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CHALLENGES AND OPPORTUNITIES IN COWPEA-BASED FOOD SYSTEMS OF THE COLOMBIAN CARIBBEAN: A REVIEW OF VARIETY IMPROVEMENT AND DIGITAL AGRICULTURE

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ABSTRACT

Cowpea (Vigna unguiculata) is a nutritional legume that plays a key role in food availability and dietary quality in smallholder-based food systems, particularly in climate-vulnerable environments. In Colombia, the Caribbean region concentrates the largest area suitable for cowpea cultivation; however, average yields remain low, limiting the crop's contribution to local food systems and food security. This review examines how the literature published, from 2015 to 2025, characterizes the interaction between cowpea variety improvement and digital agriculture technologies in enhancing food availability and productivity within smallholder cowpea-based food systems in the Colombian Caribbean. The evidence indicates that locally adapted improved varieties, such as Caupicor-50 and L-019, consistently outperform traditional farmer-saved seed under Caribbean conditions and contribute to more reliable grain supply when combined with context-specific agronomic management. Furthermore, the review identifies that while digital agriculture is nascent, Agriculture 4.0 tools–specifically IoT sensing and AI-driven decision support–can mitigate abiotic stresses and reduce water-deficit losses by up to 30 %. However, the efficacy of these agronomic gains is currently limited by structural food system challenges, including a lack of post-harvest storage and high intermediary margins. We conclude that strengthening cowpea-based food systems in the Colombian Caribbean requires an integrated seed-plus-technology strategy that combines variety improvement with accessible digital agriculture solutions and targeted capacity building for smallholders. This synthesis provides applied evidence to inform breeding priorities, technology transfer, and policy interventions aimed at improving the stability, sustainability, and food-system contribution of cowpea production in the region.

KEYWORDS: Cowpea (Vigna unguiculata); Food systems; Variety improvement; Digital agriculture; Smallholder farming; Food availability; Climate-resilient food production

1. INTRODUCTION

Current population growth poses several challenges to ensuring food security at the regional and local levels. The UN estimates that by 2100, the world's population will reach around 10.9 billion [1], implying that food systems must be improved and/or adapted to increase productivity in order to meet this demand.

In recent years, UNICEF has incorporated sustainability as a new dimension of food security, referring to it as "the long-term ability of food systems to provide food and nutrition security in a way that does not compromise the economic, social, and environmental foundations that generate food and nutrition security for future generations" [2]. Under this framework, food systems are required to promote the development and adoption of climate-resilient crop varieties, agricultural practices, and technologies capable of maintaining stable yields under conditions of drought, poor soil quality, limited water availability, and extreme temperatures [3,4]. However, this sustainability challenge is particularly acute in producer regions where a persistent gap between crop productivity and attainable yields continues to constrain food availability, especially in smallholder-based production systems that dominate many developing regions [5–8].

In this context, the cowpea (Vigna unguiculata [L.] Walp.) plays a strategic role in smallholder-based food systems due to its adaptability to drought and heat-prone environments and high protein content (20–30 %) and micronutrient density [9]. These attributes make cowpea a low-cost and reliable food source for vulnerable populations, particularly in tropical and semi-arid regions [10,11], contributing to sustainability through biological nitrogen fixation, reducing dependence on synthetic fertilizers and associated environmental and economic costs [12,13].

Increasing cowpea production among smallholder farmers represents a promising strategy to strengthen food security in regions with agroecological conditions suitable for this legume. In Colombia, the Caribbean region stands out as one of the main areas with potential for cowpea cultivation, given its predominance of semi-arid environments, limited and erratic rainfall, high temperatures, and soils of generally low fertility [14,15]. These conditions align well with the known tolerance of cowpea to drought, heat stress, and marginal soils, traits that have been widely documented across diverse production environments [16]. Despite this comparative advantage, cowpea production in Colombia remains substantially lower than in other producing countries such as Peru and Nigeria [17], highlighting a gap between agroecological potential and current productive performance.

This gap in productivity reflects a combination of interrelated challenges, including the widespread use of unimproved farmer-saved seed, high exposure to drought and heat stress, recurrent pest and disease pressures, and limited access to context-specific agronomic information [18]. Over the past decade, a growing body of literature has addressed different components of cowpea production, utilization, and the application of digital agriculture tools in smallholder cropping systems.

Specific studies conducted in Colombia and comparable tropical regions have reported yield gains associated with improved cowpea varieties and context-specific agronomic practices [12,17], while research on digital agriculture has highlighted the potential of sensing technologies, decision-support systems, and data-driven approaches to improve production stability and resource-use efficiency [19,20].

However, this evidence remains largely dispersed across agronomy, crop improvement, and agricultural technology domains, often examined in isolation and with limited explicit linkage to food-system outcomes for the Colombian Caribbean region. The aim of this review is to identify the main challenges and opportunities associated with cowpea variety improvement and digital agriculture in smallholder cowpea-based food systems for the Colombian Caribbean, by systematically synthesize the literature published between 2015 and 2025.

In section 2 the methodology followed to select and discard the sources is presented, while sections 3.1, 3.2 and 3.3 show the current status of Colombia cowpea production, best varieties suitable to improve Colombia cowpea's yield and current Colombian food systems status. Section 4 resumme the main challenges for Colombia to increase its cowpea production and section 5 maps the implementation of digital technologies for cowpea production and policies towards their implementation. In section 6 the conclusion of the study is presented.

2. RESEARCH METHODOLOGY

The methodological approach adopted in this study is described below. This review was designed as a narrative and integrative literature review, informed by selected elements of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines [21]. These elements were used as a guiding framework to enhance transparency and structural rigor in the identification, screening, and synthesis of the literature, rather than to conduct a fully systematic review. The review integrates scientific and grey literature published between 2015 and 2025 to examine challenges and opportunities related to cowpea (Vigna unguiculata [L.] Walp.) variety improvement and the application of digital agriculture technologies within smallholder-based food systems in the Colombian Caribbean.

The guiding research question was: What are the main trends, barriers, and opportunities associated with strengthening sustainable cowpea-based agricultural models under climate change conditions, from both environmental and socio-economic perspectives?

A structured and bilingual search strategy was implemented to capture both peer-reviewed publications and relevant grey literature published in English and Spanish. Boolean search strings were developed to address two complementary dimensions of the review: (i) cowpea production and variety improvement, and (ii) the application of digital agriculture technologies to food production systems. English-language search strings were applied to international scientific databases, including Scopus, Web of Science, and SciELO, while equivalent Spanish-language search strings were used to search institutional thesis repositories from Colombia universities.

The inclusion of undergraduate theses as grey literature was deliberate and methodologically justified, given the limited availability of Colombia-specific evidence on cowpea production and digital agriculture in indexed, peer-reviewed sources. In contrast, local theses frequently reported primary field data, context-specific agronomic practices, and technology adoption constraints relevant to smallholder-based food systems in the Colombian Caribbean.

2.1. Exclusion and Inclusion Criteria

Following the database and repository searches, all retrieved records were collated and duplicates were removed. The screening and selection process was conducted in two sequential stages: (i) an initial screening of titles and abstracts against predefined eligibility criteria, followed by (ii) a full-text assessment of potentially relevant sources. Any discrepancies arising during the screening process were resolved through discussion and consensus among the authors.

Sources were considered eligible if they: (i) addressed the application of digital agriculture approaches aligned with the didital agriculture approaches in relation to, or with the potential to impact, cowpea production systems; (ii) reported primary data or provided substantive ethodological or technical detail relevant to production, variety improvement, or technology implementation; (iii) were published in English or Spanish between 2015 and 2025; and (iv) provided full-text access. Grey literature was evaluated using the same inclusion criteria as peer-reviewed publications to ensure methodological consistency. The overall screening and selection process is summarized in Figure 1.

2.2. Contextualization with complementary sources

As Colombia does not have centralized, systematized information on cowpea production, this study involved a focused web search of institutional and association sources and their databases to obtain figures regarding cowpea production. The institutions and associations included: FENALCE (National Federation of Grain, Legume, and Soybean Growers), AGROSAVIA (Colombian Agricultural Research Corporation), DANE (National Administrative Department of Statistics), AGROSAVIA (Colombian Agricultural Research Corporation), AGRONET (Agricultural Information Network), and CIAT (Alliance of Bioversity International and CIAT). These contextual data were not included in the thematic synthesis, but they were used to interpret Colombia-specific patterns and to clarify data gaps.

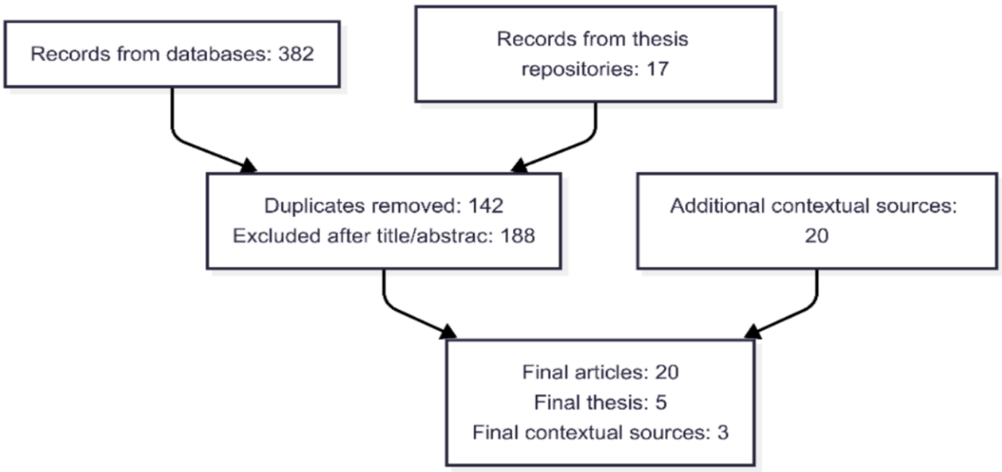

Figure 1: Research methodology (PRISMA) follow chart used in this review

3. COWPEA WITHIN COLOMBIAN FOOD SYSTEMS

Cowpea, like all edible legumes, represents an alternative for the sustainable development of growing countries like Colombia. This is because, as a legume, cowpea plants have the capacity to increase the organic matter content of cultivated soils, adding resilience to crop rotations and increasing yields [22]. Growing cowpeas also reduces pressure on land and agricultural resources used for animal protein production [23]. In nutritional terms, cowpea also aligns with two of the five key food trends shaping the future: vertical farming and plant-based diets [24].

This legume is a significant source of protein (17 − 30 %) and other important nutrients such as dietary fiber (including insoluble fiber), 19 − 30 3 − 5 %. Furthermore, previous studies have shown that cowpea may have a potential cardioprotective effect due to its high content of monounsaturated and polyunsaturated fatty acids [23].

Technologically, cowpea production could also represent a significant contribution to Colombia's food development, since, as a legume, it is capable of producing "liluva" [25], with functional properties that allow for the development and design of new food products focused on sustainable and sovereign food production. Taken together, the agronomic, nutritional, and functional properties of cowpea highlight its potential as a sustainable and health-promoting component of future food systems.

3.1. Colombia Cowpea Production

Traditionally, cowpea has been an integral component of localized food systems in the Colombian Caribbean region, where it is closely linked to cultural identity and culinary diversity. Most cowpea produced by smallholder farmers is either consumed at the household or community level or commercialized through local markets and town fairs, rather than entering large-scale distribution channels. Its culinary uses are diverse and include fritters, soups, rice and vegetable-based preparations, stews with pork, and even sweet dishes such as desserts [26]. Empirical evidence indicates that approximately 90 % of cowpea grain production in the region is destined for home consumption or local markets [11], underscoring its central role in short supply chains characterized by direct sales to consumers or small local intermediaries.

In Colombia, there are approximately 39.2 million hectares of land with agricultural potential. Currently, only 13.5 % of this land is used for cultivation [27]. According to FENALCE, 8, 000 ha were designated for bean production in 2023, of which around 11 % corresponded to the Colombian Caribbean region [28]. As shown in Figure 2 (a), this region had higher bean yields than regions with more than 104 ha of beans planted. Despite these statistics, it was not possible for this study to determine how much of the 8, 000 ha were used for cowpea production in especific as this disaggregated information was not reported in any of the sources included in the analysis. However, FENALCE reports an increase in bean cultivation in the Colombian Caribbean, as can be seen in Figure 2 (b), where it possible to see that this region's share of the national bean area increased from less than 5 % before 2021 to more than 10 % from 2021 onwards.

Regional land-evaluation guidelines specify that cowpea nodulation is optimal once the pH level exceeds 6.5; below this threshold, the aluminium toxicity begins to curb root growth. The Colombian Caribbean is characterized by drained sandy loam soils. Some regional surveys had reported pH values between 6.5 and 7.4, a neutral range that benefits the availability of molybdenum and the efficient of Rhizobium-mediated nodulation in cowpea. For instance, field measurements taken by [18] on representative Vertisols in Sucre, show a pH value of 7.74, with 2.8 % organic matter and cation exchange capacity of 77 centimol kg−1, with mean air temperatures of ∼ 29 ◦ C.

The region experiences a dry season and an annual rainfall ∼ 1, 192 mm, which falls outside the flowering period of the crop. These characteristics satisfy the photothermal requirements of cowpea while limiting fungal pressure. Unsurprisingly, national land-evaluation maps designate ∼ 4.8 million ha of the Caribbean departments to the highest aptitude class for commercial cowpea cultivation, accounting for over half of all land in Colombia that is best suited to cowpea cultivation [14].

Studies show that certain elite lines can reach iron concentrations of up to 100 mg kg−1 and zinc concentrations of up to 62 mg kg−1, in addition to a protein content of over 22 % [29,30], properties that highlight the relevance of continued research on this crop and its improvements in the Colombia Caribbean to help the country align with the Sustainable Development Goal (SDG) 2: Zero Hunger [31].

Several Vigna unguiculata genotypes have been identified as suitable seeds for the Colombian Caribbean, ranging from locally adapted varieties to improved cultivars. One key commercial cultivar is Caupicor 50, which was developed by the University of Córdoba.As 2016, it was the only improved cowpea cultivar registered in Colombia's national registry [29]. This semi-prostrate, 60-day cycle cultivar is noted for its drought tolerance and good average yield, with productivities reaching 1.0 t ha−1 in the Sinú and San Jorge valleys, significantly higher than the typical 0.6 t ha−1 for other varieties grown by local producers in the region [18].

Caupicor 50 also exhibits good adaptability and phenotypic stability in the tropical dry forest environments of the Colombian Caribbean, showing specific adaptability to favourable conditions and medium yields in unfavourable ones, and offering improved nutritional attributes like up to 26 % protein content [32]. Its performance is enhanced when it is sown in lower river valleys with heavier Vertisols, and when the row-by-plant spacing is around 0.60 m × 0.20 m, and when combined with rain-fed conditions, the cultivar has surpassed 2.0 t ha−1 [14,29].

Another advanced cultivar line is the named "L-019", which was identified following multilocation trials in eight dry-forest environments, offering yields around 1.5 t ha−1 citeAramndiz-Tatis2019. It combines broad adaptation with the highest mean grain yield and phenotypic stability, and is already recommended as a "new planting alternative" for family farms in the region [29].

Furthermore, producers in the Colombian Caribbean widely cultivate diverse local varieties, including red, black, white, and "cabecita negra" types, and a small red cowpea variety called "cuarentano", which has a very short production cycle and is highly disseminated in Montes de María [33]. Parallel studies that quantify stage-specific crop-coefficients show that a modern variety like INIAP-463 needs only ~ 254 mm of irrigation over its 80-day cycle-information that allows breeders to select for, and farmers to schedule, water-use efficiency under increasing drought pressure [34].

Nevertheless, Colombian cowpea farmers generally achieve yields of ~ 0.6 t ha−1, partly due to the time lag between research development and application and partly because many use poorly adapted seeds in unsuitable environments [32]. Furthermore, cowpea production relies on manual labour for planting and harvesting, and commerce takes place in local hubs. This results in profitability of ~ 19 % and makes the sector highly sensitive to labour availability and price shocks [33].

3.2. Distribution Channels and Market Structure

Local urban markets in coastal cities and towns are the primary retail points for cowpea grain. Consumers typically buy cowpeas as dried grains by the pound, much as they do other beans [33]. In these markets, cowpea competes with common beans and imported lentils but often at a lower price. Because cowpea production is concentrated in the coast, urban centers like Barranquilla, Cartagena, Santa Marta, Montería, Riohacha, etc., are supplied by nearby rural producers.

The market structure features multiple intermediaries, which affects pricing and producer profit. Farmers usually sell cowpeas in 50-kg sacks [11]. When intermediaries are involved, they often pick up the product at the farm or a village collection point and then transport it to bigger urban markets. Each handoff adds a margin: Martinez et al. [11] calculated a gross marketing margin of around 55 %, meaning that more than half of the final consumer price is absorbed by traders and retailers, while the farmer receives ~ 45%.

Cowpea distribution is predominantly regional. There is little evidence of long-distance trade or export of cowpeas from Colombia. The crop is essentially consumed in the same region where it's grown. For instance, even though Colombia imports some legumes, those are mostly lentils and common beans, when cowpea demand exceeds coastal supply, traders might import cowpea (or black-eyed peas) from international markets [29]. Even though this study found just one source documented this such instances.

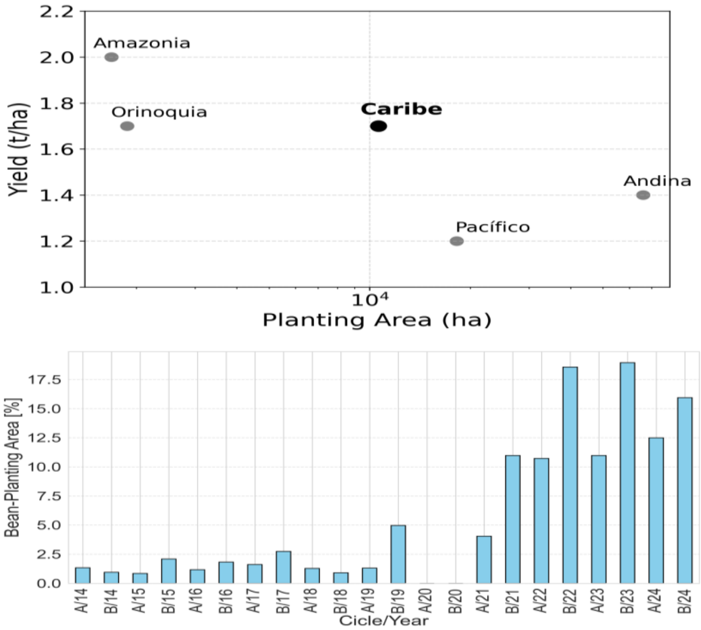

Figure 2: Top, relationship between bean yield and bean planting area for Colombian regions, highlighting of Colombian Caribbean with higher yield (1.7 t ha−1) compared to most regions despite a moderate planted area (∼10, 627 ha). Chart based on data from DANE. Bottom, Annual bean planting area by semester, aggregated across the region of Colombian Caribbean. The chart shows variations over time, with a marked increase in recent years. Chart based on data from FENALCE Statistics report [23].

3.3. Transportation, Logistics and Postharvest Constrains

Logistics for cowpea in Colombia's Caribbean are closely tied to the small-scale nature of its production. Transportation usually involves farmers or buyers moving sacks of cowpea from farms to town markets. Since farms are small and scattered, volumes per producer are low, leading to inefficiencies: intermediaries might collect from multiple farms to fill a truck. Rural road conditions (often unpaved tertiary roads) can pose challenges, especially during the rainy season. However, farmers tend to schedule the cowpea crop to avoid heavy rains at harvest. For instance, planting in October so that harvest occurs in the dry season (Jan/Feb), helping to mitigate the risk of washed-out roads or crops, but it concentrates the harvest into a narrow window [11].

Postharvest handling is a notable weak link, with the majority of cowpea growers lack proper storage facilities. Martinez et al. [11] reported that around 85 % had no on-farm storage beyond perhaps bags kept in their home. Only 14.3 % of respondents had a dedicated storage like a small warehouse for any agricultural products. As a result, farmers often rush to sell their cowpeas soon after harvest to avoid losses from pests (weevils, bruchid beetles) or humidity. Cowpea, like other legumes, is susceptible to bruchid infestation if stored improperly. None of the sources studied in this work explicitly quantified storage losses or pest incidence, but given the climate, non-hermetic storage could be a risk factor of damage from biological risk factors (e.g. insects or mods).

3.4. Cowpea Yield Production from Smallholders

It was found that cowpea cultivation is carried out predominantly under family farming production systems by small producers, typically in plots that do not exceed two hectares [35]. The major cultivated areas are concentrated in Cesar (59.5 %), Córdoba (19.0 %), and La Guajira (16.6 %), covering an estimated total of 14, 000 ha [11,29]. While national aggregate statistics often conflate cowpea with the common bean (Phaseolus vulgaris), in 2019, [29] reported a national yield of 0.6 t ha−1. However, significant variability exists; producer-reported yields in the Caribbean average 1.1 t ha−1, reaching up to 1.6 t ha−1 in humid sub-regions [32,35]. When juxtaposed with a commercial benchmarks exceeding 2.0 t ha−1 in the USA [36], or 8.6 t ha−1 in Nigeria [17], Colombia's current productivity highlights a substantial yield gap that could be bridged through improved management and genetic selection.

4. CHALLENGES FOR IMPROVING COWPEA PRODUCTION IN COLOMBIA

In the Colombian Caribbean, the cowpea is cultivated in rain-fed conditions making abiotic hazards an important issue. Field studies carried out in Sucre show that erratic rainfall and outright soil-water deficits shrink stem diameter, leaf area, pod number and ultimately grain yield; even supposedly "drought-tolerant" cultivars suffer when long dry spells trigger floral abortion and pod loss [10,18]. Because heat and moisture stresses frequently coincide on the Caribbean coast, temperatures that exceed the optimum 24 − 29 ◦ C window for Vigna unguiculata further depress photosynthetic efficiency [32]. This highlights the need to incorporate water-saving measures into climate-smart management packages [37], see Table A1 in A. Next, the main abiotic stresses identified for Colombia arelisted:

Table A1: Abiotic constraints to rain-fed cowpea (Vigna unguiculata) in the Colombian Caribbean, summarizing stated field mechanisms, management levers explicitly reported in the sources, and only those yield effects that are quantified in the cited literature.

Stress / Context	Physiological Field Effect	Management Lever	Yield Effect	Sources
Drought / erratic rainfall	↓ stem diameter, leaf area, pods; floral abortion → pod loss under prolonged dry spells	Higher plant population to boost light interception; hydro-absorbent polymers; climate-smart, water-saving inputs	Trials report up to +46%; grain yield higher density + hydro-absorbents (local context); baseline drought can cause 35–70% losses	[10, 18, 37]
Heat coinciding with moisture stress (T > optimum 24–29 °C)	↓ photosynthetic efficiency; flower/leaf drop; pollen fertility; ↓ pod set	As above (population + hydropolymers); adjust sowing windows to avoid hottest nights	High night temps may cause ~14% yield/quality losses	[10, 14, 32]
Salinity (germination/seedling phase most sensitive)	↓ germination/seedling vigor; growth depression	Site selection/monitoring EC; salinity not highlighted as major Colombian production constrain	Important globally, but not a prominent issue in Colombian production	[10, 14, 33]
Low soil fertility	Limits growth, nodulation, N fixation efficiency	Corrective P management (applied); inoculation compatibility checks	Application of 90 kg/ha P could adversely affect yield; amounts between 30 and 60 kg/ha are most beneficial for many cowpea lines	[10, 13, 38]

- **Drought:** Although cowpea is considered drought-tolerant when compared to other crops, erratic rainfall patterns in tropical and semi-arid regions can have an adverse effect on growth, development, and reproduction. This can result in a substantial reduction in grain yield and biomass, with losses of up to 35 − 69 % [10].
- **Salinity:** While salinity is acknowledged as an abiotic stress for cowpea, it does not present as a prominent issue specifically affecting agricultural production in Colombia [10,14,33].
- **Heat Stress:** High temperatures are a crucial abiotic stress, negatively impacting flower and leaf drop, pollen fertility, pod setting, and overall biomass, potentially causing 4–14 % loss in yield and quality when night temperatures are too high [10].
- **Low Soil Fertility:** Phosphorus deficiency is a critical constraint in many tropical African soils, including some in Colombia, affecting growth, nodule formation, and the efficiency of nitrogen fixation, despite cowpea's ability to fix its own nitrogen [10,13].

This study found no particular diseases caused by viruses or parasitic weeds in the Colombian Caribbean. However, around 140 viruses are known to infect cowpeas, causing yield losses of between 10 % and 100 % [38]. Meanwhile, parasitic weeds such as Striga gesnerioides and Alectra vogelii can lead to losses of between 73 % and 100 % [10]. On the other hand, it was found that diagnostic capacity is generally limited in the Colombian Caribbean, leading farmers to apply phytosanitary controls without technical criteria and to over-rely on synthetic chemical inputs [11]. See Table A2 in A.

Table A2: Biotic constraints (insects, weeds, diseases, nematodes, parasitic weeds) affecting cowpea in Colombia and comparable environments, listing stated impacts, source-reported management levers (with emphasis on resistance breeding and diagnostics-enabled IPM).

Stress/Agent	*Field Effect*	*Management Lever*	*Yield Effect*	*Sources*
Insect pests (aphids, thrips, pod borers, bean flies)	Sap-sucking → leaf curl, defoliation, stunting; virus transmission; damage across stages	Breeding for multi-pest resistance; need for IPM supported by diagnostics/decision tools	Not quantified for insects alone (virus losses below)	[10, 38, 49]
Weeds (early competition)	Strong competition in first third of the cycle	Critical control window begins soon after emergence; timely hoeing or pre-emergence herbicides	Season-long weed interference: up to 76% yield loss	[36, 42, 49]
Bacterial diseases (CoBB, pustules)	Severe damage at all stages	Implied need for IPM (no specific practice given)	Damage on several plant parts affecting the crop throughout its life cycle, impacting cowpea yield	[10, 32, 38]
Viral diseases (≥140 infect cowpea; economically important)	Severe epidemics depending on severity	Breeding + vector control implied via IPM	10% to 100% yield loss	[10, 38]
Root-knot nematodes (M. incognita, M. javanica)	Stunting; major constraint	Need for IPM (no specific tactic in excerpt)	80% to 100% yield loss	[10, 33]
System constraint: diagnostics & advisory	Misidentification; over-reliance on synthetics; rapid escalation of outbreaks	Rapid field diagnostics, decision-support tools, variable-rate application	Potential to protect realized genetic/IPM gains; essentialized from genetics/IPM	[11, 50]

5. DIGITAL AGRICULTURE PERSPECTIVES FOR COWPEA PRO- DUCTION IN COLOMBIA

5.1. *Agriculture 4.0*

The systematization of international and regional experiences demonstrates that Agriculture 4.0 technologies offer tangible, quantifiable benefits for cowpea production systems in the Caribbean context [19,39,40]. This digital framework provides very specific solutions to the limitations that hinder cowpea productivity, such as empirical irrigation cycles, management decisions unsupported by historical data, and information gaps common on small farms [27]. For instance, low-power IoT sensors enable the deployment of cloud-connected tensiometers, photometers, and insect traps without the need for expensive 3G/4G infrastructure [37]. This kind of technology has been already tested in Colombia for cowpea production, where the flux of data from sensors is used alongside crop models achieving possible to anticipate water deficits and reduce losses due to drought by up to 30 % in the Colombian Caribbean [34]. These results have also been validated for other crops and locations in Latin America, reporting yield increases of 50 − 80 % and reductions in input cost of 20 − 40 % on small farms [37].

5.2. AI/ML: Data Based Decision-Making

This data pipeline from plants to farmers's decision-making processes, requires AI/ML algorithms to convert raw data streams into information that can be used to inform agronomic decisions [41]. One example of such an algorithm is a deep vision models that can identify pests and weeds on cowpea leaves. This could complement tools like digital twins-virtual replicas that combine soil, climate, and plant phenology sensors, allowing farmers to simulate their farms and predict, days in advance, how their crops will respond to different irrigation schedules or biofertilizers days in advance [42]. Other technologies, such as digital traceability and blockchain, could be implemented to strengthen access to differentiated markets and enhance the long-term economic returns and sustainability for cowpea producers; given that Colombian Caribbean cowpea farmers currently sell their produce primarily at local hubs. See Table A3 in A.

Table A3: Documented effects of Agriculture 4.0 on cowpeas and other transferable crops.

Applied technology	Crop / Context	Measured effect	Reference
IoT + soil moisture sensors (LoRa / NB-IoT)	Smallholder pilot farms in Latin America (legumes and potato)	Yield increase of 50–80% and reduction of water/agrochemical costs by 20–40%	[37]
IoT + tensiometers + crop coefficient (Kc)	Cowpea variety INIAP-463, tropical conditions	Optimized water requirement of 254 mm during 80-day cycle; prevents yield losses of up to 30% due to late-season drought	[27, 34]
UAV / LiDAR + hyperspectral imaging	Cotton and cereals in semi-arid conditions	Stress and nutrient deficiency maps; variable-rate fertilization reduced inputs in heterogeneous soils	[19, 42]
AI / ML (yield prediction models)	Maize and wheat in diverse environments	Random forest and neural network models outperformed linear models; robust yield prediction and hybrid adaptation	[40, 42]
AI / Computer vision + digital twins	Cowpea and tropical legumes	Early detection of pests and weeds; simulation of management scenarios (irrigation, density, biofertilizers)	[27, 41]
Blockchain + digital platforms	Family farming in Latin America	Grain traceability, microcredit access, and origin certification	[37]

Despite this technological promise, operational challenges associated with infrastructure, cost, and digital literacy remain significant obstacles to widespread adoption.

5.3. Agriculture 5.0

Over the last decades, the global agri-food system has responded to these challenges by evolving from data-driven precision (Agriculture 4.0) toward a new paradigm known as Agriculture 5.0, which represents a shift towards a more human-centered, sustainable, and intelligent ecosystem by embracing advanced technologies such as AI, robotics, extended reality and forthcoming sixth-generation (6G) communication networks.

This integration enables real-time decision-making and hyper-connectivity at all stages [43]. Specifically, Agriculture 5.0 goes beyond optimizing processes to prioritize environmental sustainability and improve farmers' quality of life, offering highly tailored solutions for individual fields, animals, and farmer [44].

To put humans at the heart of agriculture, Agriculture 5.0 uses advanced technologies such as human-centered AI and collaborative robotics (cobotics) to enhance, rather than replace, the role of the farmer [45]. This paradigm focuses less on maximizing yield at all costs and more on resilience–i.e. the ability of farming systems to adapt to shock—and sustainability. For farmers, this translates into explainable AI systems that provide clear and contextualized recommendations (e.g., "The model suggests reducing watering because the digital twin predicts rain in 48 hours"), offering more than just instructions and suggestions and enabling them to make informed decisions based on their local knowledge.

Furthermore, Agriculture 5.0 emphasizes cobotics and augmented reality to offload physically strenuous tasks, thereby improving quality oflife and making farming more attractive to new generations [46,47]. See Table A4 in A. The analysis performed in this review found no evidence of Agriculture 5.0 technology being applied to cowpea production.

Table A4: Cowpea growth stages and Agriculture 5.0 enablers based on international and Colombian references.

Cowpea Stage	5.0 Enabler	Case / Example in Colombia	Operational Metric
Sowing–Emergence	Smart sensors + ICT (5G→6G) + AI-enabled seeding/soil mapping	Preparation for 6G with extended rural coverage and <1 ms latency for real-time soil and climate monitoring (aligned with the National Digital Transformation Plan 2022–2026). 6G enables massive IoT and edge analytics for sowing and fertilization recommendations	Connectivity/latency <1 ms; data rate up to ~1 Tbps; improved rural coverage enabling telemetry and instantaneous decisions
V2–R1 (Vegetative)	UAV/UGV + Edge-AI + XR (teleoperation/training)	Drone and ground robot patrols for crop health; XR used for teleoperation and remote training; 6G supports streaming and low-latency control in dispersed rural areas	Labor savings up to 4 seasonal days under high disease pressure; reduced occupational risk via XR-assisted teleoperation
R1–R5 (Flower/Fruit)	URLLC (6G) + Spraying/Weeding Robots + HRI (Human–Robot Interaction)	Fine control of irrigation/spraying and collaborative robotics for high-demand tasks; HRI ensures safety and ergonomics in field operations (applicable to tillage, weeding, and phytosanitary management)	Precision spraying: −40% pesticide use and −45% worker exposure; co-robot weeding: −58% manual labor
Post-harvest	Blockchain + 6G + XR (Training/QA) + Traceability	Integration of agri-food traceability through blockchain supported by 6G (enhanced rural coverage); XR used for training and quality assurance; consistent with Colombia's digitalization and market strategies	Blockchain: cost, risk, and time reduction; increased trust and transparency; real-time traceability updates via 6G

5.4. Colombia Policy for digital Agriculture

This review found that Colombia has started to develop a national digital transformation agenda. The National Development Plan (PND) for 2022-2026 already prioritizes sectors such as agriculture, livestock, and agroindustry for significant 6G impact [48]. The deployment of 6G-enabled IoT devices and edge computing will enable real-time environmental sensing and decision-making, ensuring productivity and sustainability, even in the challenging such as those found in the Colombian Caribbean. Promoting these advanced technologies could raise cowpea yields, reinforce food security, and build climate resilience, thus aligning directly with the country's national policy agenda to curb hunger and meet the United Nations' Sustainable Development Goals7 .

However, several bottlenecks must be resolved in order to scale up these innovations. There are still areas without signal coverage and high data costs, while sensors remain above the USD 50–100 thresholds that would make their purchase viable for a family farmer [44].

6. CONCLUSION

This review demonstrates that, despite the Colombian Caribbean possessing more than 4.8 million hectares of land with high suitability for cowpea cultivation, a persistent productivity gap limits the crop's contribution to regional food systems. Average yields remain at approximately 0.6 t ha−1, well below both experimental potential and international benchmarks. The evidence synthesized from studies published between 2015 and 2025 indicates that strengthening cowpea-based food systems in the region requires a transition from predominantly subsistence-oriented practices toward an integrated, evidence-based "seed-plus-technology" strategy.

First, the literature consistently shows that replacing farmer-saved seed with improved, locally adapted varieties–such as Caupicor-50 and L-019–can substantially increase productivity, with reported yields ranging from 1.0 to 2.0 t ha−1 under Caribbean conditions. These varieties also exhibit enhanced tolerance to drought stress and maintain high nutritional quality, including protein contents of up to 26 %, reinforcing their relevance for food availability and dietary quality in smallholder systems.

Second, applied digital agriculture tools aligned with the Agriculture 4.0 paradigm offer tangible opportunities to reduce climate-related production risks. Evidence from cowpea and transferable smallholder cropping systems indicates that IoT-based sensing and AI-supported decision tools can improve water-use efficiency and mitigate yield losses associated with heat and rainfall variability, in some cases reducing water-deficit-related losses by approximately 30 %. While more advanced Agriculture 5.0 concepts remain largely prospective, the current generation of accessible digital technologies already provides practical pathways to enhance production stability and system resilience.

Third, from a food systems perspective, the predominance of local consumption and informal markets–currently accounting for approximately 90 % of cowpea production–constrains value addition and limits the crop's integration into broader agri-food chains. Digital traceability and market-linkage tools could facilitate access to formal markets and processing opportunities, thereby increasing the economic viability of cowpea production.

However, realizing these opportunities will require addressing structural bottlenecks, including the high cost of sensing technologies and limited rural connectivity, and aligning technological interventions with national policy frameworks, such as Colombia's National Development Plan 2022–2026 and Sustainable Development Goal 2 (Zero Hunger).

Beyond agronomic factors, this review highlights that the region's cowpea-based food systems are critically constrained by logistical and market inefficiencies that diminish producer profitability. Production is currently dominated by short supply chains where approximately 90 % of the grain is destined for local consumption rather than industrial or export channels. Smallholders face substantial economic losses due to a market structure

involving multiple intermediaries, who absorb a gross marketing margin of roughly 55 %,

leaving farmers with less than half of the final consumer price. These economic challenges

are exacerbated by infrastructure deficits; notably, 85 % of producers lack on-farm storage facilities, forcing immediate sales that increase vulnerability to price fluctuations and post-harvest biological threats. Consequently, increasing productivity through improved varieties and digital agriculture must be accompanied by investments in post-harvest infrastructure and digital traceability tools to improve market access and reduce the logistical risks associated with the region's tertiary road network.

Overall, this review underscores that revitalizing cowpea production in the Colombian Caribbean depends on a deliberate convergence between variety improvement and accessible digital agriculture solutions. An integrated seed-plus-technology approach–combining the adoption of improved, locally adapted varieties with data-informed management tools–offers a robust framework for translating agronomic gains into tangible food-system outcomes. Such integration is essential to enhance food availability, strengthen climate resilience, and support the long-term sustainability of smallholder-based food systems in one of Colombia's most vulnerable agroecological regions.

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AGRONET. Spanish acronym for Agricultural Library of Colombia. https://www.siembra.co/HomeNew

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