

DOI: 10.5281/zenodo.12426452

# ENVIRONMENTAL IMPACTS OF INTENSIVE CHEMICAL FERTILIZER USE IN MAIZE (ZEA MAYS) IN BOLIVAR AND THE COLOMBIAN CARIBBEAN: A SCOPING REVIEW OF SOIL, WATER AND NUTRIENT - ENRICHMENT PATHWAYS

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Received: 21/09/2025  
Accepted: 13/02/2026

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## ABSTRACT

*Intensive chemical fertilization is widely used to sustain maize (Zea mays) productivity, but poorly synchronized rates, sources, and timing can increase nutrient losses and contribute to off-site environmental impacts. In the Colombian Caribbean, particularly Bolivar, coastal lagoons and nearshore waters connected to continental discharge pathways are environmentally vulnerable to nutrient enrichment, yet crop-specific attribution remains difficult. To map evidence published between 2010 and 2025 on the environmental problems associated with intensive or excessive chemical fertilizer use in maize and to summarize reported consequences for soil, water, and related environmental processes in Bolivar and the Colombian Caribbean, while identifying evidence gaps and research priorities. A PRISMA-ScR-informed scoping review was conducted using an iterative, layered evidence approach. Priority was given to direct Caribbean Colombia evidence on nutrient enrichment and water quality and to tropical/subtropical maize fertilization studies clarifying soil mechanisms such as nitrate mobility, gaseous nitrogen losses, acidification risk, and microbial responses. Evidence was charted into structured tables and synthesized narratively. Caribbean Colombia evidence documents water-quality vulnerability under cumulative land-based pressures in systems connected to continental discharge pathways, with nitrate and phosphate treated as relevant variables in key receiving*

*environments. However, direct studies isolating maize fertilization as the dominant driver in Bolivar remain sparse. Mechanistic evidence from tropical/subtropical maize systems supports coherent pathways by which intensive nitrogen and phosphorus inputs can increase nitrate movement beyond the root zone, elevate gaseous nitrogen losses (N<sub>2</sub>O, NH<sub>3</sub>), alter soil chemical baselines, and shift soil microbial communities. The mapped evidence supports a land-water systems interpretation: nutrient-sensitive receiving waters in Bolivar and the Colombian Caribbean face enrichment risks that can be exacerbated under high-input agriculture, but local maize-specific attribution is a key evidence gap. Future work should prioritize paired field monitoring that integrates fertilizer management data in maize with soil indicators and standardized water-quality endpoints in connected receiving waters.*

## 1. INTRODUCTION

Maize (*Zea mays*) production systems increasingly rely on chemical fertilizers, particularly nitrogen (N) and phosphorus (P) inputs, to stabilize yields under variable climatic and market conditions. Although fertilization is essential for crop nutrition, intensive or excessive application can reduce nutrient-use efficiency and increase nutrient losses through leaching, runoff, and gaseous emissions. These pathways matter environmentally because reactive nitrogen and mobile phosphorus can be transported beyond field boundaries and accumulate in downstream ecosystems.

In the Colombian Caribbean, aquatic environments are often characterized by strong land-water connectivity and high vulnerability to nutrient enrichment, especially in semi-enclosed coastal systems. Within Bolivar, the Cartagena Bay-Canal del Dique corridor has been described as a major pathway linking continental basin pressures with coastal receiving waters (Autoridad Nacional de Licencias Ambientales [ANLA], 2021). At the local scale, the Ciénaga de la Virgen has been evaluated as a water body with marked spatial-temporal variability consistent with strong external forcing and sensitivity to anthropogenic pressures (Baldiris-Navarro et al., 2025). At broader scales, regional coastal monitoring and diagnostics (REDCAM) consistently emphasize that nearshore environmental quality is influenced by continental discharges and cumulative land-based pressures across the Caribbean coastline (Instituto de Investigaciones Marinas y Costeras Jose Benito Vives de Andreis [INVEMAR], 2013, 2019). District-level reporting for Cartagena similarly frames local aquatic ecosystems as under sustained pressure, with concerns consistent with nutrient and organic matter accumulation risks (Establecimiento Publico Ambiental de Cartagena [EPA Cartagena], 2022). Inland Caribbean basins also show direct evidence of nutrient contamination: nitrate and phosphate measurements in the Cesar River have been interpreted using a nutrient pollution index in relation to land use where agriculture is prominent (Ospino-Jimenez et al., 2025).

Despite these documented water-quality vulnerabilities, crop-specific attribution remains a recurring challenge. Many local and regional sources evaluate environmental conditions under multi-pressure contexts, including urban discharges, diffuse runoff from multiple land uses, and hydrological alterations, rather than isolating the contribution of a single crop such as maize. This creates an evidence gap for management decisions:

while receiving waters may show vulnerability consistent with nutrient enrichment, the degree to which maize fertilization practices are driving nutrient export in Bolivar and the wider Colombian Caribbean remains insufficiently quantified in the peer-reviewed literature.

Mechanistic evidence from tropical and subtropical maize systems provides a coherent basis for understanding why this attribution question matters. Studies in tropical contexts show that higher N inputs can generate environmental trade-offs, including nitrate accumulation at depth under intensified cropping systems and increased risk signals for off-site impacts (Jankowski et al., 2018). Field evidence from tropical maize systems demonstrates measurable gaseous N losses (N<sub>2</sub>O, NH<sub>3</sub>) under nitrogen fertilization (Martins et al., 2015) and confirms that nitrate leaching from the maize root zone increases with fertilizer-N rate when inputs exceed crop uptake potential (Zheng et al., 2019). Fertilizer management strategies, including split urea and integration with organic amendments, can substantially alter soil chemical properties and performance outcomes in tropical maize production (Adekiya et al., 2020). Soil biological sensitivity is also relevant: tropical rhizosphere evidence indicates that fertilizer N and P sources can shift maize-associated microbial community structure and function (Aquino et al., 2025), while system diversification, such as maize intercropped with tropical grasses under N fertilization, may influence nutrient cycling and resilience (Crusciol et al., 2020). Supporting evidence from maize-based systems outside the tropics further corroborates that nitrogen source and management affect gaseous emissions (Halvorson et al., 2010), that leaching mitigation tools can reduce nitrate transport under certain conditions (Allende-Montalban et al., 2022), and that long-term fertilization can drive pH trajectories and alter soil organic carbon properties and microbial biomass indicators (Qaswar et al., 2020; He et al., 2018; Kaur et al., 2019).

Given the vulnerability of Caribbean receiving waters connected to continental discharge pathways and robust mechanistic pathways linking intensive maize fertilization to nutrient mobility and losses, a scoping review is appropriate to map what is known, identify the dominant evidence types, and clarify key research gaps for Bolivar and the Colombian Caribbean. Scoping reviews are designed to synthesize heterogeneous evidence and highlight gaps rather than produce pooled effect estimates, and they are typically reported using PRISMA-ScR guidance (Tricco et al., 2018).

**Objective.** This study aimed to map evidence published between 2010 and 2025 on the environmental problems associated with intensive or excessive chemical fertilizer use in maize cultivation in Bolivar and the Colombian Caribbean, highlighting reported consequences for soil, water, and related environmental processes, and identifying priority gaps for future region-specific monitoring and research.

## 2. METHODS

### 2.1 Review design

This study was conducted as a scoping review because the objective was not to estimate a pooled effect size, but rather to map the available evidence, identify the main environmental pathways associated with intensive or excessive chemical fertilizer use in maize, and determine where important geographic and thematic evidence gaps remain for Bolivar and the Colombian Caribbean. The review design and reporting structure were informed by the PRISMA extension for scoping reviews (PRISMA-ScR) and by the updated methodological guidance for JBI scoping reviews (Tricco *et al.*, 2018; Peters *et al.*, 2020).

### 2.2 Review question and conceptual scope

The review was guided by the following question: What evidence published between 2010 and 2025 documents the environmental problems associated with intensive or excessive chemical fertilizer use in maize (*Zea mays*) and what are the reported consequences for soil, water, and related environmental processes in Bolivar and the Colombian Caribbean?

Because preliminary exploration indicated that direct Caribbean Colombia evidence was limited, the review was structured using a layered evidence approach. First, priority was given to studies and technical reports directly addressing Bolivar and the Colombian Caribbean. Second, broader Caribbean and Colombian evidence on nutrient enrichment, water quality, and eutrophication-related pressures was incorporated when relevant to the same receiving environments. Third, mechanistic evidence from tropical and subtropical maize systems outside Colombia was included to explain how fertilization regimes can alter soil properties, increase nutrient mobility, and contribute to off-site environmental impacts.

### 2.3 Eligibility criteria

The review included documents published between 2010 and 2025. Evidence was considered

eligible when it met at least one of the following conditions: (1) it examined maize (*Zea mays*) under chemical fertilization and reported soil, nutrient, or environmental outcomes; (2) it evaluated water quality, nitrate/phosphate enrichment, or eutrophication-related risks in aquatic systems located in Bolivar or the Colombian Caribbean, even when maize was not the only or explicit crop of interest; or (3) it provided mechanistic evidence from tropical or subtropical maize systems relevant to the environmental pathways under discussion, particularly nitrate leaching, nitrous oxide or ammonia emissions, soil acidification, microbial responses, or nutrient-use inefficiency.

The review considered peer-reviewed articles, technical monitoring reports, environmental diagnostics, and grey literature with accessible full text and identifiable methods or data sources, including institutional reports and university repository documents. This broader inclusion logic is consistent with the evidence-mapping purpose of scoping reviews (Peters *et al.*, 2020; Tricco *et al.*, 2018).

Documents were excluded if they fell outside the 2010-2025 time window, focused on crop productivity only without environmental relevance, lacked sufficient methodological information, or were unrelated to fertilization, nutrient transport, or soil/water environmental outcomes.

### 2.4 Search strategy

The search process was conducted in iterative stages rather than as a single one-time search. This approach was necessary because the topic combined a highly localized geographic filter (Bolivar and the Colombian Caribbean) with a cross-disciplinary environmental question, and preliminary exploration showed that directly relevant evidence was dispersed across journal platforms, regional repositories, and technical reports.

An initial exploratory phase used AI-assisted and keyword-based searching to identify core terminology, document types, and recurrent environmental indicators. After that, targeted searches were conducted using combinations of English and Spanish terms related to maize / *Zea mays*, chemical fertilization / nitrogen / phosphorus / urea / NPK, nitrate leaching / phosphate / runoff / eutrophication / water quality, soil acidification / microbial biomass / rhizosphere / N<sub>2</sub>O / NH<sub>3</sub>, and Bolivar / Cartagena / Canal del Dique / Ciénaga de la Virgen / Colombian Caribbean / Sucre / Cesar / Cordoba.

Because directly relevant Caribbean Colombia studies were sparse, the search strategy was expanded in a structured way to include (1) Bolivar-specific water and nutrient studies, (2) Caribbean Colombia nutrient and water-quality studies, and (3) tropical and subtropical maize fertilization studies providing mechanistic support. The search process relied on a combination of publisher and journal pages, Google Scholar-retrievable scientific content, institutional and environmental authority websites, university repositories, and regional technical documentation. Priority was given to sources with accessible full text and verifiable publication metadata. This staged and adaptive search logic is compatible with scoping review guidance that recognizes the need to align search procedures with the review question, available evidence, and intended mapping exercise (Peters et al., 2020).

### 2.5 Source selection process

Titles, abstracts, executive summaries, and document descriptions were screened for thematic relevance. Potentially eligible sources were then assessed at full-text level. Selection decisions were guided by the review question and by the layered evidence structure described above.

Because the scoping purpose was to map the evidence landscape rather than to produce a narrowly restricted intervention review, documents

were not rejected solely for being non-experimental, provided that they contributed meaningfully to one of the following domains: soil impacts of intensive fertilization in maize; nutrient enrichment and water-quality deterioration in Bolivar or the Colombian Caribbean; or environmental mechanisms connecting fertilizer management to off-site impacts.

The search and selection process identified 130 records from indexed sources, publisher platforms, institutional websites, environmental authority reports, and repositories. After removal of 18 duplicates and 12 clearly irrelevant records, 100 records were screened by title, abstract, or document description. Thirty-eight full-text reports were assessed for eligibility, and 18 sources of evidence were included in the final scoping synthesis. The most common reasons for exclusion at full-text stage were absence of relevant environmental endpoints ( $n = 6$ ), productivity-only focus ( $n = 4$ ), insufficient thematic fit after full-text review ( $n = 4$ ), insufficient methodological information or inaccessible documentation ( $n = 2$ ), and exclusion after final temporal or conceptual verification ( $n = 2$ ). A PRISMA-style flow diagram is recommended for the final manuscript to report these stages in line with PRISMA-ScR reporting principles (Tricco et al., 2018). The study selection process is summarized in Figure 1.

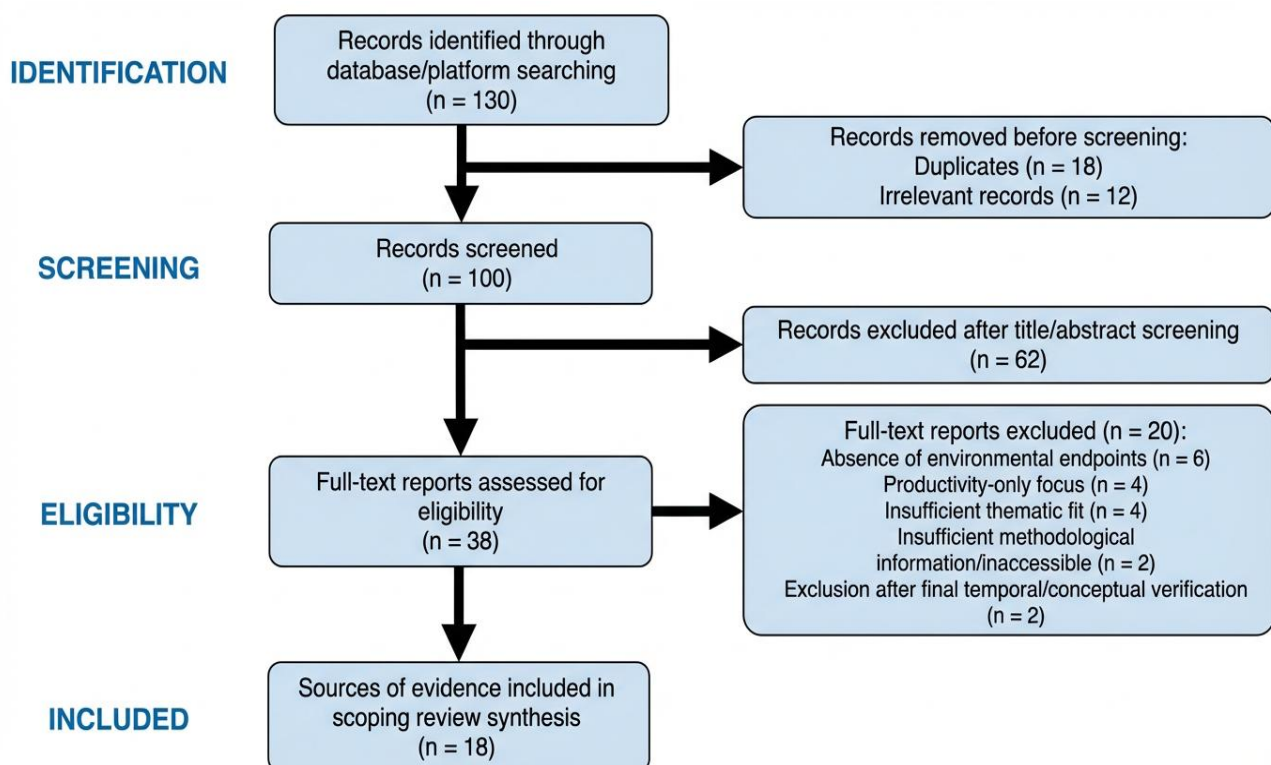


Figure 1: PRISMA flow diagram of study selection.

## 2.6 Data charting and evidence mapping

Data were extracted into structured evidence tables developed specifically for this review. For each included source, the following variables were charted when available: author or institutional source, year of publication, document type, study location, focal system or environmental receptor, crop/system context, fertilizer-related variable or environmental indicator, key finding relevant to soil, water, or nutrient transport, and interpretive role in the review.

To improve interpretive clarity, the evidence was mapped into three analytical layers: Layer A, direct evidence from Bolivar and the Colombian Caribbean; Layer B, regional water-quality and nutrient evidence relevant to Caribbean receiving systems; and Layer C, mechanistic evidence from tropical/subtropical maize systems, supplemented by a small number of supporting studies from non-tropical or rotational systems when these clarified nitrogen-loss or soil-process pathways. This evidence-mapping strategy was particularly important because local maize-specific evidence was not abundant enough to support a conventional narrow synthesis.

## 2.7 Critical appraisal and interpretation of evidence

A formal risk-of-bias assessment was not used as an exclusion criterion, which is consistent with the broad evidence-mapping purpose of a scoping review (Peters *et al.*, 2020; Tricco *et al.*, 2018). However, to improve interpretive rigor, the included documents were qualitatively differentiated according to whether they provided direct measurement or only diagnostic/contextual interpretation, whether they were crop-specific or multi-pressure environmental sources, and whether they represented core tropical/subtropical maize evidence or supporting mechanistic evidence.

This distinction was used in the Results and Discussion sections to avoid overstating causal attribution where the available literature only supported indirect or contextual inference.

## 2.8 Synthesis approach

The synthesis was conducted as a narrative evidence synthesis structured around two major environmental domains: (1) nutrient enrichment and water-quality vulnerability in Bolivar and the Colombian Caribbean, and (2) soil impacts and nutrient-loss mechanisms associated with intensive chemical fertilization in maize.

Within these domains, the evidence was interpreted through a land-water systems perspective linking fertilizer management intensity, soil chemical and biological responses, nutrient mobility and loss pathways, and downstream water-quality risks. Particular emphasis was placed on identifying where the literature supports direct local conclusions, where it supports only mechanistic extrapolation, and where major research gaps remain.

## 3. RESULTS

### 3.1 Study selection and PRISMA flow summary

A total of 130 records were identified through database/platform searching and other sources. After removal of 18 duplicates and 12 clearly irrelevant records, 100 records were screened by title, abstract, or document description. Thirty-eight full-text reports were assessed for eligibility, of which 18 sources of evidence were included in the final scoping synthesis. The most common reasons for exclusion at full-text stage were absence of relevant environmental endpoints ( $n = 6$ ), productivity-only focus ( $n = 4$ ), insufficient thematic fit after full-text review ( $n = 4$ ), insufficient methodological information or inaccessible documentation ( $n = 2$ ), and exclusion after final temporal or conceptual verification ( $n = 2$ ).

*Table PRISMA-1. PRISMA flow summary.*

Stage	Count
Records identified	130
Duplicates removed	18
Clearly irrelevant removed before screening	12
Records screened	100
Full-text reports assessed	38
Sources of evidence included	18

### 3.2 Impacts of nutrient enrichment on water bodies in the Colombian Caribbean (2010-2025)

The mapped scientific and technical evidence provides a detailed, but uneven, picture of nutrient enrichment pressures on aquatic ecosystems in the Colombian Caribbean. A central scoping finding is that direct, crop-specific evidence linking intensive chemical fertilizer use in maize to measured nutrient deterioration in receiving waters within the Colombian Caribbean is limited. Most sources assess water quality under multiple interacting pressures, including urban discharges, diffuse runoff, and hydrological alterations, rather than isolating maize fertilization as a single causal driver. Nonetheless, the assembled evidence consistently frames nitrogen and phosphorus enrichment as a relevant environmental concern and supports a plausible

pathway through which agricultural intensification may contribute to eutrophication risk in vulnerable tropical coastal and fluvial systems.

Within Bolivar, the strongest evidence base relates to the Cartagena Bay-Canal del Dique system and coastal water bodies influenced by continental discharges. The Canal del Dique is repeatedly framed as a major pathway connecting upstream basin activities with downstream ecological conditions in Cartagena Bay and adjacent environments. The national environmental diagnosis emphasizes that pressures are not attributable to a single source type and may include land-based runoff alongside urban contributions (ANLA, 2021).

At the local scale, the Ciénaga de la Virgen emerges as a key receptor system for water-quality pressures. A multivariate assessment of the lagoon system documents strong spatial-temporal variability consistent with substantial external forcing and sensitivity to anthropogenic inputs (Baldiris-Navarro et al., 2025). The district-level environmental status report for Cartagena also describes sustained pressure on aquatic ecosystems and treats nutrient and organic matter accumulation as a critical risk for ecological integrity and ecosystem services, while recognizing multi-scale drivers (EPA Cartagena, 2022). Together, the Bolivar-focused sources support two defensible conclusions: (i) Cartagena's lagoon and coastal systems are environmentally vulnerable to nutrient inputs transported through land-based pathways, and (ii) available sources do not enable crop-specific attribution, but they justify treating agricultural nutrient management, including fertilization practices in surrounding rural and peri-urban landscapes, as a plausible component of regional pressure pathways (ANLA, 2021; Baldiris-Navarro et al., 2025; EPA Cartagena, 2022).

Beyond Bolivar, quantifiable evidence from the Cesar River reports nitrate and phosphate concentrations and applies a Nutrient Pollution Index (NPI) to interpret nutrient stress in relation to basin land-use patterns where agriculture is prominent (Ospino-Jimenez et al., 2025). Although maize is not isolated as a sole contributor, this study provides direct measurement-based support that nutrient pollution can reach levels of concern in Caribbean inland waters and may affect downstream users and ecosystems.

At the coastal scale, Caribbean-wide monitoring through REDCAM provides a regional diagnostic layer. These reports emphasize the vulnerability of coastal waters influenced by continental discharges, positioning nutrient enrichment within a broader set of land-based pressures affecting nearshore environmental quality (INVEMAR, 2013, 2019). As a result, nutrient-related stress in Bolivar is best interpreted as part of a wider regional pattern shaped by upstream connectivity and cumulative pressures.

Across the mapped evidence, nutrient enrichment is consistently positioned as a risk factor for eutrophication, particularly in semi-enclosed, low-flushing systems such as cienagas and bays. Under tropical conditions, nutrient loading can facilitate excessive primary production and downstream hypoxia risks, with potential impacts on biodiversity and ecosystem services (Baldiris-Navarro et al., 2025; EPA Cartagena, 2022; INVEMAR, 2013, 2019). From a scoping standpoint, the critical implication is methodological as much as ecological: the regional evidence base is stronger for documenting nutrient-related vulnerability than for attributing that vulnerability to maize fertilization specifically, highlighting a need for site-specific studies coupling fertilizer management data with hydrological transport processes and standardized water-quality endpoints.

**Table 1. Evidence map of nutrient-related water quality studies in the Colombian Caribbean with emphasis on Bolivar (2010-2025).**

ID	Source	Location and system	Indicators	Key finding	Use in review
W1	Baldiris-Navarro et al. (2025)	Bolivar, Cartagena; Ciénaga de la Virgen lagoon	Multivariate water-quality indicators	Documents strong spatial and temporal variability linked to anthropogenic pressure	Core Bolivar water-evidence source
W2	INVEMAR REDCAM (2019)	Colombian Caribbean coast; marine and coastal network	Coastal water monitoring including nutrient-related variables	Identifies vulnerability of coastal waters to continental discharges and land-based pressures	Regional receptor-vulnerability evidence
W3	INVEMAR REDCAM (2013)	Colombian Caribbean coast; marine and coastal network	Coastal water-quality monitoring	Provides regional baseline for coastal environmental pressures	Regional baseline source
W4	EPA Cartagena (2022)	Bolivar, Cartagena; urban water bodies	Environmental indicators associated with ecosystem pressure	Reports strong pressure on aquatic ecosystems and nutrient/organic matter accumulation risks	Local diagnostic support
W5	ANLA (2021)	Bolivar; Cartagena Bay and Canal del Dique	Hydrological and environmental diagnostic indicators	Identifies the Canal del Dique as a major pathway transporting continental loads	Pathway and connectivity evidence
W6	Ospino-Jimenez et al. (2025)	Cesar River basin	Nitrate, phosphate, Nutrient Pollution Index	Measures nutrient contamination and links it to agricultural land use	Direct measurement-based comparison

W7	Scoping synthesis profile	Bolivar and the Colombian Caribbean	Integrated evidence profile	Regional evidence is stronger for documenting nutrient vulnerability than crop-specific maize attribution	Synthesis-level interpretation
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*Note.* Evidence strength and crop attribution were interpreted in the main text. The Caribbean sources mainly document environmental vulnerability and nutrient-related pressure, not crop-specific attribution to maize.

**Table 2A. Core tropical/subtropical maize evidence on soil and nutrient-loss processes (2010-2025).**

ID	Study and location	Indicators	Key finding
A1	Jankowski et al. (2018), Brazil, Amazon intensification	Deep-profile nitrate accumulation; N <sub>2</sub> O; yield response	Higher N rates increased environmental risk signals, including nitrate accumulation at depth, with limited yield gains beyond moderate rates
A2	Martins et al. (2015), Brazil, Cerrado	N <sub>2</sub> O emissions; NH <sub>3</sub> volatilization	Nitrogen fertilization generated measurable gaseous N losses in tropical no-till maize
A3	Zheng et al. (2019), Tanzania, tropical highlands	NO <sub>3</sub> - leaching from the critical root zone	Higher fertilizer-N rates increased nitrate leaching risk from the maize root zone
A4	Crusciol et al. (2020), Brazil, tropical intercropping	System response to N management	N management and system diversification altered agronomic and ecological performance in tropical maize systems
A5	Aquino et al. (2025), tropical soils	Rhizosphere microbial community shifts under N and P sources	Fertilizer N and P sources changed maize-associated microbial communities in tropical soils
A6	Adekiya et al. (2020), Nigeria, tropical field experiment	Soil chemical properties under urea and manure management	Split urea and organic integration modified soil chemical properties and maize performance under tropical conditions

*Note.* Table 2A contains the mechanistic core used to interpret nutrient mobility, soil chemical change, gaseous N losses, and soil biological sensitivity in tropical/subtropical maize systems.

**Table 2B. Supporting mechanistic evidence from non-tropical or rotational maize-based systems (2010-2025).**

ID	Study/system	Indicators	Why included
B1	Halvorson et al. (2010), irrigated no-till maize	N <sub>2</sub> O emissions	Supports fertilizer-source effects on gaseous N losses
B2	Allende-Montalban et al. (2022), maize-wheat irrigated systems	NO <sub>3</sub> - leaching; mitigation options	Supports mitigation tools for nitrate leaching
B3	Qaswar et al. (2020), wheat-maize acidic soils	Soil pH; P use efficiency	Supports long-term acidification and liming effects
B4	He et al. (2018), wheat-maize long-term sites	Soil organic carbon quantity and composition	Supports long-term soil chemical change under fertilization
B5	Kaur et al. (2019), maize-wheat long-term system	Microbial biomass carbon and carbon mineralization	Supports long-term soil biological change under sustained fertilization

*Note.* Table 2B was retained to support specific mechanisms, such as gaseous N losses, nitrate leaching mitigation, acidification, and long-term soil biological change, but these sources were interpreted as supporting evidence rather than local Caribbean evidence.

#### 4. DISCUSSION

This scoping review revealed a mismatch between the strength of mechanistic evidence and the specificity of local attribution. On the one hand, water-focused sources from Bolivar and the wider Caribbean consistently describe systems that are vulnerable to nutrient enrichment and document nitrate and phosphate as relevant variables in receiving waters, particularly in semi-enclosed lagoons and coastal environments connected to continental discharge pathways (ANLA, 2021; Baldiris-Navarro et al., 2025; EPA Cartagena, 2022; INVEMAR, 2013, 2019; Ospino-Jimenez et al., 2025). On the other hand, the soil-focused maize literature, while robust in comparable tropical and subtropical settings, rarely originates from the Colombian Caribbean itself, limiting the ability to quantify region-specific magnitudes of fertilizer-driven nutrient export.

This structure is typical in geographically localized scoping reviews: regional monitoring documents identify outcomes, nutrient pressure and ecological vulnerability, while agronomic studies in comparable environments clarify mechanisms, such as how fertilizer regimes generate nitrate mobility and gaseous losses (Martins et al., 2015; Zheng et al., 2019; Jankowski et al., 2018). The review therefore supports a defensible triangulation: (i) receiving waters in Bolivar and the Caribbean show conditions consistent with nutrient sensitivity and enrichment risk; (ii) intensive maize fertilization in tropical/subtropical systems can generate nitrate movement beyond the root zone and gaseous losses; and (iii) the missing link is site-specific coupling of fertilization regimes with hydrological transport and standardized water endpoints in the Colombian Caribbean.

Multiple sources converge on the idea that Caribbean coastal waters and lagoons influenced by continental discharges are high-risk receptors for nutrient enrichment. The Canal del Dique is framed as a key pathway connecting upstream basins to Cartagena Bay and adjacent coastal environments, implying that land-based nutrient sources may propagate through hydrological connectivity (ANLA, 2021). At the local level, the Ciénaga de la Virgen displays water-quality variability consistent with strong external forcing and anthropogenic pressure (Baldiris-Navarro et al., 2025). At the regional level, REDCAM repeatedly emphasizes vulnerability associated with continental discharges and cumulative land-based pressures (INVEMAR, 2013, 2019). Inland river evidence from the Cesar basin confirms that nitrate and phosphate contamination can be substantial where agriculture is a dominant land use (Ospino-Jimenez et al., 2025).

Mechanistic evidence from tropical/subtropical maize systems strengthens the plausibility of fertilizer-driven nutrient export pathways relevant to the Colombian Caribbean. Studies from tropical settings show that higher N inputs can generate environmental trade-offs, including nitrate accumulation at depth (Jankowski et al., 2018) and increased nitrate leaching from the maize root zone under higher fertilizer-N rates (Zheng et al., 2019). In the Brazilian Cerrado, N fertilization in no-till maize is associated with measurable N<sub>2</sub>O and NH<sub>3</sub> emissions, demonstrating substantial nitrogen losses under tropical climatic conditions (Martins et al., 2015). Together, these results imply that when fertilization exceeds crop uptake or is poorly synchronized with crop demand, nitrogen becomes more mobile and more likely to be lost through leaching and gaseous pathways, conditions that increase the likelihood of off-site impacts if hydrological connectivity exists.

Supporting evidence from non-tropical maize systems indicates that fertilizer form and management can meaningfully influence losses (Halvorson et al., 2010; Allende-Montalban et al., 2022). These studies are not directly transferable to Caribbean soils without caution, but they reinforce key management principles: nitrogen source, placement, and inhibitors can alter emission and leaching outcomes. For phosphorus and longer-term soil chemical sustainability, evidence from long-term maize-based systems indicates that fertilization can drive soil pH trajectories in acidic soils and that liming can mitigate acidification and improve nutrient-use outcomes (Qaswar et al., 2020). Fertilization may also modify soil organic carbon

stocks and composition, suggesting structural changes in soil functioning over time (He et al., 2018). In tropical maize field conditions, fertilizer management strategies can significantly modify soil chemical properties alongside performance outcomes, which is relevant for designing fertilization programs that reduce excess conditions (Adekiya et al., 2020).

Evidence also indicates that soil biological communities in maize systems can be sensitive to fertilizer regimes. Tropical rhizosphere evidence suggests that nitrogen and phosphorus fertilizers can shift microbial community structure and function in maize-associated soils (Aquino et al., 2025). System diversification, such as maize intercropped with tropical grasses under N fertilization, may provide pathways for improved system resilience and nutrient cycling compared with simplified systems (Crusciol et al., 2020). Long-term evidence from maize-based rotations indicates that sustained fertilization can affect microbial biomass carbon and soil carbon mineralization dynamics (Kaur et al., 2019), supporting the broader interpretation that intensive nutrient regimes may reconfigure soil biological capacity over time.

The scarcity of maize-specific fertilizer-water linkage studies in Bolivar and the Colombian Caribbean likely reflects a combination of monitoring designs focused on diagnosing water quality rather than attributing sources, agronomic research priorities emphasizing yield over coupled land-water outcomes, and fragmented data infrastructure for linking farm-level fertilizer management to watershed nutrient dynamics. This gap is visible in the Caribbean corpus: monitoring and environmental diagnostics identify vulnerability and nutrient variables, but source apportionment and crop-specific attribution are limited.

From an environmental management perspective, the evidence supports prioritizing interventions that reduce excess fertilizer conditions and limit off-site transport. Mechanistic evidence suggests that improved nitrogen management can reduce leaching and gaseous losses (Zheng et al., 2019; Martins et al., 2015; Halvorson et al., 2010; Allende-Montalban et al., 2022). For soil sustainability, mitigation of acidification may be relevant where long-term fertilization dominates (Qaswar et al., 2020). From a biological perspective, practices that maintain or enhance soil microbial functioning, potentially through diversification or integrated soil fertility approaches, may support

resilience and nutrient cycling capacity (Aquino et al., 2025; Crusciol et al., 2020; Kaur et al., 2019).

The most urgent research need is for paired, site-specific studies in Bolivar and neighboring Caribbean departments that integrate: (1) fertilizer management characterization in maize (type, rate, timing, placement), (2) soil indicators (pH trajectory, mineral N at depth, microbial indicators), and (3) hydrological transport and water-quality endpoints (nitrate, phosphate, and eutrophication proxies) in connected receiving waters. Such coupling would close the key attribution gap identified in this scoping review, transforming plausible pathways into quantified local evidence and actionable nutrient-management guidance.

## 5. CONCLUSIONS

This scoping review mapped evidence published between 2010 and 2025 on (i) nutrient enrichment pressures affecting aquatic ecosystems in the Colombian Caribbean, prioritizing Bolivar, and (ii) soil and mechanistic pathways linking intensive chemical fertilization in maize to off-site environmental risks. The mapped Caribbean evidence consistently indicates that key receiving systems, including coastal lagoons, bays, and river-connected coastal waters, are environmentally vulnerable to nutrient enrichment under cumulative land-based pressures, particularly where hydrological connectivity concentrates continental

discharges (ANLA, 2021; INVEMAR, 2013, 2019; EPA Cartagena, 2022). However, direct peer-reviewed evidence that isolates maize-specific fertilizer use as the dominant driver of nutrient deterioration in Bolivar and the wider Caribbean remains sparse.

In contrast, mechanistic evidence from tropical and subtropical maize systems supports coherent pathways through which intensive or poorly synchronized N and P inputs can increase nitrate mobility beyond the root zone, raise gaseous nitrogen losses, alter soil chemical baselines, and shift soil biological communities (Jankowski et al., 2018; Martins et al., 2015; Zheng et al., 2019; Aquino et al., 2025). Taken together, the evidence supports a defensible land-water systems interpretation: nutrient-sensitive Caribbean receiving waters are exposed to risks that can be exacerbated under high-input agriculture, yet the key research gap is site-specific coupling of maize fertilization regimes with transport processes and standardized water-quality endpoints in Bolivar and neighboring departments.

Future work should prioritize paired field monitoring that integrates farm-level fertilizer management, soil indicators, and watershed or coastal water-quality endpoints. Such integrated studies would move the evidence base from plausible mechanistic inference to quantified, region-specific attribution and actionable nutrient-management guidance for the Colombian Caribbean.

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