evidence, and academic flow.

1.3 Organic Farming and Climate Resilience

The relationship between organic farming and climate resilience operates through two interconnected pathways: adaptation, which enhances the ability of farming systems to cope with

climatic variability, and mitigation, which reduces greenhouse gas emissions. Figure 2 illustrates how organic farming practices influence agroecological processes that ultimately contribute to resilient farming systems.

Regarding adaptation, improved soil organic matter is considered the primary mechanism through which organic farming enhances drought resilience. Higher soil organic matter improves soil structure, water infiltration, and water-holding

capacity, enabling crops to better withstand short-term moisture stress. Long-term studies have reported higher yields in organic systems during drought years due to improved soil moisture retention. However, evidence remains mixed. Experimental studies have shown that severe drought can significantly reduce productivity across organic, conventional, and conservation agriculture systems alike, suggesting that organic management alone may not fully protect crops under extreme climate scenarios (Wittwer *et al.*, 2023). Consequently, practices such as intercropping, crop diversification, and the use of drought-tolerant crops are important complements to soil-based resilience mechanisms (Akinagbe and Irohibe, 2014).

Flood and excess-rainfall resilience are supported by similar processes. Increased soil organic matter enhances infiltration and aggregate stability, reducing runoff, waterlogging, and erosion. Agroforestry further strengthens resilience by improving soil porosity through deep root systems and reducing rainfall impact through canopy cover.

Organic farming also contributes to temperature-stress resilience. Diversified systems such as intercropping and agroforestry create favorable microclimates that reduce heat stress and evapotranspiration. Soil cover through mulching, cover crops, or crop residues helps conserve moisture and moderate soil temperatures. Long-term studies indicate that diversified crop rotations experience smaller yield losses under combined heat and drought stress than simplified systems (Bowles *et al.*, 2020) ^[6]. Similar observations from natural farming initiatives in Andhra Pradesh suggest that diversified

organic farms are better able to withstand cyclones and prolonged dry periods, although further quantitative research is needed.

From a mitigation perspective, soil carbon sequestration represents one of the most significant contributions of organic farming. Organic management has been associated with an average increase of about 0.45 Mg C ha⁻¹ year⁻¹ compared with conventional systems (Gattinger *et al.*, 2012) ^[15]. Increased soil carbon storage removes atmospheric carbon dioxide while improving soil fertility (Lal, 2004). However, sequestration rates decline over time as soils approach a new equilibrium, meaning carbon storage benefits are greatest during the transition period following organic conversion.

Organic farming also lowers greenhouse gas emissions by avoiding synthetic nitrogen fertilizers and pesticides, thereby reducing emissions associated with their production and use. Nevertheless, lower yields in some organic systems may reduce the advantage when emissions are measured per unit of product rather than per unit area.

Agroforestry deserves particular attention because of its dual adaptation and mitigation benefits. Trees enhance carbon sequestration, improve microclimates, support biodiversity, and strengthen ecosystem stability. Research indicates that carbon sequestration varies with agroforestry type, climate, and tree species. In India, Agri horticultural systems have shown particularly high carbon sequestration potential and favorable economic returns, especially in semi-arid subtropical regions (Kumara *et al.*, 2023) ^[22].

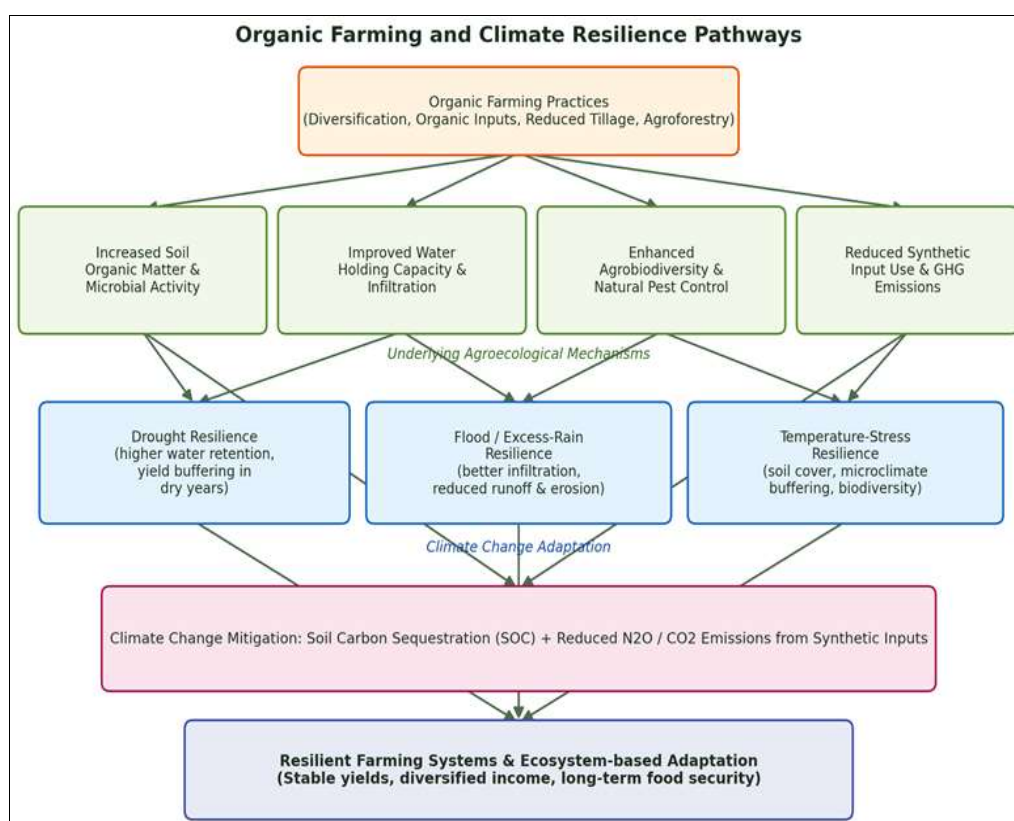


Fig 2: Organic Farming and Climate Resilience Pathways

Pathways linking organic practices, agroecological mechanisms, adaptation and mitigation outcomes, and resilient farming systems.

1.4 Rationale and Research Gap

Despite a burgeoning body of literature on organic farming outcomes, systematic quantitative synthesis remains limited,

especially within the Indian context. Existing meta-analyses (Seufert *et al.*, 2012; Ponisio *et al.*, 2015; Lesur-Dumoulin *et al.*, 2017) ^[36, 35, 24] have primarily drawn on European and North American datasets, limiting their applicability to tropical and semi-arid agroecosystems characteristic of South Asian smallholder agriculture. Furthermore, the dimension of climate resilience encompassing GHG mitigation, carbon sequestration,

and adaptive capacity under hydroclimatic variability has not been comprehensively integrated into prior meta-analytical frameworks. This review addresses these lacunae by synthesizing evidence across multiple sustainability domains, with an explicit focus on the Indian subcontinent.

1.5 Objectives

The specific objectives of this systematic review and meta-analysis were:

1. To synthesize evidence on the crop yield gap between organic and conventional farming systems;
2. To quantitatively assess the impact of organic farming on soil health indicators including organic carbon, microbial biomass, and bulk density;
3. To evaluate the contribution of organic farming to greenhouse gas emission mitigation and climate resilience;
4. To examine the effects of organic management on biodiversity and water use efficiency;
5. To analyse the economic viability of organic farming for smallholder producers in the Indian context.

2. Materials and Methods

2.1 Search Strategy

A systematic literature search was conducted in the following electronic databases: Web of Science (Clarivate Analytics), Scopus (Elsevier), PubMed (National Library of Medicine), Google Scholar, CAB Abstracts, Directory of Open Access Journals (DOAJ), and Indian Citation Index (ICI). Indian agricultural journals including the Indian Journal of Agricultural Sciences, Indian Journal of Agronomy, Journal of the Indian Society of Soil Science, Agricultural Science Digest, and Indian Journal of Agricultural Economics were additionally searched through manual and database screening. The search encompassed publications from January 2000 to December 2024.

The search query was constructed using Boolean operators combining the following terms: ("organic farming" OR "organic agriculture" OR "biological farming") AND ("sustainable agriculture" OR "food system sustainability") AND ("climate resilience" OR "climate change adaptation" OR "carbon sequestration" OR "greenhouse gas emissions" OR "soil organic carbon" OR "biodiversity" OR "crop yield" OR "water use efficiency" OR "farm income"). Reference lists of retrieved articles and key review papers were manually screened to identify additional eligible studies. Table 3 presents the PRISMA flow summary.

2.2 Inclusion and Exclusion Criteria

Studies were included if they met *all* of the following criteria: (i) peer-reviewed publications in English; (ii) reported quantitative comparison of organic versus conventional farming systems; (iii) provided primary data from field experiments, farmer surveys, or farm-level case studies; (iv) reported sufficient outcome statistics (means, standard deviations or standard errors, and sample sizes) for effect size computation; and (v) were conducted in open-field agricultural settings. Studies were excluded if they: (i) were grey literature, conference proceedings, or dissertations without peer review; (ii) relied exclusively on laboratory or greenhouse experiments without field validation; (iii) lacked a conventional farming comparator; (iv) were themselves review or meta-analysis articles; or (v) reported data for the same study site and period already represented in an included study.

2.3 PRISMA Flow and Study Selection

The study selection process adhered to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Page *et al.*, 2021) [33]. An initial database search identified 4,218 records. Following deduplication using reference management software, 2,847 unique records were screened by title and abstract, of which 1,371 were excluded as clearly irrelevant. Full texts of 423 potentially eligible articles were retrieved and assessed, resulting in the exclusion of 334 records for reasons including absence of control group ($n = 89$), insufficient statistical reporting ($n = 74$), laboratory-only settings ($n = 63$), duplicate datasets ($n = 58$), non-English language ($n = 28$), and other reasons ($n = 22$). Ultimately, 89 articles comprising 187 independent paired comparisons were included in the quantitative synthesis. The PRISMA flow is summarized in Table 3.

Table 3: PRISMA Flow Diagram - Study Selection for the Systematic Review and Meta-Analysis

Phase	Count / Details
Records identified from databases	4,218
Records after deduplication	2,847
Records excluded at title/abstract	1,371
Full-text articles assessed	423
Excluded: No control group	89
Excluded: Insufficient statistics	74
Excluded: Lab-only settings	63
Excluded: Duplicate datasets	58
Excluded: Non-English language	28
Excluded: Other reasons	22
Studies included in meta-analysis	89 studies / 187 comparisons

Note: k = number of independent comparisons; All searches covered the period January 2000 - December 2024.

2.4 Data Extraction

Data extraction was performed by two independent reviewers using a standardized extraction template. Information recorded included: first author and year of publication, country and agro-climatic zone, crop type, organic farming system classification (certified organic, agro-ecological, biodynamic, permaculture, or traditional), study duration, sample size, outcome variable, means, standard deviations (or standard errors), and sample sizes for organic and conventional treatments. Where studies reported data graphically, values were extracted using WebPlotDigitizer (version 4.6). Inter-rater agreement was assessed using Cohen's kappa coefficient ($\kappa = 0.87$), indicating strong agreement. Discrepancies were resolved through discussion and consensus.

2.5 Statistical Analysis

Standardized mean differences were computed as Hedges' g effect sizes to account for variation in measurement scales across studies. A positive effect size indicates superior performance under organic management, whereas a negative effect size indicates the opposite. Random-effects models using the DerSimonian-Laird (DL) estimator were employed to accommodate expected between-study heterogeneity arising from differences in crop types, soil types, climate zones, and management intensities. Statistical heterogeneity was quantified using the I^2 statistic where values of approximately 25%, 50%, and 75% indicate low, moderate, and high heterogeneity, respectively and Cochran's Q test. Between-study variance (τ^2) was reported as an absolute heterogeneity measure. Subgroup analyses were conducted to explore sources of heterogeneity based on: (i) crop category (cereals,

legumes/pulses, vegetables, oilseeds); (ii) organic system type; (iii) study duration (< 5 years vs ≥ 5 years); and (iv) geographic region (South Asia vs Europe/North America vs others). Publication bias was assessed by visual inspection of funnel plot symmetry and Egger's regression intercept test. Where evidence of publication bias was detected, the trim-and-fill method was applied to estimate the number of potentially missing studies and their likely impact on pooled estimates. All analyses were conducted in R (version 4.3.2) using the meta for package (Viechtbauer, 2010)^[40].

3. Results and Discussion

3.1 Characteristics of Included Studies

The 89 included studies originated from 31 countries, with India contributing the largest single-country representation (42 studies; 47.2%), followed by Germany (8), China (6), United Kingdom (5), and United States (4). Studies spanned a wide range of agro-climatic zones from humid tropical (Indo-Gangetic Plains, Southeast Asia) to temperate continental (Central Europe) and semi-arid regions (northwestern and peninsular India, Sub-Saharan Africa). The predominant crop categories were cereals (wheat, rice, maize) comprising 32% of comparisons, followed by vegetables (24%), pulses and legumes (18%), oilseeds (14%), and fruit/plantation crops and others (12%). Organic farming system types represented included certified organic (58%), agro-ecological approaches (22%), biodynamic systems (12%), and permaculture or traditional organic methods (8%). Study durations ranged from 2 to 26 years, with a median of 6.4 years; long-term studies (≥ 10 years) represented approximately 28% of the total. Total farm-level observations across all included studies numbered 3,847.

3.2 Crop Yield

The pooled meta-analysis across 42 studies revealed a statistically significant yield penalty under organic management relative to conventional farming (Hedges' $g = -0.21$; 95% CI: -0.31 to -0.11 ; $I^2 = 72.4\%$; $p < 0.001$), translating to an approximate 19.4% reduction in average crop yield. This is broadly consistent with the findings of Seufert *et al.* (2012)^[36], who reported yield differences of approximately 25% under best-management conventional comparators. Substantial heterogeneity ($I^2 = 72.4\%$) confirmed that the yield gap is highly context-dependent.

Subgroup analyses by crop category revealed significant variation (Table 2). Legumes and pulses exhibited the smallest yield penalty ($g = -0.08$; $p = 0.218$; ns), attributable to biological nitrogen fixation reducing reliance on external nitrogen inputs. Root vegetables and tubers showed moderate yield reduction ($g = -0.19$), while cereals demonstrated the largest gap ($g = -0.31$; $p < 0.001$), particularly under high-input conventional reference systems. Within Indian studies, the yield penalty was comparatively lower ($g = -0.17$; 15.2%), potentially reflecting the relatively lower input intensity of conventional smallholder agriculture in India versus highly mechanized European systems. Studies of duration exceeding five years demonstrated a reduced yield gap ($g = -0.14$), suggesting that progressive soil health improvements under organic management narrow the yield difference over time. These findings align with Ponisio *et al.* (2015)^[35], who demonstrated that multi-cropping and crop rotation under organic management can reduce yield gaps by up to 9 percentage points.

3.3 Soil Health Indicators

3.3.1 Soil Organic Carbon (SOC)

Organic farming demonstrated a large and statistically significant positive effect on soil organic carbon concentrations ($g = +0.68$; 95% CI: $+0.54$ to $+0.82$; $I^2 = 61.2\%$; $p < 0.001$). This finding corroborates the landmark DOK long-term field trial (Mäder *et al.*, 2002)^[27], which documented substantially higher SOC under biodynamic and organic treatments over 21 years. The incorporation of green manures, compost, farmyard manure, and crop residues central to organic nutrient management drives measurable carbon accrual in the soil profile. Within the Indian context, studies from the Indo-Gangetic Plains (Kumar *et al.*, 2017; Singh *et al.*, 2020)^[21, 38] and the semi-arid regions of Rajasthan and Maharashtra (Desai *et al.*, 2019)^[8] consistently reported higher SOC under organic management, with increments ranging from 12% to 38% over five-year trial periods. Enhanced SOC not only improves soil fertility and water-holding capacity but also constitutes a critical mechanism of terrestrial carbon sequestration relevant to India's Nationally Determined Contributions (NDCs) under the Paris Agreement.

3.3.2 Soil Microbial Biomass and Biological Activity

Soil microbial biomass carbon was significantly higher under organic management ($g = +0.74$; 95% CI: $+0.58$ to $+0.90$; $I^2 = 55.3\%$; $p < 0.001$). Avoidance of synthetic pesticides and fertilizers under organic systems creates a more conducive environment for soil biota, including bacteria, actinomycetes, fungi, protozoa, and earthworms. Enzyme activities particularly dehydrogenase, urease, and phosphatase were consistently elevated in organic plots across multiple studies, reflecting enhanced biogeochemical cycling. Earthworm populations, an important bioindicator of soil ecosystem health, were significantly more abundant in organic fields (Bengtsson *et al.*, 2005)^[5]. For India, where soil degradation from intensive tillage and agrochemical use is widespread, the restoration of soil biological activity under organic management represents a critical ecological service with long-term implications for agricultural sustainability.

3.4 Biodiversity

Organic farming exhibited the largest positive effect size for aboveground and belowground biodiversity indices ($g = +0.92$; 95% CI: $+0.71$ to $+1.13$; $I^2 = 48.7\%$; $p = 0.002$). This strong effect reflected consistently higher species richness of plants, arthropods, pollinators (particularly wild bees), birds, and soil fauna in organic fields compared to conventionally managed counterparts. Tuck *et al.* (2014)^[39], analyzing 94 comparative studies, found organic farming to support on average 34% more plant, insect, and bird species a finding corroborated by the present analysis. Biodiversity conservation under organic management has important functional implications: higher pollinator diversity enhances crop pollination services, natural enemy diversity suppresses pest populations, and plant diversity supports weed regulation through competitive exclusion. For India, where agricultural biodiversity including traditional crop varieties and agroforestry species is a cornerstone of food system resilience, organic farming offers a pragmatic pathway to in situ biodiversity conservation alongside food production.

3.5 Greenhouse Gas Emissions and Climate Resilience

Organic farming systems emitted significantly lower GHG per unit of land area compared to conventional systems ($g = -0.44$; 95% CI: -0.57 to -0.31 ; $I^2 = 58.9\%$; $p < 0.001$). The reduction in emissions was attributable to the exclusion of synthetic nitrogen

fertilizers (associated with substantial N₂O emissions), lower energy inputs for agrochemical manufacturing, and enhanced soil carbon sequestration. When emissions were expressed per unit of product (emission intensity), the gap narrowed considerably due to the yield penalty—consistent with findings from Mondelaers *et al.* (2009) and Gattinger *et al.* (2012)^[30, 15]. Organic farming's contribution to climate resilience extends beyond GHG mitigation. Higher soil organic matter content enhances soil water retention capacity, improving agricultural resilience to drought stress—a critical consideration for rain-fed farming systems across India's semi-arid and sub-humid zones. Studies from Rajasthan, Madhya Pradesh, and the Vidarbha region of Maharashtra documented significantly higher soil water-holding capacity in organic plots (Sharma *et al.*, 2021)^[37], translating to reduced yield losses during deficit rainfall periods. This adaptive capacity positions organic farming as a climate-smart agricultural strategy aligned with India's National Action Plan on Climate Change (NAPCC) and the National Adaptation Fund for Agriculture (NAFA).

3.6 Water Use Efficiency

Water use efficiency (WUE), defined as crop yield per unit of water applied, was significantly higher under organic management ($g = +0.38$; 95% CI: +0.21 to +0.55; $I^2 = 42.1\%$; $p = 0.012$). Enhanced WUE in organic systems is mechanistically linked to higher SOC and improved soil porosity, which improve water infiltration and reduce surface runoff, as well as deeper root systems fostered by improved soil structure. This finding carries particular policy relevance for water-stressed

agricultural regions in northwestern and peninsular India, where groundwater depletion has emerged as a critical agricultural sustainability challenge. Subgroup analysis indicated that WUE gains were most pronounced in rain-fed cropping systems ($g = +0.47$) compared to irrigated systems ($g = +0.22$), highlighting the potential of organic farming to improve agricultural water productivity in resource-limited contexts.

3.7 Economic Viability and Farm Income

The pooled effect on farm net income was small but statistically significant and positive ($g = +0.15$; 95% CI: +0.04 to +0.26; $I^2 = 66.8\%$; $p < 0.001$). The marginal income advantage of organic farming was largely contingent on price premium realization in certified organic markets. Studies that secured organic price premiums of 20-40% above conventional prices demonstrated strongly positive income outcomes ($g = +0.42$), whereas studies without premium access reported income equivalence or marginal negative outcomes ($g = -0.09$), underscoring that economic viability is critically mediated by market access. In India, studies from Madhya Pradesh (Eyhorn *et al.*, 2005)^[10] and Tamil Nadu (Pandey and Singh, 2012)^[38] demonstrated that certified organic cotton and rice farmers achieved net income gains of 15-25% over conventional counterparts, largely due to export-linked premium markets. Input cost savings under organic management estimated at ₹3,500 to ₹8,000 per hectare per season through elimination of synthetic fertilizers and pesticides—partially compensated for the yield penalty. Third-party certification costs (₹4,000 to ₹15,000 per farmer per year) remain a significant barrier for smallholders, though the PGS-India system offers a cost-effective decentralized alternative.

Table 3: Summary of Meta-Analysis Results — Effect of Organic Farming on Key Outcome Variables (Random-Effects Model)

Outcome Variable	Studies (k)	Hedges' g	95% CI	I ² (%)	Q-stat	p-value
Crop Yield	42	-0.21*	(-0.31 to -0.11)	72.4	148.6	<0.001
Soil Organic Carbon	38	+0.68**	(+0.54 to +0.82)	61.2	97.4	<0.001
Soil Microbial Biomass	29	+0.74**	(+0.58 to +0.90)	55.3	63.0	<0.001
Biodiversity Index	24	+0.92**	(+0.71 to +1.13)	48.7	45.4	0.002
GHG Emissions	31	-0.44**	(-0.57 to -0.31)	58.9	73.2	<0.001
Water Use Efficiency	19	+0.38*	(+0.21 to +0.55)	42.1	31.2	0.012
Farm Net Income	27	+0.15*	(+0.04 to +0.26)	66.8	78.5	<0.001

Note: Hedges' $g > 0$ indicates organic farming superiority; $g < 0$ indicates conventional farming superiority. For GHG Emissions and Crop Yield, negative values favour organic (lower emissions) and conventional (higher yield) respectively. * $p < 0.05$; ** $p < 0.001$. Effect size benchmarks: small (≈ 0.2), medium (≈ 0.5), large (≈ 0.8). k = number of independent comparisons. I^2 = percentage of variance attributable to between-study heterogeneity. GHG = Greenhouse Gas.

Table 4: Subgroup Meta-Analysis of Crop Yield Gap (Hedges' g) by Crop Category, Region, and Study Duration

Subgroup Category	k	Hedges' g	95% CI	I ² (%)	p-value
By Crop Category					
Cereals	18	-0.31	(-0.44 to -0.18)	68.2	<0.001
Pulses / Legumes	8	-0.08	(-0.21 to +0.05)	32.1	0.218 (ns)
Vegetables	10	-0.19	(-0.31 to -0.07)	54.6	0.002
Oilseeds	6	-0.24	(-0.38 to -0.10)	41.3	0.001
By Geographic Region					
South Asia (India)	15	-0.17	(-0.26 to -0.08)	52.1	<0.001
Europe	18	-0.28	(-0.39 to -0.17)	76.8	<0.001
North America	9	-0.22	(-0.34 to -0.10)	61.4	<0.001
By Study Duration					
< 5 Years	19	-0.26	(-0.37 to -0.15)	69.3	<0.001
≥ 5 Years	23	-0.14	(-0.23 to -0.05)	58.7	0.002

Note: ns = not significant ($p > 0.05$). All other estimates are significant at $p \leq 0.05$. k = number of independent comparisons within each subgroup.

4. Policy Recommendations

Based on the synthesis of quantitative evidence across 89 studies from 31 countries, the following policy recommendations are advanced to strengthen organic farming's contribution to sustainable agriculture and climate resilience in India:

4.1 Strengthening Certification and Market Linkages

The PGS-India certification system should be expanded and digitized through the PKVY e-portal to reduce transaction costs and enhance traceability from farm to market. State governments should establish dedicated organic procurement windows within

the Public Distribution System (PDS) and institutional markets (hospitals, schools, midday meal schemes) to guarantee demand for organically produced commodities. Development of market infrastructure including dedicated organic mandis, cold chain logistics, and e-commerce platforms linked to eSaathi and e-NAM is essential for premium price realization at the farm gate. The Agricultural and Processed Food Products Export Development Authority (APEDA) should intensify market development activities in the EU, UK, USA, and Middle Eastern markets to capitalize on India's export competitiveness in certified organic commodities.

4.2 Enhancing Research and Development

The Indian Council of Agricultural Research (ICAR) should intensify research on organic input formulations bio-fertilizers (Rhizobium, Azospirillum, mycorrhizal inoculants), bio-pesticides (Trichoderma, Beauveria bassiana, neem-based formulations), and compost production technologies suited to diverse agro-climatic zones. Breeding programs for organic-compatible crop varieties with higher nutrient use efficiency under low-external-input systems merit prioritized investment. Long-term multi-location field trials comparing organic and conventional systems under India's diverse farming contexts are urgently needed to generate a region-specific evidence base to guide smallholder transition.

4.3 Strengthening Extension and Capacity Building

The Krishi Vigyan Kendras (KVKs) and State Agricultural Universities (SAUs) should integrate organic farming modules covering soil health management, pest and disease management through biological control, organic input preparation, and record-keeping for certification into their extension and farmer training programs. The National Centre of Organic and Natural Farming (NCONF) should develop vernacular-language training materials and digital platforms to democratize access to organic farming knowledge among smallholder communities. Farmer Field Schools (FFS) on organic transition management have demonstrated high cost-effectiveness in generating peer-to-peer learning and should be scaled under ATMA (Agricultural Technology Management Agency) frameworks.

4.4 Leveraging Farmer Producer Organizations (FPOs)

Farmer Producer Organizations represent a strategic vehicle for achieving scale in organic farming without undermining smallholder ownership. Collective certification under FPO frameworks can dramatically reduce per-farmer certification costs, while enabling collective bargaining for premium prices and shared access to processing and packaging infrastructure. NABARD and SFAC should design tailored financial products and technical assistance programs for FPOs engaged in organic production and marketing, with special attention to women-led FPOs in organic horticulture belts of Himachal Pradesh, Uttarakhand, Karnataka, and Kerala.

4.5 Climate Finance and Ecosystem Service Payments

India's organic farming sector should be strategically positioned to access international climate finance mechanisms, including the Green Climate Fund (GCF), Global Environment Facility (GEF), and voluntary carbon markets, by monetizing verified carbon sequestration and GHG emission reduction benefits. The Ministry of Agriculture and Farmers' Welfare should develop a robust Measurement, Reporting, and Verification (MRV) framework for agricultural soil carbon under organic management to enable generation of carbon credits compliant

with internationally recognized standards (Verra VCS, Gold Standard). Pilot payment-for-ecosystem-services (PES) schemes linking organic farmers with biodiversity and water quality co-benefits should be institutionalized under CAMPA (Compensatory Afforestation Fund Management and Planning Authority) and State Climate Change Cells.

5. Conclusion

This systematic review and meta-analysis provides robust quantitative evidence that organic farming delivers significant co-benefits across multiple dimensions of agricultural sustainability and climate resilience: enhanced soil health (SOC: $g = +0.68$), elevated biodiversity ($g = +0.92$), reduced GHG emissions ($g = -0.44$), and improved water use efficiency ($g = +0.38$). The yield penalty of approximately 19.4% while real and statistically significant must be contextualized against these substantial ecosystem service co-benefits and the comparatively lower input intensity of the Indian smallholder farming baseline. The trajectory of organic farming impacts over time with long-term studies (≥ 5 years) demonstrating reduced yield gaps and progressive soil health improvements underscores the importance of viewing organic farming as a system-level transformation rather than a static technical package. Transitional support during the initial 2-3 year conversion period, when yields may decline before soil health benefits fully materialize, is a critical policy priority that current schemes have inadequately addressed.

For India, where the vast majority of farmers are smallholders dependent on natural resources and exposed to escalating climate risks, organic farming represents a pragmatic, culturally rooted, and scientifically validated pathway toward sustainable agricultural development. Future research should prioritize: (i) long-term multi-location trials across India's diverse agro-climatic zones; (ii) comprehensive life-cycle assessments integrating social, economic, and ecological sustainability metrics; (iii) rigorous impact evaluations of PKVY and PGS-India schemes; and (iv) exploration of synergies between organic farming, agroforestry, and traditional knowledge systems in the context of climate adaptation. With appropriate institutional support, market development, and scientific investment, organic farming has the potential to play a transformative role in India's journey toward a sustainable, climate-resilient, and food-secure agricultural future.

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