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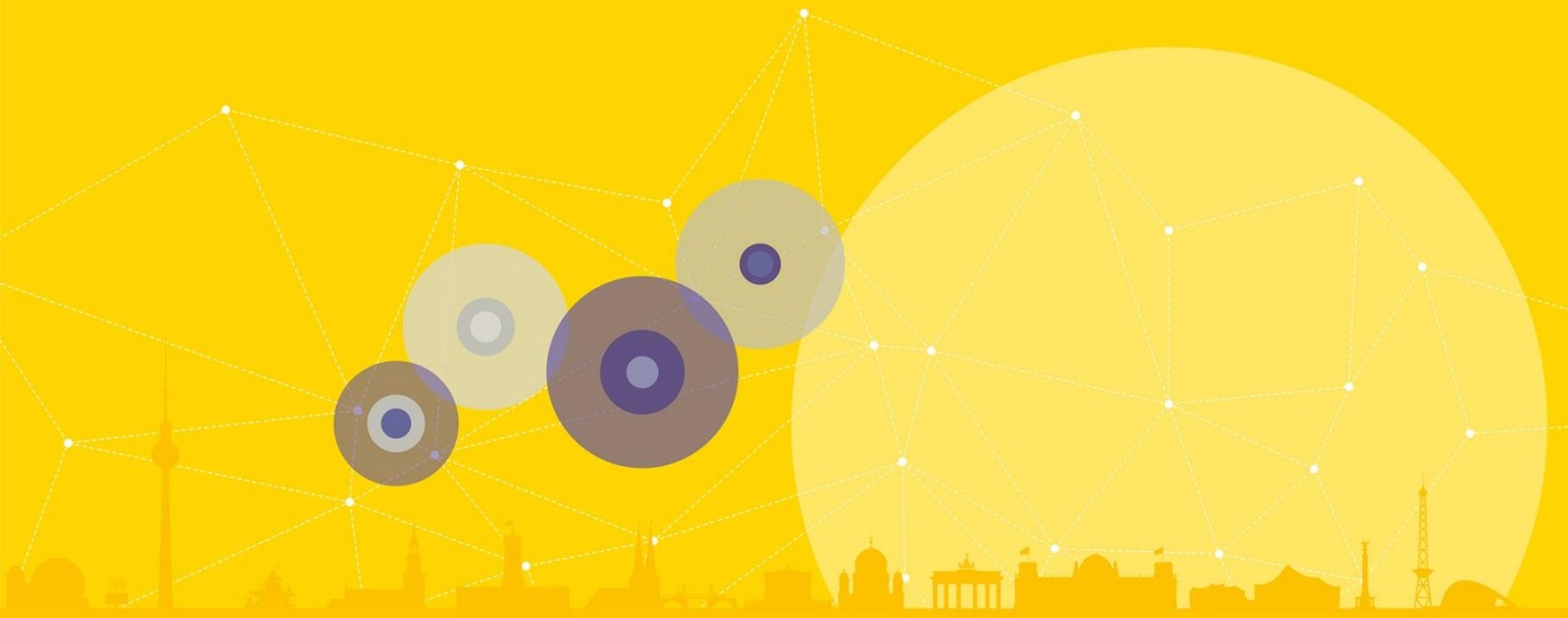

Seminar für Ländliche Entwicklung Berlin

SLE Discussion Paper

A Semi-Systematic Review on Climate-Resilient Practices in Cambodian Pepper and Cashew Nut Systems

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Das **Seminar für Ländliche Entwicklung (SLE)** gehört zum Albrecht Daniel Thaer-Institut für Agrar- und Gartenbauwissenschaften der Lebenswissenschaftlichen Fakultät der Humboldt-Universität zu Berlin. Die vier Arbeitsfelder des SLEs umfassen den Post-Master Studiengang „**Internationale Zusammenarbeit für nachhaltige Entwicklung**", **Trainingskurse** für internationale Fachkräfte aus der IZ, anwendungsorientierte **Forschung** sowie **Beratung** für Hochschulen und andere Organisationen.

Das Ziel des Forschungsprojekts „**Ländlichen Strukturwandel in Afrika sozial und ökologisch nachhaltiger gestalten**" ist es, Strategien, Instrumente und Maßnahmen zu identifizieren, die dazu geeignet sind, den ländlichen Strukturwandel in Afrika sozial inklusiver und ökologisch nachhaltiger zu gestalten. Das Projekt wird durch das Bundesministerium für wirtschaftliche Zusammenarbeit und Entwicklung (BMZ) finanziert und ist Teil der Sonderinitiative „EINEWELT ohne Hunger".

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Executive Summary

Agriculture remains the basis of rural livelihoods and national food security in Cambodia, yet it is highly vulnerable to the impacts of climate change. Farmers, particularly those in upland and rainfed regions, are increasingly exposed to erratic rainfall, prolonged droughts, and extreme temperature fluctuations that disrupt crop cycles, reduce yields, and pose significant risks to their livelihoods. As a result, climate-related shocks have pushed many smallholders toward cultivating cash crops, seeking off-farm employment, or relying on credit systems as coping mechanisms. Perennial crops such as cashew and black pepper are especially at risk because of their long growth cycles, high sensitivity to climatic stress, and the added challenges of soil erosion, fertility loss, and deforestation. These overlapping stressors highlight the urgent need to promote climate-resilient agricultural practices in Cambodia. This paper conducts a semi-systematic literature review to identify climate-resilient practices relevant to smallholder cashew and pepper production in Cambodia. The review followed a structured yet flexible process of evidence gathering across multiple academic databases, supplemented by snowballing techniques to examine influential and underrepresented literature through forward and backward citation tracing. The retrieved practices were grouped into eight main categories: water and soil management, nutrient management, crop management, intercropping and agroforestry, shade and heat stress management, disease and pest management, climate-smart tools and technologies, and climate-smart varieties. This literature review also considers the conditions shaping the adoption or non-adoption of climate-resilient practices. Adoption depends on a range of institutional and policy factors, environmental and contextual conditions, as well as socio-economic, informational, knowledge-related, and behavioral drivers. Beyond external incentives and institutional capacity, farmers' internal motivations, perceived practicality, and prevailing social norms influence their decision-making.

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CRP: Climate-resilient practice

CSA: Climate-smart agriculture

CGIAR: Consultative Group for International Agricultural Research

CCAFS: CGIAR Research Program on Climate Change, Agriculture and Food Security

HDP:High density planning

ICAR: Indian Institute of Spices Research

IISR: Indian Council of Agricultural Research

1 Background

Climate vulnerabilities of pepper and cashew production in Cambodia

In Cambodia, agriculture forms the foundation of rural livelihoods and national food security, yet it remains highly exposed to the impacts of climate change. Farmers are increasingly facing erratic rainfall patterns, prolonged dry seasons, and extreme temperature fluctuations that disrupt crop cycles and reduce yields (Kim et al., 2018, p. 2). These challenges are especially acute in upland and rainfed areas, where limited access to irrigation leaves smallholders highly dependent on natural rainfall, thus exacerbating their vulnerability to climate variability (Touch et al., 2024, p. 1632). The absence of adaptive infrastructure such as water harvesting systems, localized weather forecasts, and functioning agricultural extension services further undermines the resilience of farming communities (Touch et al., 2024, p. 1644). Climate-related shocks have been increasingly linked to disruptions in livelihoods, prompting a growing dependence on cash crops, off-farm employment, and credit systems as coping mechanisms (Dorkenoo et al., 2024, p. 13). These risks signal the need for targeted, context-specific adaptation strategies in Cambodian agriculture.

Perennial crops like black pepper (*Piper nigrum*) and cashew (*Anacardium occidentale*), both important to Cambodian smallholders, are particularly sensitive to climatic stress due to their long growth cycles and specific ecological requirements. Black pepper requires high humidity, consistent rainfall of 2,000–3,000 mm annually, and temperatures ranging between 23°C and 32°C (Ravindran et al., 2024, p. 766). Disruptions to these conditions can result in spike shedding, increased pest attacks, and reduced flowering (Ravindran et al., 2024, pp. 767–768). Similarly, cashew production is affected by high temperatures and water stress, which have been linked to flower scorching, nut shrinkage, and breakage of branches under strong winds, as observed in West Africa (Bello et al., 2017, p. 941; Esan et al., 2018, p. 2). Smallholder cashew and black pepper farmers in Cambodia's upland regions face increased soil erosion and fertility loss due to steep slopes, deforestation, and limited sustainable land management, further compounding their vulnerability to climate change (Tho et al., 2021, p. 2-4). These interlinked stressors highlight the urgency of adopting climate-resilient practices tailored to the country's agroecological zones and socioeconomic context.

Socio-economic vulnerabilities in cashew and pepper production

Smallholder cashew and pepper farmers in Cambodia face deeply rooted socio-economic vulnerabilities that limit their ability to cope with climate vulnerabilities in the country. Most producers depend heavily on farming for household income, with few alternatives during climate shocks. This heavy dependence on a single, climate-sensitive sector means that one poor season can push households into long-term financial distress (Kim et al., 2018, p. 2).

Farmers are confronted with high input costs, lack of affordable credit, and weak access to extension services that could support adaptation (Touch et al., 2024, p. 1644). Many farmers report inaction in the face of climate risks because they lack the resources, labour, and support systems to take adaptive action (Touch et al., 2024, p. 1640). These challenges leave many communities with limited options to respond to climate shocks or invest in long-term resilience.

Adaptation strategies addressing climate vulnerabilities in agriculture

In response to the above-mentioned vulnerabilities, farmers are increasingly adopting a range of climate-resilient practices to promote integrated adaptation. These practices support increased productivity, improved resilience, and reduced emissions through practices like crop cover, water-saving irrigation, among others (Erick et al., 2025, pp. 6–8; Khatri-Chhetri & Aggarwal, 2017, p. 1), in line with the FAO's three pillars of Climate-Smart Agriculture.

Strengthening the understanding of climate-resilient practices and the practical ways for scaling them up can improve the responses to climate vulnerabilities. Encouraging the use of context-specific climate-resilient practices into routine use at farm level and sharing lessons broadly, can therefore strengthen resilience and improve food security while reducing emissions.

1.1 Objectives of the review

This semi-systematic review seeks to identify climate resilient practices (CRPs) that have proven effective in the production of pepper and cashew, with a particular focus on their applicability to smallholder farming systems in Cambodia. The primary objective is to synthesize available evidence on agronomic measures, farmer-led adaptations, and institutional strategies that enhance the climate resilience of cashew and pepper production systems. The review also considers the socio-economic and institutional factors that shape the adoption of these practices, with a special focus on gender dynamics.

1.2 Methodological approach

This literature review used a mapping review approach, as conceptualized by Grant and Booth (2009), to systematically categorize and map existing research on CRPs in pepper and cashew production, and the factors for and against adoption. Mapping reviews are designed to chart the breadth and characteristics of available literature, helping identify gaps for further research or synthesis (Grant & Booth, 2009). This method enabled the contextualization of the CRP evidence base across multiple geographies and farming systems, while highlighting thematic trends and areas with insufficient empirical coverage. This is important in offering policymakers and researchers a transparent overview of where evidence is concentrated or lacking (Grant & Booth, 2009).

1.3 Search strategy

A semi-systematic review was conducted across multiple academic databases, including Web of Science, Google Scholar, Scopus, and Semantic Scholar, complemented by targeted searches of grey literature from institutional sources such as FAO, CGIAR, CCAFS, GIZ, and Cambodian research bodies. Literature selected for full-text review met at least one of the following: (a) analysis of CRPs in pepper or cashew systems; (b) relevance to perennial crops; or (c) studies situated in Cambodia, and comparable contexts.

Search terms were iteratively refined to capture relevant literature. Core keywords included:

1. "climate resilient practices" AND ("pepper" OR "cashew" OR "tree crops")
2. "climate adaptation" AND "agriculture" AND ("Cambodia" OR "South Asia")
3. "climate smart agriculture" AND ("pepper" OR "cashew")
4. "barriers to adoption" AND "climate smart agriculture"
5. "factors affecting adoption AND "climate smart agriculture" AND ("cashew OR pepper")

This keyword strategy ensured both thematic and geographic relevance and was adapted for each database. A semi-systematic review approach enabled a structured yet flexible process of evidence gathering. Ultimately, 450 titles and abstracts were screened, selected for full review, and high-quality studies were prioritized for synthesis based on credibility, contextual relevance, and insight into CRP and CRP adoption. To expand coverage and capture influential and underrepresented literature, we also applied snowballing techniques by Wohlin (2014), tracing both forward and backward citations from key studies.

1.4 Inclusion and exclusion criteria

While the inclusion criteria ensured that selected studies were directly relevant to smallholder farming systems and climate-resilient agricultural practices, the exclusion criteria were used to filter out studies that focused exclusively on crops or non-agricultural livelihoods, lacked methodological transparency, or had no clear relevance to smallholder or climate resilience outcomes. A summary of the applied inclusion and exclusion criteria is presented in the table below.

Table 1: Criteria for including and excluding documents

Inclusion criteria	**Exclusion criteria**
Peer-reviewed articles, institutional	Focused on annual crops, lack of

reports, and case studies that addressed climate adaptation in pepper or cashew systems, or in similar perennial crops under smallholder conditions. Focused on agronomic CRPs, and/or socio-economic drivers of adoption English-language publications.	methodological transparency, or irrelevant to climate resilience or smallholder contexts. Older than 2010, exceptions: critical context or technical benchmarks.

1.5 Data charting and thematic synthesis

Key findings from the reviewed literature were extracted and organized thematically, guided by both inductive insights from the data and a structured analytical framework rooted in the FAO's pillars of Climate-Smart Agriculture (CSA). These pillars, productivity, adaptation, and mitigation, also form the conceptual foundation of how this review defines Climate-Resilient Practices. An explanation of these three pillars is presented in Table 2 below.

Table 2: Description of FAO's pillars of CSA

CSA pillars	**Description**
Productivity	Practices that sustainably increase agricultural output. This includes yield-enhancing interventions such as improved irrigation systems, high-yielding crop varieties, and efficient nutrient management (FAO, 2021a).
Adaptation	Practices that reduce vulnerability to climate stresses, such as mulching, crop diversification, or intercropping, which help build resilience against droughts, pests, and shifting rainfall patterns (FAO, 2021a).
Mitigation	Practices that lower greenhouse gas emissions or enhance carbon sequestration, such as organic fertilization, low-input production systems, and agroforestry (FAO, 2021a).

In alignment with the FAO, Wakweya (2023, p. 3) emphasizes that climate-smart approaches aim to support both global and local efforts to secure food systems while enabling adaptation and mitigation in the face of climate change. Similarly, Sardar et al. (2021, p. 10122) define CSA as a strategy that integrates three interconnected goals:

maintaining or increasing productivity, strengthening the resilience of rural livelihoods and ecosystems, and reducing emissions from agriculture.

To facilitate comparative analysis across practices, geographies, and farming systems, CRPs were further clustered into typologies as presented in table 3 in the Annex. These categories were developed inductively based on recurring patterns and thematic similarities observed during the review process. This clustering also supports a clearer interpretation and allows for a structured synthesis of findings in the subsequent sections.

In addition to practice typologies, factors influencing adoption were inductively categorized into five overarching categories: socioeconomic and demographic factors, institutional and policy factors; environmental and contextual factors; information and knowledge-related factors psychosocial and normative factors. These categories provided a basis for synthesizing diverse influences across contexts, facilitating a detailed understanding of what shapes the uptake of CRPs among smallholder farmers.

1.6 Limitations

First, as a mapping review that applies semi-systematic methods to structure and analyze the literature, this study provided a broad overview of the landscape of CRPs rather than quantitatively assess the effectiveness of specific practices. While this approach offers breadth and thematic synthesis, it inherently limits the depth of inferences.

Second, the scope of the review was constrained by the decision to include only English-language sources, which may have introduced language bias. This is particularly relevant for Cambodia, where research, policy reports, and farmer-led documentation may be published in Khmer.

Third, the review also recognizes that farmer-led, indigenous, or traditional adaptation strategies are often underrepresented in the formal literature. This underrepresentation may bias the findings toward more formalized and externally promoted practices, overlooking locally grounded knowledge systems.

Fourth, the review was conducted by a team of researchers primarily trained in the social and political sciences. While this disciplinary lens brings valuable insights into the institutional, behavioural, and socio-political dimensions of CRP adoption, it may also limit the depth of technical agronomic analysis. This limitation emphasizes the importance of interdisciplinary collaboration in future research that seeks to fully integrate agronomic, ecological, and social perspectives on climate resilience.

Finally, while mapping reviews are valuable for identifying thematic trends and research gaps, they may oversimplify heterogeneity between studies. Differences in methodologies, sample sizes, geographic contexts, and definitions of CRPs mean that the patterns identified here should be interpreted as indicative rather than definitive.

2 Climate-resilient Practices in Cashew Production

2.1 Introduction

Cashew (*Anacardium occidentale L.*), a tree crop native to Brazil, is now cultivated across tropical and semi-arid regions worldwide. It belongs to the Anacardiaceae family, which includes 60–74 genera and 400–600 species of trees and shrubs, many of which are found in tropical zones (Bezerra et al., 2007, p. 449; Eradasappa et al., 2022, p. 5). Cashew thrives in semi-arid environments and performs best under 1500–2000 mm of annual rainfall, temperatures between 25–28 °C, and a distinct dry season lasting five to six months. The crop prefers well-drained, light- to medium-textured soils with a pH range of 4.5–6.5 (Adu-Gyamfi et al., 2021, p. 614) and is generally considered drought-tolerant (Avtar et al., 2013, p. 2025). Despite its tolerance to dry conditions, cashew remains vulnerable to the effects of climate change, particularly during its reproductive phase. Unpredictable rainfall patterns, prolonged droughts, and rising temperatures can lead to flower abortion, poor fruit setting, immature fruit drop, and increased pest and disease pressure; all of which contribute to yield decline and reduced nut quality (Adu-Gyamfi et al., 2021, p. 614). Moreover, unseasonal rains, excessive humidity, and dew during flowering and fruiting periods create favourable conditions for pest and disease outbreaks (Rupa et al., 2013, p. 190). These challenges are especially concerning given that cashew is often cultivated in ecologically sensitive regions such as coastal belts and hilly terrains, where climate-related risks are more pronounced. The following sections review climate-resilient practices in cashew cultivation, drawing from recent literature (mainly from India, but also from Brazil and numerous African countries) to explore strategies that can help farmers adapt to changing environmental conditions.

2.2 Water and soil management

Climate change is intensifying water-related challenges. In many cashew-growing regions, intense and erratic rainfall events are increasingly common, contributing to severe surface runoff and soil erosion (Mangalassery et al., 2024, p. 263). These processes strip away topsoil, deplete soil nutrients, and reduce the land's capacity to retain moisture. These conditions are especially damaging in rainfed systems. During the fruiting season, inadequate soil moisture has been identified as a key factor limiting cashew yields (Mangalassery et al., 2022, p. 48). To counter these challenges, researchers emphasize the importance of adopting region-specific soil and water conservation strategies, including **mulching**, **moisture-retentive soil amendments**, and **low-cost irrigation** solutions (Mangalassery et al., 2024, p. 263).

Selecting appropriate land based on a thorough assessment of soil capability is the first step in long-term soil management (Guo, 2021; Mangalassery et al., 2024, p. 262). Once soil

limitations are identified, **tailored conservation strategies** must be implemented to reduce vulnerability.

In rainfed regions, water deficits during the fruiting season can severely affect yield outcomes. To address this, a variety of soil and water conservation practices, from cashew grown on slopes or hills in India, have been identified that aim to retain moisture, reduce erosion, and improve tree growth. Among the most effective techniques are **modified crescent bunds**, which are crescent-shaped earth embankments placed upstream of cashew plants. These bunds not only trap rainwater but also reduce surface runoff and soil erosion. Research shows that they can lower annual runoff from 36.9% to 22.3% of total rainfall and cut soil loss by more than half (Rupa et al., 2013, p. 187). In addition, **staggered trenches** dug across slopes or between trees help intercept and store water. These trenches are often combined with **coconut husk burial**, a practice in which layers of coconut husks are laid inside trenches. When buried properly (with alternating layers of concave husks, soil, and organic matter), these husks act like sponges, holding water for longer periods and supporting root zone hydration. This method has also been shown to improve yields and soil moisture content (Rupa et al., 2013, p. 187). Other widely recommended techniques include **reverse terraces** and **tree base terracing**, which form level steps around trees to slow runoff and improve infiltration. By the second or third year of planting, constructing a 1.8-meter-radius terrace around each cashew tree helps capture rainfall, runoff, and seepage water directly into the root zone, thereby minimizing erosion and nutrient loss. **Natural gullies**, often formed during monsoons, should be stabilized by filling them with boulders and soil and planting fast-rooting grasses that quickly bind the soil and reduce further erosion. Over time, these depressions trap silt and regenerate into productive ground (Adiga, 2022 , p. 60). **Catch pits**, small, excavated holes that trap water, soil, and organic litter near the base of trees, further enhance water retention and reduce erosion. **Continuous contour trenches**, which follow the land's natural contour lines, are especially helpful on sloped terrain to slow water movement and allow time for infiltration. Techniques such as **zero tillage**, **cover cropping**, **crop rotation**, and **soil amendments** also improve soil structure and moisture-holding capacity. **Stone bunds**, **gully plugging**, **furrow diking**, and **subsoiling** are further soil-water conservation strategies adapted to different slopes and landscape conditions (Mangalassery et al., 2022, p. 48).

While many of these practices were originally developed to stabilize degraded or hilly landscapes, they also serve as effective tools for water management, especially in rainfed areas. Complementing these approaches, **rainwater harvesting systems** such as check dams, dugout ponds, percolation tanks, and Jalkunds (a water collection pond) enable the storage of rainfall for later use (Mangalassery et al., 2022, p. 48). When combined with **water-efficient irrigation techniques**, such as drip systems, sprinklers, or rain guns, harvested water can be reused for supplemental irrigation during dry spells, reducing dependency on groundwater and improving overall water security (Rao et al., 2025, p. 15–16).

While effective water management and retention are essential in cashew cultivation, their benefits are limited if **soil degradation** is not addressed. Without healthy, stable soils, rainfall and irrigation water are easily lost through runoff, and root systems struggle to access moisture and nutrients. In many cashew-growing regions, soils are increasingly vulnerable due to declining organic matter, nutrient deficiencies, and inadequate conservation practices (Mangalassery et al., 2024, p. 253).

Biochar, a carbon-rich material produced through the pyrolysis of organic biomass, is increasingly recognized as a valuable soil amendment in cashew cultivation. Its porous structure enhances the soil's physical and biological properties, significantly increasing water holding capacity and nutrient retention (Nduka et al., 2019, p. 111). This is particularly beneficial in sandy soils, where water and nutrients tend to drain quickly beyond the reach of plant roots. By improving moisture availability in the root zone, biochar promotes more efficient water and nutrient uptake by cashew plants, thereby enhancing overall water productivity. Studies have confirmed that cashew trees grown in soils with high biochar content exhibit improved growth, yield, and water-use efficiency compared to those in untreated soils (Gondim et al., 2024, p. 3769). Positive outcomes have been reported not only in terms of overall yield but also in the weight of individual cashew apples and the number of nuts and peduncles produced per unit of irrigation water applied (Gondim et al., 2024, p. 3781). Research from Nigeria also supports the use of biochar, either alone or in combination with compost, for enhancing the growth and development of cashew seedlings. Trials have shown improved nutrient uptake, healthier vegetative growth, and better soil physicochemical characteristics when biochar is incorporated into nursery substrates (Mangalassery et al., 2024, p. 269; Nduka et al., 2019, p. 111).

Cover crops are another key practice for improving soil stability and fertility. Species like *Pueraria phaseoloides*, *Calopogonium mucunoides*, *Mimosa invisa*, and *Mucuna bracteata* can be sown along contour bunds and between rows during the monsoon season. These legumes rapidly establish a protective ground cover, reducing soil temperature and evaporation, improving soil structure, and suppressing weed growth. Cut material from excess growth can be used as mulch at the base of the trees, further enhancing soil health and moisture retention (Adiga, 2022, p. 60). Maintaining soil organic matter is central to building resilience against both water scarcity and excess rainfall, since healthy soils absorb and retain water more effectively, reducing runoff, erosion, and downstream flooding (Bello et al., 2017, p. 942).

Mulching is a critical low-cost practice for soil and water conservation suitable for all slopes. It reduces water evaporation, stabilizes soil temperature, and suppresses weed growth. (Rupa et al., 2013, p. 188). It involves covering the soil surface with organic or inorganic materials to reduce evaporation, suppress weed growth, moderate soil temperature, and improve overall soil structure. These functions are particularly relevant in climates experiencing increased rainfall variability and prolonged dry periods, where maintaining soil

moisture is critical for tree survival and productivity. The range of mulching types extends beyond organic materials to include soil mulch, stubble, straw, live mulch, plastic mulch, and vertical mulch, each adapted to specific environmental conditions and management goals (Rao et al., 2025, p. 15). Beyond moisture conservation, mulching also contributes to the accumulation of soil organic carbon by returning renewable plant residues and manure to the soil, thereby improving soil fertility and structure (Bello et al., 2017, p. 942). Among the various mulching techniques used in cashew cultivation, **green mulching** plays a significant role. Green mulching involves the planting of green crops and cutting them down to serve as herbaceous biomass on the soil surface around the cashew trees soon after planting. This practice not only suppresses weed growth but also reduces surface evaporation and helps regulate soil temperature during dry periods (Adiga,2022, p. 65). Alongside green mulching, **dry mulches** composed of dead leaves or plant residues are also widely used to cover the basin area of cashew plants. **Coconut coir pith**, when applied as a soil mulch, has demonstrated significant benefits by increasing water retention by over 14% and suppressing weeds by nearly 74%. These mulching practices are often integrated with physical soil and water conservation structures mentioned above such as terraces and crescent bunds, where mulching with cashew leaf litter and available orchard biomass further reduces runoff and soil erosion (Rupa et al., 2013, p. 188). In coastal areas, circular trenches filled with **coconut husks and leaf litter** around the tree base have also been adopted to enhance water storage in the root zone (Mangalassery et al., 2022, p. 48). Recent research from Brazil has highlighted that organic mulches such as cashew leaves and Brachiaria grass outperform others, like coconut leaves, in terms of water retention and absorption. (Lopes et al., 2025, pp. 1, 16–17).

2.2.1 Irrigation

Cashew is traditionally grown as a rainfed crop in many tropical and subtropical regions. However, evidence suggests that irrigation can substantially increase productivity, particularly during flowering and fruit setting, when water deficits negatively impact flower development and nut retention (Rupa et al., 2013, p. 188; Mangalassery et al., 2019, p. 484). Controlled studies have shown that irrigated cashew plots produce 1.5 to 2 times higher yields compared to non-irrigated ones (Adiga, 2022, p. 64; Rupa et al., 2013, p. 188). Water stress during the reproductive phase often reduces the number of hermaphrodite flowers and leads to immature nut drop, compromising both yield and quality.

To mitigate this, protective **irrigation strategies** are commonly employed, especially during the dry season. The application of approximately 200 litres of water per tree every 15 days during drought has been reported to improve nut set and filling (Rupa et al., 2013, p. 188). In the establishment phase, ensuring continuous soil moisture is critical, with planting ideally timed to coincide with the monsoon season. Young, grafted plants under dry conditions require watering every 3 to 7 days to maintain root-zone moisture without waterlogging. Mature trees develop deep taproots that allow survival through moderate dry spells, but

long-term productivity declines in the absence of supplementary irrigation (Mangalassery et al., 2022 p. 48).

Among available irrigation technologies, **drip irrigation** has emerged as a particularly effective system. (Mangalassery et al., 2022, p. 53). It has been shown to reduce water use by 40–70% compared to conventional methods, while increasing cashew yields by 25–80% (Mangalassery et al., 2022, p.53). Beyond water savings, drip systems also limit weed growth, enhance infiltration, and perform well on uneven terrain. Nevertheless, challenges include the risk of emitter clogging from soil particles and algae, physical damage to components from pests, and higher initial costs and maintenance requirements.

Irrigation also plays a pivotal role in modern orchard systems utilizing **dwarf cultivars**. Since the 1980s, the introduction of high-yielding, compact cashew genotypes combined with reduced spacing, improved fertilization, pest management, and irrigation has enhanced orchard performance. These systems still show alternate bearing tendencies, with yield oscillating between years. Irrigation was found to increase nut counts per tree, although average nut weight decreased in older trees with heavier fruit loads (Oliveira et al., 2006, p.406).

Fertigation is the application of dissolved fertilizers via irrigation, primarily through drip systems. This method synchronizes nutrient delivery with crop demand and root activity, achieving fertilizer use efficiencies of up to 90% (Mangalassery et al., 2022, p. 56). Studies report that fertigation can halve fertilizer requirements while doubling yields (Rupa et al., 2013, p. 188). Advantages include improved nutrient uptake, reduced leaching and water pollution, minimized labour and energy inputs, and targeted micronutrient application. The system also limits weed growth by avoiding excess surface moisture. However, technical issues such as uneven nutrient distribution from emitter failures and clogging due to chemical precipitation must be managed carefully. Only fertilizers that are highly soluble, chemically compatible, and low in insoluble residues are suitable for fertigation systems.

2.3 Crop management

Effective crop management is essential to achieving sustained yields and climate resilience in cashew cultivation, especially under high-density planting and variable climatic conditions. This encompasses a combination of practices such as propagation, pruning, canopy control, varietal selection, pollination support, and biophysical monitoring. Cashew trees have dense green foliage with high photosynthetic capacity, making them suitable for **high-density systems** where canopy management becomes especially important (Rupa et al., 2013, p. 188). **Monitoring biophysical parameters** such as tree height, age, crown diameter, diameter at breast height, basal area, and tree density is important for informing decisions on yield estimation, thinning, harvesting, replantation, and carbon stock assessment (Avtar et al., 2013, p. 2024).

Pruning is a core management practice that contributes to canopy uniformity, pest control, and yield improvement. It is usually carried out once a year, typically after seasonal fruiting, and includes the removal of crisscross branches, water shoots, pest-damaged stems, and other unwanted growth. As cashew is highly sensitive to shade and produces flowers on current-season shoots, pruning of lateral and leader branches encourages new shoot growth and improves light penetration. Trees are generally maintained at a height of 4 to 5 meters to facilitate orchard operations (Dendena and Corsi, 2014, p. 760).

In graft-based plantations, early training during the first two to three years promotes proper plant architecture and facilitates cultural operations. The **modified leader system** and **open center system** are the two most widely used training approaches, with the former being suitable for both normal and high-density orchards (Adiga, 2022, p. 66).

Cashew crops have widely developed across the continent with new cashew varieties emerging. Cashew varieties that produce higher yields or are drought-resilient have been adapted and grafted. In India alone, 61 cashew varieties have been released through systematic germplasm evaluation and hybridization efforts, including 34 selections and 27 hybrids (Eradasappa et al., 2022, p. 16). These varieties differ in canopy habit, nut yield, and adaptation potential. **Varietal selection** is particularly relevant under high-density systems, where architecture and vigour determine compatibility with spacing and pruning regimes. To expand the narrow genetic base of cashew and breed high-yielding cultivars, a clonal selection program in Ghana identified and evaluated high-yielding trees from farmer fields across diverse agroecological zones, resulting in the recommendation of five top-performing clones adapted to both marginal and near-optimal environments. (Adu-Gyamfi et al., 2021, p. 613)

Planting density plays a critical role in the growth, yield, and resource use efficiency of cashew (Mangalassery et al., 2024, p. 261). **High-Density Planting** (HDP) systems, in which cashew trees are planted more closely than under traditional spacing, aim to maximize productivity per unit area. However, implementing HDP requires corresponding adjustments in canopy management, irrigation scheduling, and nutrient input, particularly the rate of fertilizer application, which must be adapted to the number of trees per hectare (Mangalassery et al., 2024, p. 261). Empirical trials indicate that increased planting density can significantly enhance raw cashew nut yields by as much as 75–81% during the fifth and sixth years after planting (Mangalassery et al., 2019, p. 493).

Although high-density planting tends to reduce individual stem girth and canopy size, it can improve land productivity and economic returns, especially when integrated with efficient irrigation practices (Mangalassery et al., 2019, pp. 483, 493). Widely spaced trees showed comparatively higher water-use efficiency, suggesting that deficit irrigation strategies may be more suitable in high-density orchards (Mangalassery et al., 2019, p. 483). Under high-density conditions (e.g., 500 plants per hectare), yields were found to be 2.2 times higher than under normal spacing (Janani et al., 2022, p. 2381). The selection of suitable varieties is

crucial for the success of HDP systems. Varietal performance under HDP is influenced by factors such as vigor, canopy architecture, and responsiveness to inputs, making genotype selection a central consideration (Janani et al., 2022, p. 2382). Cashew crops, in an HDP system, can help mitigate climate change. Since cashew is an ideal crop for carbon sequestration, and under high density planting, 2-fold high carbon has been found to be sequestered (Rupa et al., 2013, p. 181).

2.4 Nutrient management

Sustainable nutrient management plays a vital role in improving cashew yield, maintaining long-term soil health, and enhancing climate resilience. Cashew is frequently grown on degraded, nutrient-poor soils under rainfed conditions, yet research consistently shows its strong response to **fertilization**. Continuous nutrient extraction by mature cashew trees without replenishment can lead to multi-nutrient deficiencies, declining productivity, and soil degradation (Mangalassery et al., 2022, p. 38).

Nitrogen applications during the main vegetative phase are especially effective in enhancing yield and reducing nut drop (O'Farrell et al., 2010, p. 19; Dendena and Corsi, 2014, p. 758). However, excessive or ill-timed nitrogen input can lead to soil acidification and environmental contamination (O'Farrell et al., 2010, p. 27). **Phosphorus** and **sulfur** contribute to improved plant development and nut yield, but phosphorus availability is often limited in acidic soils commonly found in cashew-growing regions (Dendena and Corsi, 2014, p. 759; Mangalassery et al., 2022, p. 38). **Micronutrient** deficiencies, especially of zinc, boron, iron, manganese, and copper, are widespread and should be addressed either through **foliar sprays** applied at flushing, panicle initiation, and fruit setting or through periodic soil applications every two years. These inputs must be carefully dosed and are often mixed with sand to improve distribution (Mangalassery et al., 2022, p. 43).

Organic amendments are central to restoring degraded soils and enhancing soil structure, moisture retention, and microbial activity. **Organic manures** such as poultry droppings, cow dung, composted cashew biomass, and cocoa pod husk ash have shown greater yield responses than inorganic sources alone (Rejani et al., 2012, p. 1; Mangalassery et al., 2024, p. 270). **Green manure crops** like Gliricidia, Sesbania, and Sunhemp can be cultivated along plantation borders or between rows to supply organic biomass for mulch and compost. This practice increases organic matter, reduces erosion, and supports soil moisture conservation (Mangalassery et al., 2024, p. 266; Rupa et al., 2013, p. 188). **Biomass recycling** from fallen cashew leaves, twigs, flowers, and apples contributes significantly to nutrient cycling. This can be composted with cow dung slurry and reused after six months as mature compost (Mangalassery et al., 2024, p. 268). Studies show that up to half of the cashew's nutrient requirements can be met through on-farm biomass recycling alone (Mangalassery et al., 2024, p. 271).

Integrated nutrient management has been shown to sustain yields and improve soil fertility. In a comparative study, cashew trees receiving 50% nitrogen from chemical fertilizer and 50% from poultry manure achieved the highest yield (Rejani et al., 2012, p. 1). Similar results were observed when nitrogen was fully supplied via compost in combination with biofertilizers. Fertilizer application should align with periods of high root activity, particularly during flushing and early flowering. The general recommendation is to apply fertilizers in two split doses at the onset of the monsoon and post-monsoon, ensuring adequate soil moisture (Mangalassery et al., 2022, p. 40). Over time, nutrient inputs may be reduced based on soil test results and biomass contributions, reinforcing the need for site-specific nutrient strategies.

Biofertilizers such as arbuscular mycorrhizal fungi, *Azospirillum*, phosphate-solubilizing bacteria, and *Pseudomonas fluorescens* are effective in enhancing nutrient availability and uptake in nutrient-poor soils. These microbial inputs support mineral mobilization and help reduce dependency on chemical fertilizers (Mangalassery et al., 2024, p. 268).

Soil acidity remains a common challenge, limiting nutrient availability and causing toxic buildup of elements like aluminum. **Liming**, based on soil testing, is advised to correct pH levels and improve nutrient uptake. It is ideally done 2–3 months before planting in new orchards or once every 3–5 years in established plantations (Mangalassery et al., 2022, p. 38).

Regular weeding is essential to reduce competition for nutrients, water, and light, especially during early plant establishment when cashew seedlings and weeds occupy the same rooting zone. Weeding operations generally align with fertilizer applications and can be carried out manually or with herbicides. In low rainfall areas, **mulching** may also be used as a supplementary weeding strategy that supports moisture retention and moderates soil temperature (Dendena and Corsi, 2014, p. 757; Adiga, 2022, p. 65). Despite the clear benefits, nutrient management in cashew remains a neglected area for many growers. Variability in soil types, fertilizer availability, and knowledge gaps often hinder optimal application. Farmers frequently depend on extension agents and scientific recommendations to determine appropriate dosages and application timings (Mangalassery et al., 2024, p. 272).

2.5 Intercropping and mixed-crop systems

Intercropping is the simultaneous cultivation of two or more crops on the same land. It is increasingly recognized as a key climate-resilient strategy in cashew cultivation (Olufemi Aremu-Dele et al., 2021, p. 282). Due to the relatively wide spacing used in cashew orchards, particularly during the early years of establishment, intercropping provides a means to utilize vacant interspaces while improving land productivity, enhancing biodiversity, and promoting environmental sustainability (Mangalassery et al., 2024, p. 266; Visalakshi et al., 2015, p. 295). Research shows that intercropping systems can improve soil

cover, reduce erosion and runoff, suppress weeds, and conserve soil moisture (Mangalassery et al., 2024, p. 266). Moreover, intercropping enhances resource use by combining crops with complementary growth patterns, root depths, or nutrient demands (Olufemi Aremu-Dele et al., 2021, p. 282). When well-planned, such systems can also boost cashew seedling growth and improve overall orchard productivity without negatively affecting cashew development in its early stages (Olufemi Aremu-Dele et al., 2021, p. 283). The following sections present different types of intercropping.

Leguminous crops: Leguminous crops such as cowpea, groundnut, mungbean, horse gram, and tur are among the most widely recommended intercrops in cashew plantations in India due to their nitrogen-fixing ability and soil-improving properties (Visalakshi et al., 2015, p. 296; Sulok et al, 2024). Their inclusion in intercropping systems reduces the need for synthetic nitrogen fertilizers and improves nutrient cycling. Cowpea and yardlong bean intercropping led to significant increases in available soil nitrogen, phosphorus, and potassium levels (Gajbhiye et al., 2020, p. 454). These legumes are often rotated with vegetables to ensure steady income during the juvenile plantation phase (Visalakshi et al., 2015, p. 295)

Vegetables and root crops: Vegetables such as aubergine, chilli, okra, bitter gourd, and amaranthus have been tested as intercrops in India, consistently providing the highest cashew yields in experimental settings (Olufemi Aremu-Dele et al., 2021, p. 285). Root and tuber crops like yam, cassava, and tapioca are also used in India and Sri Lanka, often improving seedling growth and early returns without impairing cashew performance (Visalakshi et al., 2015, p. 296). Intercropping with ginger and turmeric is common during the first three to four years of cashew establishment (Visalakshi et al., 2015, p. 296).

Cereals and pulses: Cereal crops, including maize, sorghum, and ragi are sometimes used for intercropping, particularly in Ghana and Sri Lanka. These crops contribute to food security and weed suppression. In Sri Lanka, intercropping with maize and groundnut during specific seasons yielded higher land equivalent ratios without negative impacts on cashew (Visalakshi et al., 2015, p. 296; Olufemi Aremu-Dele et al., 2021, p. 285).

Fodder crops and forages: Fodder grasses (e.g., Guinea grass, para grass) and forage legumes (e.g., *Stylosanthes hamata, Mimosa invisa*, Lupinus) have been evaluated for intercropping in India. Among these, NB-21 grass and *S. hamata* showed the highest green fodder yields, offering both soil cover and livestock feed benefits (Adiga, 2022, p.69).

Fruit and lantation crops: Pineapple is one of the most common fruit intercrops grown in India and Vietnam. It is highly profitable during the first 4–7 years of cashew establishment and contributes to soil moisture conservation when grown in contour trenches (Visalakshi et al., 2015, p. 296; Adiga, p. 69). Other crops interplanted with cashew in Vietnam include banana, papaya, and perennial peanut (Nguyen et al., p. 10). Coconut-cashew intercropping systems are practised in Sri Lanka, where cashew serves as ground cover, adds organic matter, and utilizes residual nutrients with minimal competition (Olufemi Aremu-Dele et al.,

2021, p. 285). In agroforestry settings in Côte d'Ivoire, trees such as *Mangifera indica, Vitellaria paradoxa*, and *Parkia biglobosa* are maintained as companion species for their income, food, and medicinal value (Kpangui et al., 2025, p. 15).

Spice crops: Pepper is occasionally intercropped with training vines into mature cashew trees (older than six years). This system, commonly practiced on the Indian west coast, benefits from the rough cashew bark and partial canopy light, with vines producing for up to 18 years (Visalakshi et al., 2015, p. 295).

Successful intercropping depends on careful crop selection, spatial arrangement, and seasonal planning. Intercropping with more than two crops is discouraged (Olufemi Aremu-Dele et al., 2021, p. 281). Ideal intercrops should suppress weeds, avoid excessive shading, not compete heavily for light, moisture, or nutrients, and not host pests or diseases harmful to cashew (Visalakshi et al., 2015, p. 296). Despite its multiple benefits, including income diversification, food security, weed control, and soil protection, intercropping can be labour-intensive and requires location-specific planning to ensure sustainability (Olufemi Aremu-Dele et al., 2021, p. 285; Visalakshi et al., 2015, p. 295).

2.6 Disease and pest management

Pests and diseases represent some of the most significant constraints to cashew production, causing substantial reductions in yield and nut quality. More than 190 species of insects and mites have been identified as cashew pests globally (Dendena and Corsi, 2014, p. 760). Among these, the tea mosquito bug , along with stem and root borers , are considered a major threat across most cashew-growing regions (Raviprasad, 2022, p. 85). These pests cause direct damage to foliage, floral shoots, and developing nuts, often resulting in early nut abortion and reduced yields (Dendena and Corsi, 2014, p. 760; Rupa et al., 2013, p. 185). Other important insect pests include shoot tip caterpillars, thrips, leaf miners, blossom webbers, nut borers, chrysomelid beetles such as *Monolepta longitarsus* and *Neculla pollinaria*, lepidopteran caterpillars like *Lymantria and Euproctis spp*., and sap-sucking bugs such as *Anoplocnemis curvipes* and *Pseudotheraptus devastans* (Vanitha et al., 2022, p. 95; Anato et al., 2015, p. 1). In West Africa, *Apate terebrans*, *Acrocercopos syngramma*, and various thrips species have also been identified as damaging pests (Anato et al., 2015, p. 1).

Fungal pathogens are the primary disease-causing agents in cashew, with *Colletotrichum gloeosporioides* (anthracnose), *Pilgeriella anacardii* (black mold), and *Oidium spp.* (powdery mildew) cited as particularly harmful (Dendena and Corsi, 2014, p. 760). These diseases affect various stages of the crop, and their severity is often influenced by climatic conditions, especially during periods of high humidity and temperature fluctuations.

Chemical control remains the most widely used strategy for pest and disease management. Farmers in Bangladesh practice **weeding** and **hand-picking** as a strategy to reduce pests and diseases (Ahmed et al., 2023, p. 9). While biological methods are also practiced, such as

using **parasitoids** or **microbial agents,** their efficacy and economic viability remain limited. A major barrier to their adoption is the insufficient transfer of knowledge between researchers and farmers (Dendena and Corsi, 2014, p. 758).

One promising approach is the integration of **agrometeorological tools** into pest and disease management. For instance, weather parameters such as temperature and relative humidity can provide early warnings about bio-aggressor activity, helping to guide timely interventions (Amani et al., 2023, p. 2). However, recommended practices such as **tree spacing** for disease prevention often lack regional specificity and must be adapted to local agroecological conditions (Amani et al., 2023, p. 11).

Efforts are also being made to incorporate **climate-adapted management strategies**, such as selecting early maturing cashew genotypes in zones prone to fungal outbreaks during the wet season. These genotypes flower and mature earlier, thus escaping critical disease periods (Amani et al., 2023, p. 12).

Integrated Pest and Disease Management systems that combine chemical, cultural, and biological measures are increasingly promoted. **Weaver ants** (*Oecophylla longinoda* and *O. smaragdina*) have shown effectiveness in protecting cashew trees from a wide range of insect pests by preying on and deterring harmful species. In field experiments, trees managed with ants or integrated methods produced significantly higher nut yields up to 151% more than untreated control trees (Anato et al., 2015, p. 1–2).

Despite these advancements, implementation challenges persist, including gaps in farmer training, variable pest pressure across regions, and the need for better coordination among plant pathologists, weather specialists, extension agents, and growers (Amani et al., 2023, p. 12). Ongoing research and localized recommendations remain essential to making pest and disease control both effective and sustainable.

2.7 Climate-smart tools and technologies

In India, the Indian Council of Agricultural Research's Directorate of Cashew has implemented cashew-based information and **communication technology tools** to facilitate the dissemination of information. They have created the Cashew India App, which provides the user with information on cashew cultivation, cashew grafts, the market, and plant protection. It is also possible to detect some pests and diseases, as well as nutrient deficiencies, with the help of artificial intelligence (Panda, 2023). Additionally, a cashew pest database was created as a website with a photograph gallery and information on pests, their damages, symptoms and a calendar. Moreover, an app which serves as a cashew nutrient manager calculates fertilizer dosage depending on the soil conditions. The app also offers general recommendations on nutrient management and additional information, such as liming or foliar application. Lastly, a cashew community WhatsApp group was created and managed by the Directorate, which provides an exchange platform for different cashew stakeholders (Chandrakumar, 2022, p.152)

3 Climate-resilient Practices in Pepper Production

3.1 Introduction

Black pepper (*Piper nigrum*), a perennial climbing vine belonging to the family *Piperaceae*, originates from South and Southeast Asia and is widely cultivated across the humid tropics. The crop begins to bear fruit in its third or fourth year, with peak productivity reached between 7 and 20 years of age, although vines can remain productive for up to three decades (Sharangi et al., 2024; Simelton, 2016).

Optimal growth occurs under warm and stable tropical conditions. While the plant tolerates a wide temperature range of 10–40 °C, the ideal range is 23–32 °C, with an average of around 28 °C, and minimal temperature variation over the day (Sharangi et al., 2024; International Pepper Community, 2007). The crop is adaptable to various soil types, from sandy loam to clay loam, but performs best in friable, humus-rich soils that combine good drainage with sufficient water-holding capacity and nutrient availability (Srinivasan et al., 2008). Soil pH is another critical factor, with an optimal range of 5.5–7.0 (Zu et al., 2014). Black pepper requires consistently high humidity, rainfall of around 2,000–3,000 mm annually, and stable climatic conditions, which makes it particularly vulnerable to climate variability (Ravindran et al., 2024, p. 766). While short dry spells followed by rainfall can stimulate flowering, the crop is highly sensitive to prolonged drought, excessive rainfall, or sudden shifts between different conditions that are happening increasingly because of climate change. Such extremes during berry development often trigger spike shedding and yield losses (Kandiannan et al., 2018; Sharangi et al., 2024).

The following chapter presents climate-resilient practices in black pepper production found globally. Although much of the scientific literature on black pepper cultivation comes from India, significant contributions also originate from Indonesia, Malaysia, and Vietnam, with additional studies available from Bangladesh, Brazil, Cambodia, China, Ethiopia, Laos, Sri Lanka, Thailand, and São Tomé e Príncipe.

3.2 Water and soil management

Water management strategies are essential for enhancing the climate resilience of black pepper cultivation, especially given the increasing frequency of erratic rainfall, drought, and extreme weather events. Basic infrastructure, such as **drainage channels**, can prevent waterlogging and diseases like foot rot (Thankamani et al., 2024, pp. 3968). Methods like **rainwater harvesting and water recycling** have been recommended to address irregular rainfall and water scarcity (Kandiannan et al., 2018, p. 267; Sharangi et al., 2024, pp. 794). Furthermore, **early morning irrigation** is used as a protective measure to reduce abiotic stress on black pepper plants (Mulia & Simelton, 2018, p. 138). Later, the section on climate-

smart tools also introduces how technologies like enhanced sprinkler systems can optimize water use.

In sloped or hilly terrain, **contour planting, bunding, and terracing** stabilize soil, reduce runoff, enhance water infiltration, and lower the risk of erosion and disease spread (International Pepper Community, 2007, p. 39). For young plants, **pit planting and basin irrigation** are common practices that retain moisture around the root zone. Basin irrigation can also enhance nutrient availability by concentrating water and organic matter near the base of the plant (Thankamani et al., 2024, pp. 3967; Sharangi et al., 2024, p. 767).

Advanced systems, such as **drip irrigation**, provide precise, water-efficient delivery, especially when paired with **organic mulching** (e.g., rice straw, palm leaves, or crop residues), which reduces evaporation losses and maintains soil moisture (Thankamani & Ashokan, 2011; Mulia & Simelton, 2018, p. 138; Sharangi et al., 2024, p. 795; Thankamani et al., 2024, pp. 3967). **Drip fertigation**, the delivery of fertilizers, preferably bio-fertilizers, inside of the drip irrigation, further enhances nutrient uptake efficiency and reduces leaching (Prasath et al., 2015, p. 71; Krishnamurthy et al., 2020, pp. 30).

In some parts of South and Southeast Asia, **bamboo pipe irrigation** offers an inexpensive, environmentally friendly solution for black pepper irrigation that is plastic-free and biodegradable. This system uses gravity to transport water through hollow bamboo poles, providing an energy-efficient, locally adapted method (Adhikari & Taylor, 2012, pp. 57; Meetei et al., 2023) that is suitable for slope farming black pepper.

3.3 Shade and heat stress management

During periods of intense sunlight, it is essential to protect pepper plants from heat stress with effective shade and cooling strategies. One option is to use **shade nets** and **overhead sprinklers** to create a cooling mist that lowers leaf temperatures (Kandiannan et al., 2018, p. 127). For more targeted protection, studies recommend coating the surface of the leaves with **mineral-based antitranspirants**, such as lime or kaolin. These antitranspirants create a thin, reflective coating that reduces transpiration and helps leaves retain moisture under heat stress (Krishnamurthy et al., 2021, p. 20; Kandiannan et al., 2018, p. 127). During particularly hot spells, it is also helpful to **cover the soil** around young plants with palm leaves to keep the root zone cool (Mulia & Simelton, 2018, p. 138).

Agroforestry approaches offer natural solutions. For example, pepper plants can be intercropped with taller trees that serve as living poles, as mentioned earlier. Alternatively, plantations can be surrounded by easy-to-manage **windbreak species.** These trees provide shade and reduce the impact of hot, dry winds (Mulia & Simelton, 2018, p. 143). Mulia and Simelton (2018, p. 143) recommend trees such as bamboo or jackfruit.

3.4 Integrated nutrient management

Climate change-enhanced stressors, such as heat stress, irregular rainfall, and soil degradation, can significantly reduce soil quality and nutrient availability. Enhancing soil health, fertility and improving nutrient uptake by black pepper plants are therefore important strategies for increasing climate resilience (Kandiannan et al., 2018, pp. 125).

Srinivasan and co-authors (2008, p. 6) explain how deficiencies in key soil nutrients, such as nitrogen, phosphorus, potassium, and calcium, can be identified by **observing specific symptom**s in black pepper plants. These visual indicators help diagnose soil nutrient imbalances and guide targeted soil improvement strategies. To enhance soil fertility and plant health, the authors recommend sustainable practices such as organic farming, intercropping, and green manuring. These practices are described in the intercropping section (3.5). The authors also recommend recycling farm waste, the use of vermicompost, biofertilizers, and plant growth–promoting microorganisms. These will be mapped out in the following section (Srinivasan et al., 2008).

3.4.1 Compost and vermicompost

In Malaysia and India, organic materials such as **farmyard manure, cow dung neem cake, vermicompost, prawn and fish meals, guano, organic leaves, coffee compost, and green biomass compost** are commonly used to improve soil fertility, decrease susceptibility to disease and increase black pepper yields (Thankamani et al., 2024, pp. 3965). These amendments improve soil pH, enhance nutrient availability and stimulate microbial activity. Leaf extracts generally promote biomass and plant growth; however, compost made from black pepper or coffee leaves should be avoided due to their allelopathic effects, which inhibit growth (Thankamani et al., 2024, p. 3965). Interestingly, a study by Fatiqin et al. (2025) found that **coffee skin waste** significantly improved shoot height and leaf development in pepper cuttings when used as a propagation medium.

Vermicompost plays a particularly important role in enhancing plant growth and suppressing disease (Thankamani et al., 2024; Mustakim et al., 2022; Srinivasan et al., 2007). It supports beneficial microbes, such as plant growth-promoting bacteria and fungi, which help to control pests and pathogens. Suseela Bhai et al. (2 019, 2021) demonstrated that combining vermicompost with microbes such as *Pseudomonas aeruginosa* and ***Trichoderma harzianum*** increased pepper growth and reduced the risk of Phytophthora foot rot disease. Further information on vermicompost and plant growth-promoting microbes can be found in the disease management section.

3.4.2 Enriched biochar

Biochar, which is produced by the pyrolysis of agricultural waste improves soil fertility and releases nutrients slowly due to its porous structure, making it highly effective (Dhanapala et al., 2025; Mendonça et al., 2024; Sulok et al., 2021a, 2021b; Mustakim et al., 2022). To

further enhance its benefits, it is often enriched with compost, mineral fertilizers or manure. **Phosphorus- or potassium-enriched biochar** has been shown to improve soil health, increase the availability of nitrogen and phosphorus, and stabilize heavy metals (Dhanapala et al., 2025). Although combining biochar with synthetic fertilizers can increase yields, using biofertilizers from on-farm organic byproducts instead is a more environmentally friendly and cost-saving option.

Sulok and co-authors (2020, 2021a, 2021b) thus recommend combining **biochar with compost and fermented plant or fruit juices** for improved soil health. They used materials like palm kernel shell biochar, compost made from tapioca leaves, banana plants, and vegetable waste, and juices from water spinach, mustard greens, banana stem, or overripe fruit. This mix boosted soil structure, nutrient content, and microbial activity, while being affordable and easy to apply for farmers.

In Bangladesh, Mustakim et al. (2022) found that biochar outperformed vermicompost and cow dung as a propagation medium for black pepper. Similarly, in Brazil, Mendonça et al. (2024) found that **biochar made from waste** of the açaí fruit enhanced pepper seedling growth.

3.4.3 Plant Growth-Promoting Microbes

Plant-growth-promoting microorganisms, such as beneficial bacteria and fungi, can improve the resilience of black pepper plants by enhancing their phytomicrobiome, or the microbial community around their roots. A healthy phytomicrobiome increases nutrient absorption and prevents disease. However, climate change disrupts these systems (Chen et al., 2013; Thomas & Krishnakumar et al., 2024, pp. 23). Microbial-based fertilizers help stabilize the phytomicrobiome, supporting both plant health and stress resistance.

One effective strategy is the **Integrated Plant Nutrition System**, which combines chemical fertilizers with organic materials such as compost, biofertilizers, and agroforestry residues to improve long-term soil fertility (Sangeeth & Bhai, 2015). Although synthetic fertilizers are still widely used, biofertilizers, such as *Azospirillum* for nitrogen and *Pseudomonas* for phosphorus, are promising alternatives as they are not harmful to human and environmental health.

These **microbes can be applied with compost or vermicompost** (Krishnamurthy et al., 2021, p. 41; Naik et al., 2013, p. 356). To improve their survival and effectiveness, researchers propose encapsulating the plant-growth-promoting microbes in alginate beads, a technique known as the **biocapsule method.** This method offers targeted delivery to plant roots and is easy to store and apply (Sangeeth & Bhai, 2015, pp. 448; Krishnamurthy et al., 2020, pp. 14). Another approach involves commercialized **effective microorganisms'** mixtures, which have their origin in Japan, but have been developed for different uses. For pepper, this liquid mixture contains yeast, lactic acid bacteria, actinomycetes,

photosynthetic bacteria, and fungi. When combined with compost or biochar, effective microorganisms can enrich the health of soil in natural farming systems (Sulok et al., 2018).

3.4.4 Other nutrient strategies

Following on from this, research from Vietnam has highlighted specific mineral nutrient management strategies that can be used to enhance soil fertility and pepper resilience. Tien et al. (2014) recommend applying **polyhalite**, a natural mineral containing potassium, magnesium, calcium and sulphur, together with **potassium chloride**, to improve nutrient availability, boost plant resistance and increase yield and profitability when producing black pepper on acidic soils. In cases of high soil acidity, Nguyen Van et al. (2025) recommend adding **lime to balance pH levels**. While liming alone may not directly suppress soil-borne pathogens or increase yields, it significantly improves soil chemical properties and encourages root colonization by beneficial fungi (Nguyen Van et al., 2025).

In Cambodia, Martini et al. (2025) demonstrate that **reforestation**, particularly through agroforestry, can improve soil health. Their study found that **termite activity** in these areas increases organic matter and electrical conductivity, creating localized hotspots of nutrients and biodiversity. This insight is particularly relevant in the Lower Mekong Basin, where termite mounds are common and could provide valuable ecological benefits for black pepper farming if utilized more effectively.

Additionally, **traditional knowledge systems** offer insightful contributions. For example, **Kunapajala**, a fermented liquid nutrient formulation derived from animal and plant materials with roots in the ancient Indian text Vrikshayurveda, has shown promising effects as a biofertilizer (Vaz et al., 2025). According to Vaz et al. (2025), Kunapajala promotes the natural selection of beneficial bacterial communities and enhances growth-promoting genes in plants.

3.5 Intercropping, agroforestry and mixed-crop systems

One of the most well-established and widely studied climate-resilient practices in black pepper cultivation is **intercropping**, the practice of growing black pepper alongside other crops or trees. This approach avoids vulnerable monocultures and provides multiple benefits: it promotes agro-biodiversity, supports integrated nutrient management for healthier soils, helps control pests and diseases, diversifies income sources and food supply for farmers, and offers protection against climate-related stresses by creating more stable microclimates (Rigal et al., 2023; Mulia and Simelton, 2018, pp. 133; Thankamani et al., 2024; International Pepper Community, 2007, p. 41). In Cambodia, Martini et al. (2025) demonstrate that **reforestation**, particularly through agroforestry for black pepper production, can improve soil health and boost biodiversity. Their study also found that **termite activity** in these areas increases organic matter and electrical conductivity, creating localized hotspots of nutrients and biodiversity and serving as natural soil amendments.

This insight is particularly relevant in the Lower Mekong Basin, where termite mounds are common and could provide valuable ecological benefits for black pepper farming if utilized more effectively.

3.5.1 Agroforestry

In black pepper cultivation, integrating trees, such as timber trees, fruit trees, shade trees, or other tropical species, ideally indigenous or native to the area, offers a climate-resilient practice by serving as **living support poles** for the pepper vines (Karmawati et al., 2022; De Costa, 2020, pp. 118, pp. 130; Evizal & Prasmatiwi, 2021, Changtom et al., 2017). This versatile agroforestry system has proven itself in different environments because it improves microclimate conditions, manages shade and wind, enhances soil health, and diversifies income. Furthermore, agroforestry practices and the use of living poles can mitigate pest and disease risks because increased biodiversity generally reduces crop vulnerability (Global Nature Fund, 2019). To ensure optimal growing conditions, these live support trees should be **pruned at least twice a year**, or as many times as necessary, to maintain a balanced level of shade and sunlight for the pepper plants (International Pepper Community, 2007, p. 42; Evizal & Prasmatiwi, 2021, p. 6). Additionally, it is recommended to plant **two to three black pepper cuttings per support tree** to maximize productivity (Evizal & Prasmatiwi, 2021, p. 6). The subsequent section outlines various agroforestry options for intercropping black pepper.

Intercropping black pepper with **coconut trees** is a popular and climate-resilient practice applied in India and other parts of South and Southeast Asia (Subramanian et al., 2012; Nath et al., 2021; Kandiannan et al., 2018, p. 128). Farmers often expand on **coconut-pepper-based systems by integrating other fruit crops**, such as pineapple, banana, lime, lemon and guava (Ghosh & Bandopadhyay, 2011; Soriaga et al., 2024, p. 4; Sharangi et al., 2024, p. 796). More complex, high-density **coconut-based multi-species systems** may also incorporate nutmeg, cinnamon, turmeric, ginger and elephant-foot yam (Subramanian et al., 2016; Thomas & Krishnakumar, 2024, pp. 14). These arrangements resemble **multi-tier or multi-storey cropping systems**, in which crops such as coconuts, bananas, black pepper and ginger grow together in layers (Dagar et al., 2020, pp. 172). Intercropping black pepper with **fruit trees only**, such as banana, jackfruit, mango, orange, pomelo, and lime is also recommended, based on research in Vietnamese home gardens by Mulia and Simelton (2018, pp. 133).

Intercropping black pepper with **areca nut tree** (betel nut tree), has been frequently cited (Li et al., 2025; Sujatha et al., 2016; Dagar et al., 2020, p. 372; Raj et al., 2019, p. 72; Kandiannan et al., 2018, p. 128). Some studies also highlight successful intercropping systems combining black pepper, areca nut, and vanilla (Thankamani et al., 2024, p. 3949, p. 3964; Chen et al., 2023, pp. 2736).

Leguminous trees such as Albizia, Gliricidia, Leucaena, Erythrina, Jengkol and Cassia siamea are ideal for intercropping with black pepper as they fix nitrogen in the soil (Karmawati et al., 2022, pp. 4; Dagar et al., 2020, pp. 381; Evizal & Prasmatiwi, 2021, pp. 5; Martini et al., 2020, p. 38; Changthom et al., 2017). Additionally, Evizal and Prasmatiwi (2021, p. 5) recommend intercropping the leguminous jengkol trees with coffee and black pepper.

In Brazil and India, black pepper is commonly intercropped with **rubber trees** (Oliosi et al., 2021; Oliveira et al., 2018; Thankamani et al., 2024, p. 3963). There is also a mention of intercropping black pepper with cashew (Thankamani et al., 2024, p. 3963). In Malaysia, black pepper is alley cropped alongside **oil palms** and ginger (Ashraf et al., 2021).

In Vietnamese home gardens, **macadamia trees** are used for intercropping, often combined with the leguminous cover crop Arachis pintoi (Simelton, 2016; Mulia & Simelton, 2018, pp. 136; Simelton & Tam, 2018, p. 4). Additionally, fruit trees such as avocado, durian, macadamia, banana, papaya, and mango are intercropped with black pepper and **coffee** or **cocoa** in Vietnam and São Tomé e Príncipe (Rigal et al., 2023; Fonseca et al., 2021, pp. 39). There are also reports of intercropping **silver oak trees with coffee** and black pepper (Mohan Kumar et al., 2021, p. 653).

When intercropping with live trees is not possible and wooden poles are to be avoided, a promising alternative is a **vertical column support with integrated rooting media** (Prasath et al., 2015, pp. 103). This structure is a 3 m-high plastic-coated wire mesh filled with a mix of composted cocopeat and cow dung, irrigated via drip and supplemented with foliar feeding. As pepper vines climb the column, their clinging roots develop into absorbing roots along the media, promoting faster growth, earlier flowering, and higher yields than conventional supports. Moreover, the W-configuration planting method is considered innovative because it allows black pepper to grow in a W-shape instead of a single vertical line (Ee & Shang, 2017). It can be integrated into tree-free intercropping systems and has been shown to increase yield per plant as it can develop in more directions and receives more sunlight. However, this method is not compatible with the living pole support system.

3.5.2 Non-arboreal intercropping

Cover crops are commonly used in black pepper intercropping systems to increase resilience to climate-change-induced stresses, such as intense heat, and to reduce the risk of pests and diseases. Studies in Indonesia have shown that intercropping with cover crops maintains soil temperature and moisture levels, increases organic carbon content, improves soil porosity, and enhances fertility (Kurniawati et al., 2024, p. 451). These benefits lead to higher land productivity and better drought resistance. Additionally, **leguminous cover crops** contribute to nitrogen fixation, improving overall soil health and nutrient enrichment (Kurniawati et al., 2024, pp. 458).

Arachis pintoi is commonly used as a **leguminous cover crop** to enhance the soil of black pepper systems (Nguyen Van et al., 2024). Other recommended leguminous cover crops include **groundnut** and **citronella** (Sulok et al., 2024; Karmawati et al., 2024, p. 5). ***Centrosema pubescens*** was particularly effective at reducing weeds, stabilizing soil conditions, and enriching nutrient content. It improved the levels of chlorophyll and carotenoids in pepper plants, thereby supporting plant health (Kurniawati et al., 2024). Thankamani et al. (2014) reviewed leguminous **pulses**, such as cowpea, green gram, black gram, and horse gram, as effective intercrops. Additionally, napier grass, guinea grass, and Congo signal grass, which are fodder crops, have been tested and recommended for black pepper intercropping (Thankamani et al., 2011; Kandiannan et al., 2018, p. 126).

These cover crops can also be used as **green manure**, releasing nutrients when incorporated and decomposed into the soil and reducing reliance on chemical fertilizers. For instance, a Brazilian study by Trevisan et al. (2016) revealed that intercropping black pepper with leguminous species as green manure such as *Mucuna pruriens, Canavalia ensiformis, Cajanus cajan and Crotalaria juncea* elevated micro- and macronutrient levels, as well as improving soil dry matter content. However, careful management of cover crops is essential, as excessive growth of the cover crop near the base of the pepper plants should be avoided to prevent competition for nutrients at root level (International Pepper Community, 2007, p. 45).

Next to soil enhancing leguminous intercrops, **commercially viable intercrops** can be of interest. Thankamani et al. (2012a, 2012b) identified several **medicinal plants**, namely vetiver, snap ginger, shatavari, malabar nut, Indian leadwort, patchouli, salparni and water hemp, as promising intercrops for black pepper with commercial potential. Various **vegetables**, such as okra, tomatoes, aubergines, amaranth and capsicum, are also suitable intercrops (Thankamani et al., 2014). **Tuber crops**, including cassava, elephant foot yam, coleus, ginger and turmeric, can also help to improve soil health (Thankamani et al., 2011). In Sri Lanka and India, black pepper is often intercropped with **tea** (Sewwandi et al., 2019; Kandiannan et al., 2018, p. 126), though it is more commonly intercropped with coffee. **Coffee-based systems** often include multiple species, such as spices (e.g. cardamom, ginger, cinnamon and cloves), trees or areca nuts, and have been reported in India, Vietnam, Laos, Indonesia and São Tomé and Príncipe (ICEM, 2013, p. 16; Vernooy, 2015, pp. 73; Prasath et al., 2015, pp. 7; Anil Kumar et al., 2018; Evizal & Prasmatiwi, 2021; Anjitha et al., 2024; Rigal et al., 2023; Fonseca et al., 2021).

3.6 Disease and pest management

Climate change can increase the frequency of pest and disease outbreaks or lead to the emergence of new forms. Several **comprehensive resources** are available for detailed guidance on pest and disease management in black pepper cultivation. Nair (2020) and Rai and Upadhyay's (2023) offer in-depth descriptions of biotic stresses, symptoms, spread, and

control strategies. Additional valuable insights can be found in the annual reports of ICAR-IISR (*inter alia* Krishnamurthy et al., 2021).

For **organic practices**, Thankamani and co-authors, offers practical methods for managing pests and diseases organically. Similarly, M.K. and co-authors (2019) present detailed integrated strategies. Another recommended read is by Karmawati et al. (2025), who provide a critical review of the challenges of implementing integrated pest management for the pepper stem borer among Indonesian smallholder farmers, addressing technical and non-technical factors. Due to limited space, readers are encouraged to consult these sources directly for specific, step-by-step treatment protocols. These sources are also recommended for further information on less common diseases and pests not covered in this review.

In general, effective pest and disease management begins with **regular surveillance, accurate identification, and prompt action** to prevent their spread (International Pepper Community, 2007, p. 47).

Traditional **hygienic, phytosanitary, and cultural practices**, for example, removing affected plants and destroying pathogens by burning or using minimum tillage to not disrupt root systems, lay a basis for advanced pest and disease management. The International Pepper Community (2007, pp. 48) promotes an **integrated pest management approach** which increases pepper plants' resilience pests and diseases by combining different control methods and enhancing natural pest control mechnisms. These include using biofertilizers, mulching, planting resistant varieties, and using cover crops to reduce water splash disease spreading (Thankamani et al., 2024; Kandiannan et al., 2018; Karmawati et al., 2025; Nair, 2020, p. 54).

A **healthy soil microbiome** is essential for robust pepper plants and closely links pest and disease management with soil and water management practices (Nguyen et al., 2020; Varghese et al., 2022; Chen et al., 2023). Applying **sustainable soil amendments,** such as farmyard manure, vermicompost, biopesticides, biofertilizers, and neem cake, can reduce pathogen buildup while promoting beneficial, antagonistic microorganisms (Rai & Upadhyay, 2023, pp. 38). More information on how to create a healthy soil can be found in the integrated nutrient management section. It is also important to note that most infestations already start at the nursery stage. Therefore, using **disease-free planting material** is critical to preventing field-level infections later on (Rai & Upadhyay, 2023, p. 86; Krishnamurthy et al., 2021; pp. 20).

3.6.1 Disease management

Foot rot or wilt, a common disease affecting black pepper, is caused by the soil-borne fungus *Phytophthora capsici*. This disease typically occurs during the monsoon season or when soil humidity is excessively high (Nair, 2020, p. 55; Rai & Upadhyay, 2023, pp. 81; Thankamani et al., 2024, pp. 3968).

To prevent stagnant water and reduce the risk of disease, it is strongly recommended that effective **drainage systems** be installed and that smart water management, see the water section above, be applied (Thankamani et al., 2024, p. 3968). In addition, during floods, **pruning branches, runner shoots, and leaves** at least 10–15 cm above the soil surface helps prevent rotting (Mulia & Simelton, 2018, p. 138). Some black pepper varieties that are more resistant to foot rot disease, like IISR Shakti and IISR Thevam, are introduced under the climate-smart varieties section (Sharangi et al., 2024, p. 794).

When the pathogenic fungus is present, it is essential to take **phytosanitary and hygienic measures**. These measures include removing affected plant parts and applying fungicides, such as the **Bordeaux mixture**, which is a copper and lime compound (Nair, 2020, p. 56; Rai & Upadhyay, 2023, pp. 82). Information on different mixture ratios is easily accessible. Additionally, **organic amendments**, such as oil cakes derived from neem seeds, groundnuts, coconuts, and chicken manure, have antifungal properties and can promote plant growth (Nair, 2020, pp. 56). **Copper-based fungicides**, including Bordeaux mixture, copper hydroxide, and copper oxychloride, are also effective, but they should be applied carefully under supervision (Thankamani et al., 2024., p. 3969). **Talc-based formulations** combined with farmyard manure can be applied twice yearly to control diseases and encourage healthy plant development (Thankamani et al., 2024, p. 3969).

Another common disease is slow decline, also known as **slow wilt**. This disease is often caused by **parasitic nematodes**, particularly during humid seasons (Nair, 2020, pp. 57; Rai & Upadhyay, 2023, pp. 82). These microscopic roundworms infect the root system and lay eggs there. Nematode infections are often accompanied by fungal pathogens, so both can frequently be managed simultaneously. Certain pepper varieties, such as the *Pournami* variant discussed in the climate-smart varieties section, show greater resistance to nematodes and are preferable for planting (Rai & Upadhyay, 2023, p. 82).

If an infestation occurs, it is advisable to implement phytosanitary measures alongside **preventative treatments**, such as **neem cake and biocontrol agents** (Nair, 2020, pp. 59; Rai & Upadhyay, 2023, pp. 82). Prevention is key, therefore Mulia and Simelton (2018, p. 138) recommend **applying lime** to control nematodes and fungal infections. There are also **specific nematicides**, such as fluopyram (Krishnamurthy et al., 2021, p. 56), that can effectively control nematodes. However, improper or excessive use may harm the environment and human health. Therefore, nematicide application is best limited to the nursery stage. Harni et al. (2024) further suggest **combining organic biocontrol agents with biofertilizers** to enhance black pepper's stress tolerance and yield.

Trichoderma harzianum is a beneficial, mycoparasitic fungus that combats fungal diseases and nematodes. Research from various sources supports this practice (Thankamani et al., 2024; Fauziyah et al., 2017; Krishnamurthy et al., 2021; Iswoyo et al., 2021). It can be effectively incorporated into cow dung–neem cake mixtures for use in potting media, nursery beds, and fields (Thankamani et al., 2024). *Trichoderma's* use as a disease

management tool and biofertilizer is widely recommended in literature as part of plant-growth-promoting microbes (Anith et al., 2011; Bhai et al., 2016; Syam et al., 2021; Kodithuwakku et al., 2016; Thankamani et al., 2024).

Combining *Trichoderma* with vermicompost creates an ideal potting medium for black **pepper nurseries**, resulting in disease-free cuttings and enhanced growth (Prasath et al., 2014; Pandey et al., 2017). Another beneficial fungus, ***Piriformospora indica***, has been shown to improve plant health and pepper quality (Anith et al., 2018). At the nursery stage, inoculation with ***vesicular arbuscular mycorrhizae*** **(VAM)** enhances root development and suppresses root diseases.

Some studies highlight the benefits of **combining various plant-growth-promoting microorganisms**, including fungi like *Trichoderma* and beneficial bacteria such as *Pseudomonas fluorescens*, with biofertilizers like VAM (Kodithuwakku et al., 2016; Lau et al., 2020). This integrated approach suppresses diseases and promotes overall plant health, resulting in higher yields and better-quality produce (Varghese et al., 2022; Kodithuwakku et al., 2016; Lau et al., 2020).

3.6.2 Pest management

Ecosystem-based pest control, for example through agroforestry or the use of cover crops, are a preventative measure against harmful pests and favour farmer-friendly insects. For example, intercropping black pepper with citronella grass or Arachis pintoi are recommended because they promote biodiversity, which encourages populations of beneficial arthropods and wasps that prey on pest larvae (Karmawati et al., 2025; Global Nature Fund, 2019). The GIZ India manual titled "Biodiversity Action Plan for Pepper, Cinnamon, Cardamom, and Nutmeg" (Global Nature Fund, 2019) is a valuable resource for **ecosystem-based climate adaptation strategies**.

Mechanical pest control is a simple, cost-effective, and eco-friendly approach. For instance, **plant shaking**, which is used in Vietnam, India, and Malaysia, can effectively control borers by knocking them off the plants (Karmawati et al., 2025). The fallen insects can be collected in soapy water or trapped with **nets and adhesive traps** placed beneath the plants.

Pepper fields infested with pests such as the pollu beetle, borers, leaf gall thrips and scale insects can be treated with innovative **low-risk insecticides** if mechanical pest control is not sufficient (Krishnamurthy et al., 2021). These insecticides are environmentally friendly alternatives to traditional chemical insecticides (Rai & Upadhyay, 2023; Krishnamurthy et al., 2021). Tests by ICAR-IISR found several low-risk insecticides, such as flonicamid, chlorpyriphos, buprofezin, and diafenthiuron, to be highly effective for root mealybug control (Krishnamurthy et al., 2021). Additionally, **natural plant extracts from tobacco, custard apple seed, neem, and Chinese chastetree** are recommended as insecticidal treatments against root mealybugs. Experiments showed that chlorantraniliprole is an

effective, low-risk insecticide against the pollu beetle (Krishnamurthy et al., 2021). Low-risk insecticides such as chlorantraniliprole, flubendiamide, and spinosad, when applied on an optimized spray schedule, proved effective against shoot borers.

To reduce the risk of pests, it makes sense to choose pest-resistant varieties, although limited research exists. Still, the Malay pepper varieties, such as *Natar 1* and *Natar 2*, offer protection against pepper stem borers (Karmawati et al., 2025).

3.7 Climate-smart varieties

Research on improving black pepper varieties has been ongoing for many years, with numerous countries developing **cultivars** suited to their **specific conditions**. For example, Vietnam has developed several high-yielding, high-quality varieties, including *Vinh Linh, Lada,* and *Loc Ninh* (Oanh et al., 2021). Similarly, Ethiopia has introduced improved varieties such as *Gacheb* and *Tato* (Bekele et al., 2025).

However, promoting varieties that are not only improved for taste and yield, but also exhibit tolerance or resistance to biotic and abiotic stresses is important to enhance climate resilience. It is important to mention that different **varieties** are groomed to become **resistant to specific stresses** and there is no "poly-resistant" variety developed yet. Examples of "more resistant" pepper varieties include *IISR Thevam* and *IISR Shakti*, which are resistant to foot rot disease, and *Pournami*, which is resistant to root-knot nematodes (Krishnamurthy et al., 2021). Drought-tolerant varieties include *Panniyur-5, Panniyur-8, ACCS 1380 (IC 316801), ACCS 1387 (IC 316803), ACCS 1410 (IC 316817), ACCS 1423 (IC 316825),* and *ACCS 1430 (IC 316832)*. These varieties are also deemed very suitable for organic cultivation (Thankamani et al., 2024; Sharangi et al., 2024; I P et al., 2024).

Finally, Varghese and Ray (2024) analyzed 24 black pepper varieties in India and found that *Panniyur*-1, the most cultivated, high-yielding improved variety, performed well across diverse soil conditions, demonstrating its adaptability. Additionally, Krishnamoorthy and Parthasarathy (2010) reviewed 45 black pepper varieties and found that the *Kalluvally* and *Kottanadan* varieties are drought tolerant. They also noted that the *Narayakodil*, *Neelamundi*, and *Thevanmundi* varieties are less susceptible to foot rot disease. Also, as previously mentioned, the varieties *Natar 1* and *Natar 2* are resistant against pepper stem borers (Karmawati et al., 2025).

3.8 Climate-smart tools and technologies

Various climate-smart diagnostic and decision support tools have been developed to improve black pepper production, particularly regarding nutrient management and pest and disease control. **Soil characterization using chemometric tools** provides a better understanding of soil needs, enabling more precise fertilization and irrigation practices (Ferde et al., 2021). Krishnamurthy et al. (2021) also emphasize the importance of analysing

physicochemical soil properties and providing farmers with **personalized nutrient advisory cards** tailored to their fields.

Other innovative technologies include **pH monitoring using sensors and mobile apps** to guide fertilizer use and help farmers optimize their inputs (Fletcher et al., 2020). Around 100,000 pepper farmers in Indonesia use digital services such as the **"Spice Up" app** to boost production, income, and food security while reducing water, fertilizer, and pesticide use. This financially sustainable service integrates geospatial data and precision agriculture techniques, enhancing farmers' knowledge of good agricultural practices (Nanda et al., 2020; Simelton & McCampbell, 2021).

New **combined sensor and detection models** measure various parameters, such as temperature, humidity, soil nutrients, moisture, and the presence of diseases. These data are fed into **deep learning models** that predict plant health and optimal growth conditions. The models inform farmers of the best times to irrigate, fertilize, or apply biocontrol agents for pest and disease management (Ranjan & Sathiya, 2025; Kini et al., 2024; Subasinghe & Kulathilake, 2025). Additionally, **automated sprayer and sprinkler irrigation systems** that respond to temperature and humidity have been tested and have resulted in significantly higher yields compared to conventional watering methods (Madato et al., 2022).

Lastly, **unmanned aerial vehicles** (UAVs or **drones**) are emerging as high-tech tools in pepper production research, used in Brazil for fungal disease detection (Lacastagneratte et al., 2021) and in Malaysia for environmental monitoring and fertilizer prediction (Nuyak et al., 2023). Malaysian studies also explore geospatial technologies, including remote sensing, geographic information systems (GIS), and global navigation satellite systems (GNSS), for comprehensive crop monitoring (Kamsan et al., 2021). While these technologies show promise, their practical use for smallholder farmers will depend on partnerships with technical experts.

4 CRP Adoption in Pepper and Cashew Production

4.1 Benefits of CRP Adoption

Adoption of CRPs among smallholder farmers has demonstrated substantial benefits, particularly in enhancing **food security**, protecting household **incomes**, and building long-term **resilience** to climate variability. CRPs can help to significantly increase crop yields and input-use efficiency while reducing greenhouse gas emissions (Khatri-Chhetri & Aggarwal, 2017, pp. 2–5)(Khatri-Chhetri & Aggarwal, 2017, pp. 2–5), improving soil health Erick (2025, pp. 9–10) and reducing input dependency (Korn, 2021, pp. 152–158). Evidence from Cambodia (Dorkenoo et al., 2024, p. 13) and Indonesia (Irawan, 2021, pp. 6–9) show that CRPs can also lower the dependence on reactive coping mechanisms like migration or high-interest loans, allowing households to stabilize incomes and avoid food insecurity during adverse seasons.

Research also highlights that CRPs are **most effective when combined**. Essentially, evidence across different contexts demonstrates that the benefits of CRP adoption extend beyond immediate yield gains, and points to a move toward more resilient, self-sustaining rural livelihoods in the face of deepening climate challenges.

4.2 Factors Influencing the Adoption of Climate Resilient Practices

Adoption (or non-adoption) of climate-resilient practices depends on diverse factors, ranging from institutional and environmental to socio-economic, knowledge related and behavioural factors. Myeni & Moeletsi (2020) illustrate how adoption decisions are embedded in a complex matrix of assets, awareness, and perceived practicality, thus validating the multi-dimensional nature of adoption explored throughout this review. The following section provides an overview of these factors as described in literature from around the globe:

4.2.1 Socioeconomic and demographic factors

Socioeconomic status and demographic profiles significantly shaped the likelihood of CRP adoption. Erick (2025, p. 9) emphasized that factors such as **education**, **household size**, **income**, and **gender** were central to shaping adoption behaviours.

Farmers with **secure land tenure** and **stable income** streams were more likely to invest in long-term climate-resilient practices, whereas those with limited resources often prioritized short-term gains. Erick (2025, p. 9) also noted that land and financial security significantly increased the likelihood of CRP adoption by lowering perceived investment risks. Similarly, Obe et al. (2025, p. 15) identified **limited access to credit, high initial costs, and low**

household income as major barriers to uptake. These insights aligned with findings from Wakweya (2023), Khatri-Chhetri and Aggarwal (2017, pp. 5–6), and Myeni and Moeletsi (2020). In South Africa, Myeni and Moeletsi (2020, pp. 10–12) reported that income from livestock increased the likelihood of adopting scientific practices, while larger land sizes sometimes discouraged adoption due to labour requirements.

While some studies saw **education** as a key enabler, others challenged this assumption. Erick (2025, p. 9) linked higher education with better understanding and uptake of CRPs. However, Irawan (2021, p. 8) found no significant correlation between formal education and adoption in Indonesia, suggesting that peer learning and observation often played a stronger role. Touch et al. (2024, p. 1640) similarly highlighted the influence of local knowledge systems and neighbour behaviour in shaping decisions around CRP use.

Household characteristics such as age, farming experience, and family size also influenced adoption. In Kenya, Asule et al. (2024) showed that older, **experienced farmers** in larger households were **more likely to adopt** crop rotation, soil fertility management, and organic inputs.

Gender dynamics further played a critical role. They are discussed in 4.3.

4.2.2 Institutional and policy factors

A recurring theme across the literature is the vital role of **institutional support** in enabling climate-resilient practice adoption. Multiple studies emphasize that access to **extension services**, participation in farmer groups or cooperatives, and access to financial services are among the most consistently cited enablers (Asule et al., 2024a; Erick et al., 2025; Irawan, 2021; Ishtiaque et al., 2024; Myeni & Moeletsi, 2020; Obe et al., 2025; Wakweya, 2023). Institutional support in the form of extension services, **cooperative membership**, and training programs was reported as a key driver, enhancing farmers' knowledge, confidence, and access to resources (Erick et al., 2025, p. 9). These dynamics aligned with the findings of Irawan (2021) and Ishtiaque et al. (2024), who noted that farmer networks and information dissemination played an enabling role.

However, several studies point to the consequences of weak institutional structures. Esan et al. (2018, p. 6) argued that limited institutional engagement hindered not only the diffusion of CRPs but also restricted smallholders' decision-making space. In the absence of effective formal services, farmers often relied on informal channels such as family, peers, or radio broadcasts for climate related information. Touch et al. (2024, p. 1640) similarly found that despite awareness of climate risks, many Cambodian farmers remained **inactive due to** lack of information on viable adaptation options, limited financial means, and the **absence of tailored institutional support**.

Ishtiaque et al. (2024, p. 111) highlighted the chronic **underperformance of government extension systems** in South Asia, often underfunded, understaffed, and ill equipped to provide localized, context specific training. Wakweya (2023) also reported that across Sub

Saharan Africa, CRP adoption remained low due to insufficient access to credit, advisory services, and technical resources. Smallholder and marginalized farmers in particular faced heightened risks due to these systemic deficiencies. Echoing Esan et al. and Irawan, Wakweya (2023) emphasized that even well-designed technologies may fail to take hold without consistent institutional support.

Beyond service delivery, **poor policy implementation** and **institutional fragmentation** also emerged as significant barriers. Obe et al. (2025, pp. 15–16) and Dorkenoo et al. (2024) pointed to weak coordination and lack of coherent implementation strategies as persistent challenges. Ishtiaque et al. (2024, p. 112) criticized conflicting policy incentives, noting that while governments often subsidize CSA technologies on paper, they simultaneously promote conventional alternatives, undermining the market for sustainable options.

Concerns about equity and **elite capture** were also raised. Ishtiaque et al. (2024, pp. 111–113) observed that wealthier and well-connected farmers were often the first to access CRP demonstrations and resources, marginalizing poorer or socially excluded groups. These findings were echoed by Irawan (2021, p. 9) and Wakweya (2023, p. 5), who reported that without equitable and coherent institutional arrangements, adoption remained uneven and limited in scale. Insecure land tenure and poorly enforced conservation policies added further layers of constraint, as noted by Wakweya (2023) and Khatri Chhetri and Aggarwal (2017).

4.2.3 Environmental and contextual factors

Climate context and environmental conditions significantly shape how and whether climate-resilient practices are adopted. Farmers are often aware of increasing climate variability and the severity of its impacts, yet their **responses remain constrained by broader contextual challenges**. In upland Cambodia, for example, Touch et al. (2024, p. 1644) found that despite widespread awareness of changing weather patterns, many farmers did not implement adaptation strategies. Financial limitations, lack of irrigation, and poor infrastructure were cited as key barriers, while decisions were more often driven by market expectations, ease of crop management, and neighbour behaviour (Touch et al., 2024, p. 1640).

Similar findings were reported in South Africa by Myeni and Moeletsi (2020, pp. 10–12), where the degradation of land and poor water access limited the uptake of soil and water conservation techniques. Region specific climate stressors further influenced CRP relevance. In Benin, for example, cashew farmers turned to mulching and organic amendments to address declining soil quality and moisture loss (Bello et al., 2017, p. 941). In coastal regions of Bangladesh and Vietnam, farmers adapted their strategies to cope with salinization and increased flood risk, highlighting the importance of tailoring CRPs to specific environmental conditions.

Agroecological suitability also determines the success or failure of adoption. As noted by Asule et al. (2024), some farmers perceived no immediate need for CRPs when they believed their soil fertility remained adequate. Erick et al. (2025) similarly emphasized that the relevance and uptake of CRPs often depend on whether they align with local conditions. Practices rooted in locally available technology and compatible with existing farming knowledge were more likely to be adopted (Ishtiaque et al., 2024; Obe et al., 2025). These studies illustrate that environmental realities, such as rainfall variability, land degradation, and ecological fit, are as critical to adoption as economic and institutional factors.

4.2.4 Information and knowledge related factors

Access to timely and relevant information, both formal and informal, consistently emerged across the reviewed studies as a critical enabler or barrier to the adoption of climate-resilient practices. Farmers frequently relied on **peer learning**, local observation, and farmer to farmer exchange where formal advisory services were weak, underfunded, or inaccessible (Touch et al., 2024, p. 1640; Esan et al., 2018, p. 6; Ishtiaque et al., 2024, p. 111). These informal sources of knowledge often substituted for professional guidance, especially in rural communities. However, as noted by Ishtiaque et al. (2024, p. 113), such peer led systems could lead to inequitable access, with wealthier or more socially connected farmers often benefiting more from demonstrations and support.

Formal structures such as **farmer groups, cooperatives, and extension programs** played an important though mixed role. Irawan (2021, p. 3) and Erick (2025, p. 9) reported that institutional membership increased the likelihood of CRP adoption by expanding access to training, demonstrations, and technical knowledge. Yet, Irawan (2021, p. 9) also found that not all institutional affiliations were beneficial. While participation in extension groups promoted the use of organic fertilizers, cooperative membership was sometimes associated with lower uptake (Irawan, 2021, p. 9).

Media access was also highlighted as enablers. Obe et al. (2025, p. 14) observed that farmers with greater exposure to media were more likely to adopt innovations. Myeni and Moeletsi (2020, p. 11) found that access to weather forecasts and early warning systems significantly influenced farmers' ability to shift from traditional to scientific adaptation strategies. Literature also highlighted how **access to accurate climate information**, such as rainfall forecasts and risk projections, reduced dependence on traditional practices and encouraged evidence based adaptation (Erick et al., 2025; Esan et al., 2018; Myeni & Moeletsi, 2020). Conversely, where this information was lacking, adoption was often delayed or avoided altogether, reinforcing the role of trust, clarity, and access in shaping farmer behaviour(Touch et al., 2024, p. 1640).

4.2.5 Psychosocial and normative drivers

The adoption of climate resilient practices is influenced not only by external incentives and institutional capacity but also by **internal motivations**, perceived practicality, and

prevailing social norms. Farmers often weigh the expected outcomes and personal relevance of practices before deciding to adopt them. Wang et al. (2025, pp. 6–7) reported that perceived value, such as higher yields, reduced losses, and improved market competitiveness, was a dominant driver of acceptance. Similarly, Wakweya (2023, pp. 3-5) and Khatri Chhetri and Aggarwal (2017, pp. 5–6) noted that farmers often prioritized practices that promised **short term gains**, especially when livelihood pressures limited their ability to invest in long term strategies. Ishtiaque et al. (2024, p. 112) found that practices like mulching or zero tillage were often perceived as unattractive because their returns were delayed.

Perceived compatibility and effort also shaped adoption behaviour. Wang et al. (2025, pp. 6–8) explained that farmers preferred practices that aligned with their routines, existing knowledge, and time constraints. Practices that appeared too complex or labour intensive were less likely to be taken up. This was echoed by Erick (2025, p. 10), who found that unfamiliar or culturally incompatible technologies were frequently rejected.

Moral and social considerations also played a role. Wang et al. (2025, p. 8) observed that some farmers were driven by a sense of environmental responsibility, adopting CRPs out of concern for sustainability and future generations. In Indonesia, Irawan (2021, p. 9) found that farming decisions were often made collectively within households, reflecting shared values and practical needs. Peer influence was also significant: in Cambodia and Nigeria, farmers commonly looked to their neighbours' actions as cues for their own decisions (Touch et al., 2024, p. 1640; Esan et al., p. 6). All these findings show that psychosocial and normative drivers, such as perceived benefit, compatibility, social learning, and moral values, are central to understanding why farmers adopt or reject climate resilient practices.

4.3 Gender roles in CRP adoption

Gender plays a significant role in shaping the awareness, access, and adoption of climate-resilient practices. Globally, women represent about 43% of the agricultural labour force (FAO, 2021b). In Cambodia, agriculture serves as both a vital source of rural livelihoods and the primary employer of women compared to the service and industrial sectors. As of 2016, 39.3% of women and 33.7% of men were engaged in agricultural employment (Procházková & Chaloupková, 2025, p. 3).

Despite the significance of women in the agricultural sector across the world, men and women engage with agricultural innovations differently due to inequalities in resource ownership, labour distribution, and decision-making power. Studies such as Asule et al. (2024) and Irawan (2021) showed that female-headed households were more likely to adopt less labour- or resource-intensive practices like mulching and intercropping, while male-headed households engaged in more input-heavy practices.

This differentiation often stems from **systemic disparities** in access to land, credit, extension services, and agricultural technologies. As noted by Hailemariam et al. (2024, p.

780), women are more likely to adopt low-risk, low-return strategies such as water harvesting and pest management, whereas men tend to adopt high-yielding or chemically intensive practices, reflecting broader gendered differences in risk exposure and access to capital. Irawan (2021, pp. 8–9) found that female farmers were more likely to adopt organic fertilization and crop diversification, often in consultation with family members. Wakweya (2023, p. 6) supported this. These findings illustrated that CRP adoption was influenced by a combination of material assets, financial capacity, and social identities, thus affecting farmers' adaptation to climate risks. Beyond access to resources, gendered **expectations around household** and community **roles** further constrain women's participation in CRP adoption. For instance, women often bear disproportionate responsibility for unpaid domestic labour, reducing their time and mobility for on-farm activities and training (Procházková & Chaloupková, 2025, pp. 6, 48). Cultural norms also limit women's autonomy in financial and agricultural decisions, even when they actively contribute to farming. However, evidence also highlighted women's resilience and innovation in adopting local, affordable CRPs like organic pest control, especially when given tailored support (Dasgupta et al., 2025, pp. 2–4). **Promoting gender-responsive strategies**, including equitable extension services, group-based learning models, and better recognition of women's informal contributions, is essential for improving CRP adoption rates and ensuring sustainable agricultural development across diverse farming systems.

In Cambodia, gender disparities in agricultural adaptation are similarly pronounced, particularly among ethnic minority groups and subsistence farmers. Women in rural communities often contribute substantially to farming yet their roles remain undervalued and underrepresented in extension and training programs (FAO, 2021; Dorkenoo et al., 2024; Procházková et al., 2025). Limited access to land titles, productive assets, and financial credit further restricts their ability to invest in long-term resilience strategies (CIFOR, 2022; Chan et al., 2020). While women's agricultural knowledge is rich and context-specific, decision-making remains male-dominated in many farming households, especially when it comes to adopting new technologies or participating in cooperatives (Procházková & Chaloupková, 2025, pp. 48–49). Procházková et al. (2025) further highlighted how intersecting factors such as ethnicity, language barriers, and intra-household dynamics compound these challenges for women, particularly in indigenous and upland communities. All the evidence from literature compounds our focus on gender roles especially in CRP adoption in Cambodia.

5 Way forward

Cambodia stands at a critical juncture where climate risks increasingly threaten pepper and cashew smallholders, while opportunities for adaptation remain underexplored. This review highlights that although a broad range of climate-resilient practices have been studied globally, there is little evidence in academia of their effectiveness or adoption in Cambodia. Many of the CRPs identified are costly, labor- or input-intensive, and require technical or expert support in implementation. These factors limit their suitability for smallholder farmers without further adaptation, as adoption is further shaped by a mix of socioeconomic and institutional barriers, including limited access to training, credit, and irrigation, as well as land tenure insecurity and gendered inequalities in participation. These findings underscore the need for context-specific, low-cost, and farmer-centered CRPs that are co-developed with Cambodian farmers, building on local knowledge and tailored to their constraints and preferences.

Findings from a baseline study by Angkor Research & Consulting Ltd. (2025) for the GIZ/EU CAPSAFE project echo these challenges. The study found that more than 65% of cashew and pepper farmers had never received training on sustainable practices, and only 38% had access to irrigation infrastructure. Most farmers continue to rely on monocropping with minimal soil fertility management, particularly in pepper cultivation. At the same time, some farmers are already practicing sustainable management techniques such as applying organic pesticides and fungicides, rotating crops, maintaining soil nutrition through liming, improving irrigation and drainage, and regularly cleaning machinery and equipment (Angkor Research & Consulting Ltd., 2025), several of which overlap with CRPs identified in this review. In addition, around one in three farmers reported using one or more soil protection strategies, including crop covers, organic seeds, reduced tillage, crop diversification, and soil pH monitoring (ibid.).

This literature review provides the foundation for a technical workshop hosted by GIZ CAPSAFE and SLE on the 26th of August 2025 in Phnom Penh. The workshop will bring together experts and organizations working with pepper and cashew farmers to assess which CRPs are already in use or being trained in Cambodia, identify overlooked local knowledge, and prioritize promising practices for further research. To evaluate whether CRPs genuinely strengthen climate resilience, additional in-depth analysis is required. One possible approach is Stöber et al.'s (2025, p. 96) "Checklist to assess farming practices for climate resilience," which examines criteria such as water-saving potential, carbon capture, energy efficiency, nitrogen use, resilience to weather extremes, cultural and knowledge aspects, and economic viability. Promising CRPs identified through this process will then be tested in field trials.

6 Annexes

Table 3: Typologies of CRPs

CRP Cluster	Description
Crop diversification, intercropping and agroforestry	Practice of cultivating a variety of crops within a farming system rather than relying on a single crop. This strategy helps smallholder farmers manage climate risks by spreading vulnerability across different crops, reducing dependence on any one harvest (Irawan, 2021, p. 7). It involves integrating multiple crop types or agricultural activities to spread climate-related risks.
Soil and Water Conservation	Techniques that simultaneously protect soil health and improve water retention. Common practices include mulching, conservation tillage, and tie-ridging, which help smallholder farmers maintain soil structure, reduce erosion, and increase moisture infiltration, especially under conditions of irregular rainfall. These approaches build resilience in climate-stressed environments where soil degradation and water scarcity threaten yields (Erick et al., 2025).
Soil Conservation	Soil-focused practices aimed at enhancing and sustaining soil fertility, such as the application of organic and inorganic fertilizers, composting, and soil amendment techniques. These strategies counteract soil degradation. Studies highlight that maintaining soil health ensure long-term productivity among smallholder farmers (Erick et al., 2025).
Water management	Techniques such as rainwater harvesting, efficient irrigation systems, and water conservation methods aimed at optimizing water use in farming. These practices help smallholder farmers maintain productivity in water-scarce or drought-prone areas, enhancing resilience to climate variability (Erick et al., 2025).
Integrated Nutrient Management (INM)	INM improves soil fertility and plant resilience by combining organic and biological inputs such as compost, vermicompost, biofertilizers, and plant growth-promoting microbes. These inputs help crops cope with climate stressors like erratic rainfall and heat, while addressing

	nutrient deficiencies in nitrogen, phosphorus, potassium, and calcium. Sustainable practices like intercropping, green manuring, and recycling farm waste are also promoted to maintain long-term soil health (Kandiannan et al., 2018; Srinivasan et al., 2008).
Disease and Pest Management	This involves strategies to prevent and control crop damage caused by pests and diseases through regular monitoring, use of resistant varieties, biological controls, and eco-friendly inputs. Integrated approaches combining healthy soils, timely interventions, and cultural practices are key to reducing outbreaks and crop losses under climate stress (Rai & Upadhyay, 2023; Thankamani et al., 2024; Nguyen et al., 2020).
Climate-smart tools and technologies	These tools use soil analysis, mobile apps, sensors, and geospatial technologies to guide nutrient use, irrigation, and pest management. They help farmers optimize inputs, improve yields, and respond to climate conditions more effectively (Krishnamurthy et al., 2021; Nanda et al., 2020).
Climate-smart varieties	These are crop cultivars bred or selected to perform well under changing climate conditions. These varieties typically exhibit tolerance or resistance to abiotic stresses such as drought, heat, and salinity, as well as biotic stresses including pests and diseases. They are important for sustaining productivity, reducing vulnerability, and enhancing the resilience of farming systems in the face of climate change (Krishnamurthy et al., 2021; Varghese & Ray, 2024).

Table 4: Summary of findings on the barriers & prospects for CRP adoption

Authors/year	**Title**	**Country/ Region**	**Key findings on the challenges and prospects of adopting CRPs**
(Esan et al., 2018)	Analysis of Cashew Farmers Adaptation to Climate Change in South-Western Nigeria	Nigeria	Institutional disconnect limits CRP adoption; farmers rely on informal sources like radio and personal experience for climate information.

Authors/year	Title	Country/ Region	Key findings on the challenges and prospects of adopting CRPs
(Esan et al., 2018)	Analysis of Cashew Farmers Adaptation to Climate Change in South-Western Nigeria	Nigeria	Institutional disconnect limits CRP adoption; farmers rely on informal sources like radio and personal experience for climate information.
(Khatri-Chhetri & Aggarwal, 2017)	Adapting Agriculture to Changing Climate in South Asia	South Asia (India)	Financial constraints, institutional gaps, and short-term risk aversion hinder adoption; farmers prioritize immediate needs over long-term CRP investment.
(Dorkenoo et al., 2024)	Climate change impacts on rainfed cropping systems in the tropics and the case of smallholder farms in Northeast Cambodia	Cambodia	Adoption influenced by economic expectations, neighbor observation, and resistance traits of crops; low response despite awareness of climate impacts.
(Irawan, 2021)	Adaptation Strategy to Climate Change Among White Pepper Smallholder Farmers in Bangka Belitung, Indonesia	Indonesia	Adoption influenced by cooperative membership, gender, and perception of strategy suitability; education and experience showed limited influence.
(Wakweya, 2023)	Challenges and prospects of adopting CSA practices and technologies: Implications for food security	Sub-Saharan Africa	Financial and policy constraints are key barriers; adoption improves food security and living standards.
(Wang et al., 2025).	Driving mechanism for farmers' acceptance of climate-smart agriculture	China	Perceived value, task-technology fit, and moral responsibility influence adoption. Ease of use and compatibility are critical for uptake.
(Myeni & Moeletsi, 2020)	Factors Determining the Adoption of Strategies by	South Africa	Income, livestock ownership, access to credit, and awareness increase adoption.

Authors/year	Title	Country/ Region	Key findings on the challenges and prospects of adopting CRPs
(Esan et al., 2018)	Analysis of Cashew Farmers Adaptation to Climate Change in South-Western Nigeria	Nigeria	Institutional disconnect limits CRP adoption; farmers rely on informal sources like radio and personal experience for climate information.
	Smallholder Farmers in Eastern Free State, South Africa		Large farms and lack of climate info hinder uptake.
(Obe et al., 2025)	Barriers to climate change adaptation innovations among smallholder farmers	Developing Countries (Meta-Analysis)	Financial, informational, institutional, and technological barriers dominate. Education and access to extension are critical enablers.
(Ishtiaque et al., 2024)	Overcoming barriers to climate-smart agriculture in South Asia	South Asia	Weak extension services, conflicting subsidies, and inequity in access affect adoption. Emphasizes need for post-adoption support and inclusive
(Asule et al., 2024b)	Awareness and Adoption of Climate-Resilient Practices by Smallholder Farmers in Kenya	Kenya	Awareness and adoption are influenced by training, age, experience, household size, and land size. Extension gaps and perceptions of soil fertility affect decision-making.
(Erick et al., 2025)	Adoption of CSA among smallholder leafy vegetable agripreneurs in semi-arid regions	Semi-arid regions	Education, income, cooperative membership, and technology compatibility are key to adoption. Perception of benefits significantly influences adoption.

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