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Review

Nano-Enabled Precision Fertilization: A Critical Scoping Review and Research Roadmap for Operational Convergence

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Highlights

- An S–N–O framework maps spatial decisions, nano-enabled deployment, and outcomes.
- Conceptual convergence dominated the evidence base.
- Two studies reached partial S-N or S-O convergence; none demonstrated S-N-O.
- Secondary claims sometimes exceeded the maturity of the supporting primary evidence.
- Field-scale closed-loop studies are needed to validate operational double precision.

Abstract

Nano-enabled fertilizers and precision agriculture are increasingly framed as complementary strategies to enhance nutrient-use efficiency and reduce environmental footprints. However, their operational integration remains unclear because precision denotes either spatial field management or targeted nano-enabled release. This scoping review evaluated whether nanofertilizers have been operationally integrated into spatially explicit nutrient-management systems. Systematic searches in Scopus and Web of Science, complemented by citation tracing, identified 60 reports representing 59 unique evidence units. An operational framework disaggregated integration into spatial decision-making (S), differential nano-enabled deployment (N), and spatially resolved outcome validation (O), with validation maturity coded from V0 to V6. Of the 59 evidence units, 52 (88.1%) represented conceptual convergence, five (8.5%) technological proximity without operational coupling, and only two (3.4%) advanced partial integration. The review did not identify a fully assessed study that demonstrated the complete S–N–O sequence. The two most advanced cases followed complementary pathways: S-N without spatial outcome validation, and S-O

Check for updates

Academic Editor: Cristina Abbate

Received: 16 September 2026
Revised: 14 October 2026
Accepted: 23 October 2026
Published: 1 November 2026

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with uniform nano-input application. Citation tracing also revealed that secondary claims often overstate operational maturity relative to primary evidence. Closing this gap requires establishing field-scale S–N–O workflows that explicitly link spatial diagnosis, differential nano-actuation, and multi-zone agronomic and environmental validation.

Keywords: site-specific nutrient management; nano-enabled delivery; variable-rate fertilization; spatial decision support; nutrient-use efficiency; evidence mapping; technology readiness

1. Introduction

Efficient nutrient management remains a central challenge for sustainable crop production because fertilizer requirements are rarely uniform within agricultural fields. Soil properties, nutrient availability, crop growth, water status, and yield potential can vary substantially over space and time, while conventional management frequently applies fertilizers at uniform rates. Precision agriculture addresses this heterogeneity by combining sensing, positioning, information systems, and application technologies to adjust management according to field variability [1,2]. In nutrient management, this principle is implemented through approaches such as soil and crop sensing, management-zone delineation, prescription mapping, and variable-rate fertilization, in which fertilizer application can be modified according to spatially resolved information [3,4].

In parallel, agricultural nanotechnology has developed nutrient-delivery systems intended to improve the efficiency and functionality of fertilizers. Nano-enabled fertilizers have been investigated for their ability to modify nutrient release, availability, uptake, transport, and interaction with the soil–plant system. Their proposed advantages include controlled or sustained release, improved nutrient-use efficiency, reduced nutrient losses, and more effective delivery of macro- and micronutrients [5–7]. Nanomaterial properties can also be engineered to influence nutrient release and biological interactions, creating opportunities for delivery systems whose behavior differs substantially from that of conventional fertilizer formulations [8]. At the same time, these potential benefits must be considered together with questions regarding dose, transformation, environmental fate, non-target effects, and realistic field performance [5,9].

The growing sophistication of both technological domains has stimulated increasing interest in their convergence. Nanotechnology and artificial intelligence have been proposed as complementary tools for sustainable and precision agriculture, with sensing, crop modeling, digital decision support, and nano-enabled delivery potentially operating within increasingly integrated management architectures [10]. Zain et al. [11] similarly positioned nanofertilizers, nanosensors, GIS, GPS, and remote sensing within a broader precision-agriculture framework. More recent perspectives extend this concept toward AI-assisted nano-enabled systems and potentially autonomous or closed-loop nutrient management [12,13]. Meanwhile, advances in nano-enabled precision delivery increasingly emphasize control over transport, release, uptake, and biological targeting rather than fertilizer composition alone [9].

However, this apparent convergence is complicated by a fundamental ambiguity in the meaning of precision. Within precision agriculture, precision commonly refers to management of spatial or temporal variability using information that differentiates interventions among locations. Variable-rate systems, for example, translate soil or crop information into changes in fertilizer rate or placement across a field [2,4]. Within nanotechnology, precision may instead describe controlled release, stimulus responsiveness, enhanced transport, or targeting of active compounds toward specific plant tissues or physiological compartments [9].

These forms of precision are complementary, but they operate at different scales and should not be treated as equivalent.

This distinction has important implications for how nano-enabled precision fertilization is defined. A nanofertilizer with sophisticated controlled-release behavior may achieve high functional precision while still being applied uniformly across an entire field. Conversely, a variable-rate fertilizer prescription may achieve high spatial precision while using a conventional fertilizer. Likewise, the inclusion of a UAV, sensor, artificial-intelligence algorithm, or digital model does not by itself demonstrate that spatial information has altered nano-enabled fertilizer deployment. UAV remote sensing, for example, can characterize crop nutrient status at high spatial resolution, whereas variable-rate application requires an additional decision and actuation step linking that information to differentiated fertilizer management [2,3].

The emerging field can therefore be interpreted in terms of double precision. The first dimension, spatial precision, determines where nutrient management should differ according to variation in soil or crop conditions. The second, functional precision, determines how the nutrient-delivery system behaves through characteristics such as controlled release, enhanced uptake, transport, responsiveness, or biological targeting. Nanofertilizer research has extensively developed the latter dimension [6,7], whereas precision-agriculture research has established increasingly sophisticated approaches for spatial diagnosis and variable-rate nutrient management [1,4]. Full nano-enabled precision fertilization would require these dimensions to become operationally connected rather than merely coexist within the same technological landscape.

In this review, functional precision is used as a conceptual descriptor of the capacity of nano-enabled fertilizers to modify nutrient release, protection, availability, uptake, transport, responsiveness, or biological targeting. It is not treated as a separate quantitative performance score because these functions are reported using highly heterogeneous materials, characterization methods, crops, application routes, and experimental conditions. The systematic evidence map instead examines whether nano-enabled nutrient delivery, as reported and defined in the original studies, has been operationally connected to spatially explicit nutrient-management decisions. Accordingly, the S–N–O framework evaluates operational coupling with spatial precision rather than comparatively ranking the degree of functional precision achieved by individual nano-enabled formulations.

What remains insufficiently resolved is how far this operational connection has actually progressed in the published literature. Reviews and perspectives increasingly describe nanofertilizers together with sensing technologies, artificial intelligence, UAVs, digital agriculture, and precision-management systems [10,11]. Nevertheless, conceptual compatibility between technologies does not establish that spatial diagnosis has been used to control differentiated nano-enabled fertilizer application, nor that such differentiated deployment has subsequently been validated through spatially resolved agronomic, environmental, or economic outcomes. The recent literature itself continues to identify field translation, large-scale validation, system integration, and environmental assessment as important challenges for nano-enabled agricultural technologies [9,12,13].

This distinction is also relevant for technology-readiness assessment. A field-tested nanofertilizer may have substantial agronomic validation while remaining spatially uniform, whereas a digital prototype may demonstrate targeted nano-enabled actuation without establishing crop-level or environmental benefits under field conditions. Consequently, operational integration and validation maturity represent different dimensions and should be evaluated separately. Treating fixed-rate drone spraying, post-treatment UAV monitoring, conceptual AI–nano architectures, and genuinely site-specific nano-enabled nutrient

management as equivalent forms of precision would obscure the specific interfaces that remain unresolved.

Accordingly, the present study conducted a critical scoping review with systematic evidence mapping focused specifically on the intersection between nano-enabled fertilizer delivery and spatially explicit or site-specific nutrient management. Rather than reviewing the complete nanofertilizer and precision-agriculture literatures independently, the analysis evaluates whether their convergence has progressed from conceptual association toward operational implementation. Three components were examined: S, an explicit spatial decision layer; N, differential nano-enabled fertilizer deployment governed by that decision; and O, spatially resolved outcome validation. Integration level was evaluated independently from experimental validation maturity. The primary research question was: to what extent, and in what forms, have nano-enabled fertilizers been operationally integrated into spatially explicit or site-specific nutrient-management systems?

More specifically, the review examined (i) which empirical studies link spatial nutrient-management decisions to nano-enabled fertilizer deployment; (ii) which S–N–O components have been directly demonstrated within the same system; (iii) how far the available evidence has progressed from conceptual development to field and operational validation; and (iv) which missing interfaces currently prevent complete operational convergence.

2. Materials and Methods

2.1. Review Design and Scope

This study was conducted as a critical scoping review with systematic evidence mapping, following methodological guidance for scoping reviews developed by the Joanna Briggs Institute (JBI) [14]. Reporting was informed by the PRISMA extension for scoping reviews (PRISMA-ScR) [15] and the PRISMA 2020 framework for transparent reporting of study identification and selection [16]. This design was selected because the literature at the intersection of nanotechnology and precision nutrient management is heterogeneous, encompassing conceptual reviews, technological frameworks, controlled experiments, field studies, and prototype-level systems rather than a homogeneous set of interventions suitable for meta-analysis. The purpose of this review was therefore not to estimate the comparative agronomic effectiveness of integrated systems or to determine whether nano-enabled precision fertilization is ready for routine implementation. Rather, consistent with the purposes of scoping reviews and systematic evidence mapping, the analysis was designed to characterize the types and maturity of available evidence, clarify the operational meaning of convergence, identify where the S–N–O sequence remains incomplete, and define research priorities for an emerging interdisciplinary field. The scarcity of empirical studies was treated as a finding regarding the current maturity of the evidence base, while the conclusions were restricted to questions of evidence distribution, operational coupling, and validation status.

The review focused specifically on the operational convergence between nano-enabled fertilizer delivery and spatially explicit or site-specific nutrient management. Accordingly, it was not intended to exhaustively review either the complete nanofertilizer literature or the broader precision-fertilization literature independently. Instead, these two established research domains were treated as the technological foundations from which evidence of convergence was identified and evaluated. Foundational Type I nanofertilizer studies were therefore used to establish the material and agronomic context, but they were not automatically eligible for the convergence evidence map unless they also contained an explicit spatial, site-specific, sensing, decision-support, or differential-application component. This boundary was necessary to prevent the much larger standalone nanofertilizer literature from

obscuring the review question, which concerns operational coupling between nano-enabled nutrient delivery and spatial nutrient management.

For eligibility purposes, a fertilizer was classified as nano-enabled when the original report described the nutrient itself as nanoscale or indicated that the nutrient was incorporated into a nano-enabled carrier, coating, composite, or delivery system. This classification identified the nano-enabled component reported by the original authors and did not constitute independent verification of particle size, formulation quality, controlled-release performance, or commercial product claims.

The review further examined which components required for operational convergence were present or absent in the available evidence, and the level of experimental or field validation achieved by the identified systems. This distinction allowed conceptual convergence, technological proximity, and operational integration to be evaluated separately rather than treating all studies using terms such as *precision, smart, targeted, or nano-enabled* as equivalent evidence of integration.

2.2. Search Strategy and Study Selection

A systematic literature search was conducted in Scopus and the Web of Science Core Collection (WoSCC). Scopus was searched on 19 August 2026, and WoSCC on 25 August 2026. No restrictions were applied regarding publication year, geographical region, subject category, document type, or open-access status. Search procedures were documented in accordance with PRISMA-S recommendations to facilitate transparency and reproducibility [17]. Scopus and WoSCC were selected as the primary information sources because they provide broad multidisciplinary coverage spanning agricultural science, nanotechnology, materials science, environmental science, and engineering, while supporting reproducible field-based search strings, structured export, and transparent deduplication. ScienceDirect was not treated as a separate bibliographic database because it is a publisher-specific full-text platform, and Google Scholar was not used as a primary systematic-search source because its dynamic ranking, limited query control, and restricted export reduce search reproducibility. To mitigate dependence on database indexing and terminology alone, the database searches were complemented by structured backward and forward citation searching, as described in Section 2.4 [14–17]. Nevertheless, the search should not be interpreted as exhaustive across all agricultural information sources.

Two complementary search strategies were developed. Search 1 (S1) targeted explicit convergence between nano-enabled fertilizers and precision or site-specific nutrient management, including terms related to variable-rate fertilization, management zones, prescription mapping, and spatially differentiated nutrient application. Search 2 (S2) served as an operational–geospatial supplementary strategy and incorporated terms related to GIS, georeferencing, remote sensing, UAVs/drones, soil mapping, real-time sensing, and sensor-based or variable-rate application. This complementary strategy was used because potentially relevant studies may describe spatial or operational components of precision nutrient management without explicitly using the term precision agriculture. Complete database-specific search strings, search dates, retrieval counts, and within-database overlaps are provided in Supplementary Data S1, Table S1.

Records retrieved through both search strategies were combined into a master screening dataset. Within- and cross-database duplicates were removed primarily by DOI matching, complemented by normalized title matching when DOI information was unavailable or inconsistent. Title and abstract screening were subsequently conducted using predefined eligibility criteria. Records with insufficient information to determine eligibility were retained for full-text assessment to minimize premature exclusion.

Reports were eligible when they explicitly addressed nano-enabled fertilizers or nano-enabled nutrient-delivery systems in relation to spatially explicit, site-specific, sensor-guided, georeferenced, variable-rate, or digitally supported nutrient management. Conceptual and secondary publications were eligible when they explicitly proposed or evaluated convergence between these domains. Empirical studies were eligible when they combined a nano-enabled fertilizer component with at least one spatial, sensing, decision-support, modeling, UAV, or differential-application component relevant to nutrient management. Reports were excluded when nanofertilizers and precision-management approaches were discussed only as unrelated topics, when the nano-enabled component was not associated with nutrient delivery, or when no substantive relationship with spatial or site-specific nutrient management could be established.

Reports for which a full text could not be obtained were recorded as "not retrieved" rather than excluded on substantive eligibility grounds. These reports were not assigned an integration type or validation level because the presence of the S, N, and O components could not be verified reliably from titles and abstracts alone. Consequently, statements concerning the absence of Type IV evidence refer specifically to the included and fully assessed corpus and should not be interpreted as proof that no qualifying study exists outside that corpus. Full-text exclusions were based on the presence of separate precision-management and nanofertilizer treatment arms without operational coupling, conceptual co-mention without an operational relationship, or the absence of an eligible nano-enabled fertilizer component. The complete numerical results of identification, deduplication, screening, retrieval, and eligibility assessment are presented in Section 3.1 and summarized in the PRISMA flow diagram (Figure 1), following the PRISMA 2020 reporting framework [16].

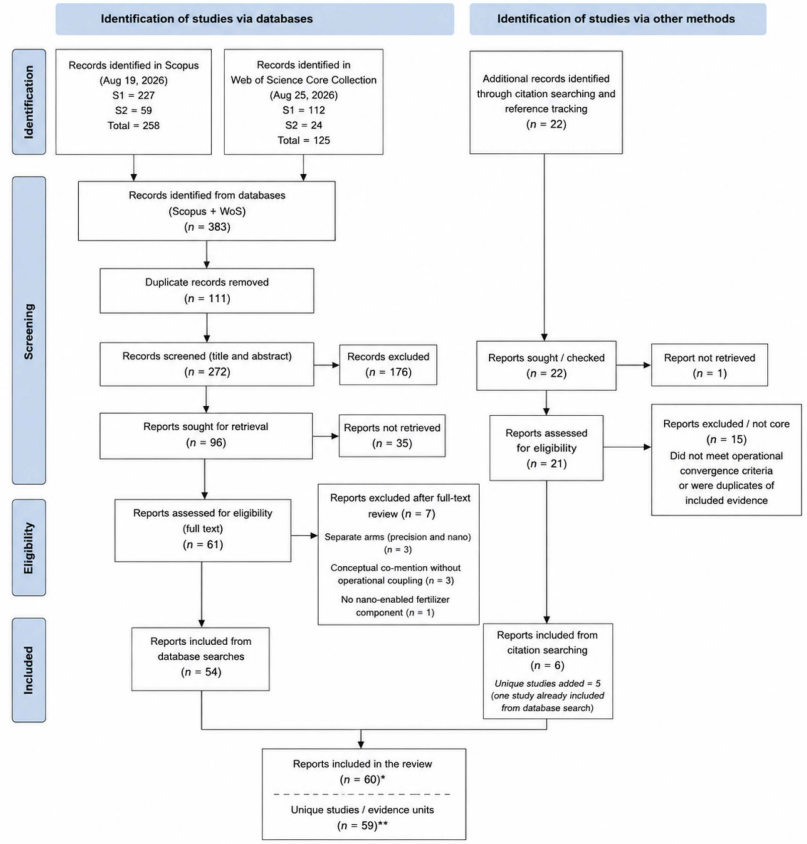


Figure 1. PRISMA 2020 flow diagram of study identification, screening, eligibility assessment, and inclusion. S1, core convergence search; S2, supplementary operational–geospatial search; WoSCC,

Web of Science Core Collection. Sixty included reports corresponded to 59 unique studies/evidence units because two companion publications originated from the same experimental system. * n = 60; ** n = 59.

2.3. Operational Convergence Framework and Evidence Classification

A central methodological challenge in this review was distinguishing spatial precision in nutrient management from the broader use of precision to describe controlled, targeted, or responsive nano-enabled delivery. The literature increasingly links nanotechnology with precision agriculture and digital decision support [10], while nano-enabled precision delivery may also refer to targeting nutrients or active compounds to specific tissues, cells, or physiological compartments within plants [9]. To prevent these different meanings from being treated as equivalent evidence of operational integration, an S–N–O convergence framework was developed for the present review (Figure 2).

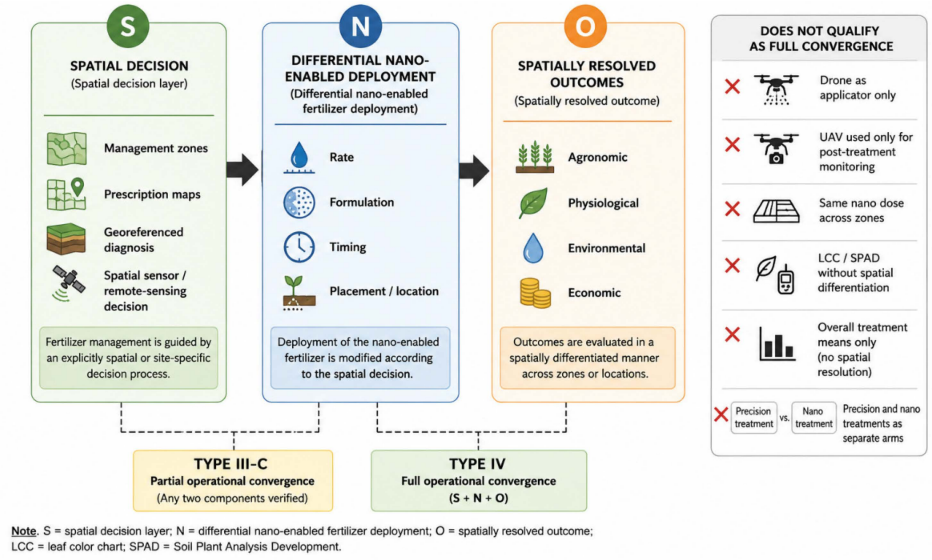


Figure 2. S–N–O operational convergence framework for nano-enabled precision fertilization.

The S–N–O framework was designed to assess operational integration, not to score the intrinsic functional performance of nano-enabled fertilizer formulations. Thus, the presence of a nano-enabled fertilizer component did not by itself demonstrate spatial precision, while the S–N–O classification did not establish that one nanoformulation provided superior controlled release, responsiveness, uptake, or biological targeting relative to another. Functional nano-enabled delivery and spatial nutrient management were treated as the two parent domains, whereas S–N–O was used to determine whether and how those domains became connected within the same management workflow.

The framework evaluates three sequential components: S, spatial decision layer; N, differential nano-enabled fertilizer deployment; and O, spatially resolved outcome. S was considered present when nutrient management was guided by an explicitly spatial or site-specific decision, including management zones, prescription maps, georeferenced soil or crop diagnosis, spatial remote-sensing information, or sensor-derived information used to differentiate management among locations. The presence of a drone, UAV, sensor, or GIS component alone was insufficient when the technology served only for application, monitoring, or post-treatment assessment.

N was considered present when the spatial decision directly modified deployment of the nano-enabled fertilizer. Differentiation could involve fertilizer rate, formulation, timing, placement, or application location. Thus, a fixed nanofertilizer treatment applied uniformly

across management zones did not satisfy N, even when a spatial decision layer was present elsewhere in the study.

O was considered present when agronomic, physiological, environmental, nutrient-use, or economic outcomes retained explicit spatial differentiation among management zones, locations, or other spatial management units. Overall treatment means without spatial resolution were considered insufficient to close the operational loop.

Within this framework, S → N represents operational coupling because the spatial decision directly governs nano-enabled deployment, whereas O provides outcome-based closure by linking the consequences of that deployment to the spatial management unit. Type IV therefore represents fully validated operational convergence rather than technological actuation alone. Accordingly, full operational convergence (Type IV) required simultaneous verification of all three components: Type IV = S + N + O.

This definition deliberately distinguishes operational integration from technological co-occurrence. For example, drone-based application of a fixed nanofertilizer rate, UAV monitoring following uniform nanofertilizer application, crop-status-triggered application without spatial differentiation, or experiments comparing precision-nutrient-management and nanofertilizer treatments as independent arms were not considered evidence of full convergence.

Evidence was subsequently organized according to the classification framework shown in Table 1. Type I represents the functional nano-enabled nutrient-delivery domain without spatially explicit nutrient management, whereas Type II represents spatially differentiated nutrient management using conventional or non-nano fertilizers. These categories define the two parent technological domains and provide the conceptual basis for evaluating their operational convergence. The Type I designation identifies the presence of a reported nano-enabled nutrient function but does not constitute a comparative rating of material performance or evidence quality. Direct evidence of convergence was classified as Type III-A (conceptual convergence), Type III-B (technological or empirical proximity without verified operational coupling), Type III-C (advanced partial operational convergence), or Type IV (full operational convergence). Type III-C required direct verification of two of the three S–N–O components, whereas Type IV required the complete S–N–O sequence within the same operational workflow.

Table 1. Evidence classification framework for nano-enabled precision fertilization.

Type	Definition	Operational Characteristics	Typical Evidence
I	Nano-enabled nutrient functionality	Nano-enabled nutrient innovation involving modified release, availability, uptake, transport, protection, responsiveness, or targeting, without spatially explicit nutrient management	Controlled or responsive nutrient release, nutrient protection, modified availability or uptake, nano-enabled transport or targeting, and nanoformulations applied without spatially differentiated management
II	Spatial nutrient precision	Spatially differentiated nutrient management using conventional or non-nano inputs	Management zones, prescription maps, variable-rate fertilization
III-A	Conceptual convergence	Explicit conceptual linkage between nano-enabled fertilization and precision/site-specific agriculture	Reviews, perspectives, frameworks, roadmaps

Table 1. *Cont.*

Type	Definition	Operational Characteristics	Typical Evidence
III-B	Technological or empirical proximity	Nano-enabled fertilizer combined with sensing, UAVs, drones, models, or digital tools, but without verified spatial decision-controlled nano deployment	Fixed-rate drone spraying; UAV monitoring following nanofertilizer application
III-C	Advanced partial operational convergence	Two of the three S–N–O components are directly verified	S-N without O, or S-O without N
IV	Full operational convergence	Spatial decision controls differentiated nano-enabled deployment and spatially resolved outcomes are demonstrated	S + N + O

Integration level was evaluated independently from validation maturity, since the degree of technological integration and the scale at which a system has been experimentally validated represent distinct dimensions. Validation was coded from V0, representing conceptual evidence, to V6, representing operational or commercial-farm implementation. Detailed S–N–O coding rules, predefined boundary cases, and definitions of validation levels V0–V6 are provided in Supplementary Data S1, Table S2.

2.4. Data Extraction, Citation Searching, and Evidence Synthesis

For each eligible study, data were extracted into a structured evidence matrix containing bibliographic information, publication year, document type, study design, nano-enabled fertilizer characteristics, spatial or site-specific management component, S–N–O coding, integration type, validation level, discovery route, full-text status, and study-family membership. Reviewer notes were retained to document classification decisions and potentially ambiguous cases. The complete study-level evidence matrix is provided in Supplementary Data S1, Table S3. S–N–O coding, integration type, and validation maturity were initially assigned by one reviewer and independently verified by a second reviewer for all empirical evidence units considered potentially eligible for Type III-B, Type III-C, or Type IV classification.

Following full-text assessment of the database-derived corpus, backward and forward citation searching was used as a supplementary retrieval method. This step was considered particularly relevant because terminology at the intersection of nanofertilizers and precision agriculture was inconsistent, and potentially relevant operational studies could therefore be poorly captured by text-based database searches. Citation searching followed the terminology and general reporting principles of the TARCiS statement, which recommends backward and forward citation searching as complementary approaches when topics are difficult to retrieve using terminology alone [18]. Seed references comprised studies showing the closest empirical proximity to operational convergence, together with influential reviews and frameworks making explicit claims about site-specific, sensor-guided, AI-assisted, variable-rate, or targeted nano-enabled nutrient management.

Citation searching was progressively focused on combinations capable of satisfying the operational criteria defined in Section 2.3, including site-specific, management zone, prescription map, variable rate, targeted yield, sensor-based, GreenSeeker, LCC, UAV, and drone in association with nano-enabled fertilizers. The procedure identified 22 additional candidate reports outside the original database corpus. Twenty-one were assessed for eligibility, one could not be retrieved, and six eligible reports representing five unique studies/evidence units were incorporated through citation searching. These

records were maintained separately from the Scopus/WoSCC search arm and are reported under "other methods" in the PRISMA flow diagram, consistent with the PRISMA 2020 reporting structure [16]. A detailed audit of the citation-searching process is provided in Supplementary Data S1, Table S4.

When multiple publications originated from the same experimental system, they were grouped into a single study family to avoid double counting. Integration classifications and validation levels were assigned at the study/evidence-unit level rather than according to publication count. Full bibliographic details for all 60 included reports are provided in Supplementary Data S1, Supplementary References.

For secondary sources making strong claims regarding site-specific nano-delivery, AI-controlled fertilizer application, closed-loop management, or quantified reductions in fertilizer inputs, the cited evidence was additionally traced to its underlying source whenever possible. This claim-level traceability check was used to distinguish direct empirical support from statements propagated through reviews or conceptual papers. Cases in which the operational strength of a secondary claim exceeded that demonstrated by the cited primary evidence were retained as conceptual evidence but were not treated as proof of operational convergence. The corresponding citation-traceability audit is provided in Supplementary Data S1, Table S5.

Evidence synthesis was descriptive and mapping-based rather than statistical. No meta-analysis was performed because the included literature comprised heterogeneous evidence types, crops, nano-enabled nutrient systems, sensing technologies, decision architectures, spatial scales, and validation levels. The primary synthesis therefore examined the distribution of evidence across integration Types III-A to IV, the presence or absence of individual S–N–O components, and validation maturity from V0 to V6.

3. Results

3.1. Study Selection and Characteristics of the Evidence Base

The database searches identified 383 records, comprising 258 records from Scopus and 125 from the Web of Science Core Collection. After removal of 111 duplicates, 272 unique records underwent title and abstract screening. Of these, 176 were excluded and 96 reports were sought for full-text assessment. Thirty-five reports could not be retrieved, leaving 61 reports for full-text eligibility assessment. Seven reports were excluded following full-text examination, resulting in 54 reports included from the database-search arm. The complete selection process is presented in Figure 1.

Directed backward and forward citation searching subsequently identified 22 additional candidate reports that were not present in the original database corpus. Twenty-one were assessed, of which six reports representing five unique studies/evidence units satisfied the convergence eligibility criteria. After accounting for companion publications arising from the same experimental system, the final evidence base therefore comprised 60 reports corresponding to 59 unique studies or evidence units. The complete study-level dataset is provided in Supplementary Data S1, Table S3, while the citation-searching audit is reported in Supplementary Data S1, Table S4. Complete bibliographic details for all 60 included reports are provided in Supplementary Data S1, Supplementary References.

The evidence base was strongly dominated by conceptual convergence. Of the 59 unique included studies/evidence units, 52 (88.1%) were classified as Type III-A, reflecting reviews, perspectives, frameworks, or other studies that explicitly connected nanotechnology with precision or site-specific agriculture without demonstrating an operational S–N–O workflow. Only five studies (8.5%) were classified as Type III-B, indicating technological or empirical proximity to integration, and two studies (3.4%) reached Type III-C, representing advanced but incomplete operational convergence. No study within the in-

cluded and fully assessed evidence base fulfilled the complete Type IV criterion (S + N + O). These percentages describe the composition of the mapped evidence base and should not be interpreted as equivalent proportions of experimental evidence. Type III-A consisted predominantly of the conceptual or secondary literature, whereas the seven Type III-B and Type III-C evidence units represented the empirical or technological subset used to assess the current boundary of operational integration.

This distribution reveals a pronounced narrowing of the evidence base as increasingly stringent operational requirements are applied: 52 Type III-A → 5 Type III-B → 2 Type III-C → 0 Type IV. Thus, although convergence between nano-enabled fertilization and precision agriculture is well established at the conceptual level, empirically verified operational integration remains scarce. This distribution is summarized in Figure 3.

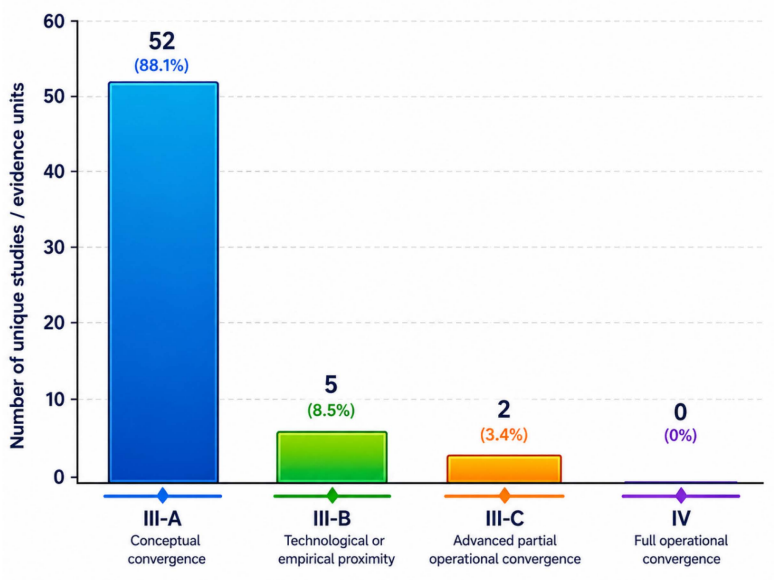


Figure 3. Distribution of included evidence across operational integration levels.

3.2. From Conceptual Convergence to Technological Proximity

The evidence map showed that convergence between nano-enabled fertilization and precision agriculture has developed predominantly at the conceptual rather than operational level. As shown in Section 3.1, the evidence base was dominated by Type III-A literature. These publications commonly described nanofertilizers, nanosensors, artificial intelligence (AI), remote sensing, Internet of Things (IoT) platforms, and precision-agriculture technologies as mutually reinforcing components of future nutrient-management systems, but did not demonstrate their integration within a complete spatially differentiated workflow.

Several influential reviews illustrate this pattern. Zhang et al. [10] proposed the convergence of nanotechnology and AI as an enabling pathway for sustainable precision agriculture, including the potential integration of crop and nutrient models with nanoinformatics. Similarly, Zain et al. [11] explicitly framed nanotechnology and precision agriculture as complementary approaches and discussed nanofertilizers, nanosensors, GIS, GPS, and remote sensing within the same technological landscape. However, the examples reviewed largely represented parallel developments in nano-enabled nutrient delivery and precision-agriculture sensing rather than field implementations in which a spatial prescription directly controlled differential nanofertilizer application.

The more recent literature extends this conceptual architecture toward AI-assisted and potentially closed-loop systems. Sun et al. [13], for example, proposed AI-assisted nanofertilizer customization based on soil characteristics and described a progressive pathway toward intelligent nutrient delivery, while Ma et al. [12] positioned nano-enabled precision

agriculture within a future closed-loop system incorporating sensors, intelligent algorithms, and advanced nano-inputs. In both cases, however, field-scale operational integration was identified as an outstanding translational challenge rather than as an already validated technology [12,13].

Only five studies (8.5%) progressed to Type III-B, where nano-enabled fertilization was empirically associated with technologies conventionally linked to precision agriculture, but the connection stopped short of a verified spatial decision-to-deployment workflow. These studies followed three recurring configurations: UAV-based crop monitoring following nanofertilizer treatments, drone-assisted application of fixed nanofertilizer rates, and digital or modeling tools used alongside rather than to control nano-enabled nutrient application.

Sinde-González et al. [19], for instance, combined nanofertilizer treatments in Lupinus mutabilis with field spectroscopy, active crop sensing, and UAV multispectral imagery. The study generated vegetation indices and demonstrated the capacity of remote sensing to characterize crop responses, but nanofertilizer application was not spatially modified according to UAV-derived information. The sensing component therefore functioned primarily as an outcome-monitoring layer rather than a prescriptive spatial decision layer.

A second Type III-B configuration involved drones as application platforms. Kumar et al. [20] evaluated nano-urea applied by a knapsack sprayer and drone in Indian mustard over two growing seasons, while Kashyap et al. [21] evaluated drone- and sprayer-assisted nano-NPK application in wheat. Both studies demonstrated agronomic benefits associated with nano-enabled nutrient treatments and showed the practical feasibility of UAV-based foliar application. However, the nano-input rates and application timings were predefined experimental treatments rather than outputs of a spatial diagnosis or prescription process [20,21].

The same distinction was evident in maize. Sahni et al. [22] compared drone and tractor-operated gun spraying of nano-urea and reported comparable NDVI, SPAD, and grain-yield responses, together with substantial operational advantages of the drone platform, including reduced water use. Nevertheless, both application systems delivered predetermined nano-urea treatments; no within-field spatial diagnosis modified the nanofertilizer rate or placement. Thus, the study demonstrated precision of application technology, but not spatially differentiated nano-enabled nutrient management as defined by the S–N–O framework.

A related pattern occurred when modeling and nano-enabled fertilization coexisted within the same agronomic system. Ashwini et al. [23] used DSSAT to evaluate rice yield and resource-use responses under conventional and alternate wetting and drying management, with drone-applied nano-urea forming part of the field-management system. Although the model incorporated detailed soil, meteorological, crop, and management information, the modeling output did not generate a spatial prescription governing differentiated nano-urea deployment. The study therefore remained technologically close to convergence without establishing the operational S → N link required for Type III-C or Type IV.

Taken together, the Type III-B evidence indicates that the principal technological building blocks of nano-enabled precision fertilization—nano-inputs, UAVs, crop sensors, spectral monitoring, modeling, and automated application platforms—have already been combined experimentally. However, in these studies, digital or spatial technologies primarily measured crop responses, improved application logistics, or supported broader management analysis, rather than directly controlling spatial differentiation of the nano-enabled fertilizer itself. The complete study-level classification underlying these findings is provided in Supplementary Data S1, Table S3.

3.3. Advanced Partial Operational Convergence: Two Complementary Type III-C Pathways

Only two of the 59 unique studies/evidence units (3.4%) reached Type III-C, indicating advanced but incomplete operational convergence. Importantly, these studies did not fail at the same stage of the S–N–O sequence. Instead, they represented two complementary pathways toward full integration: one demonstrated a spatial decision linked to targeted nano-enabled deployment but lacked spatially resolved outcome validation (S-N, O absent), whereas the other demonstrated site-specific nutrient prescription and differentiated field outcomes but retained uniform nano-enabled fertilizer application (S-O, N absent) (Figure 4).

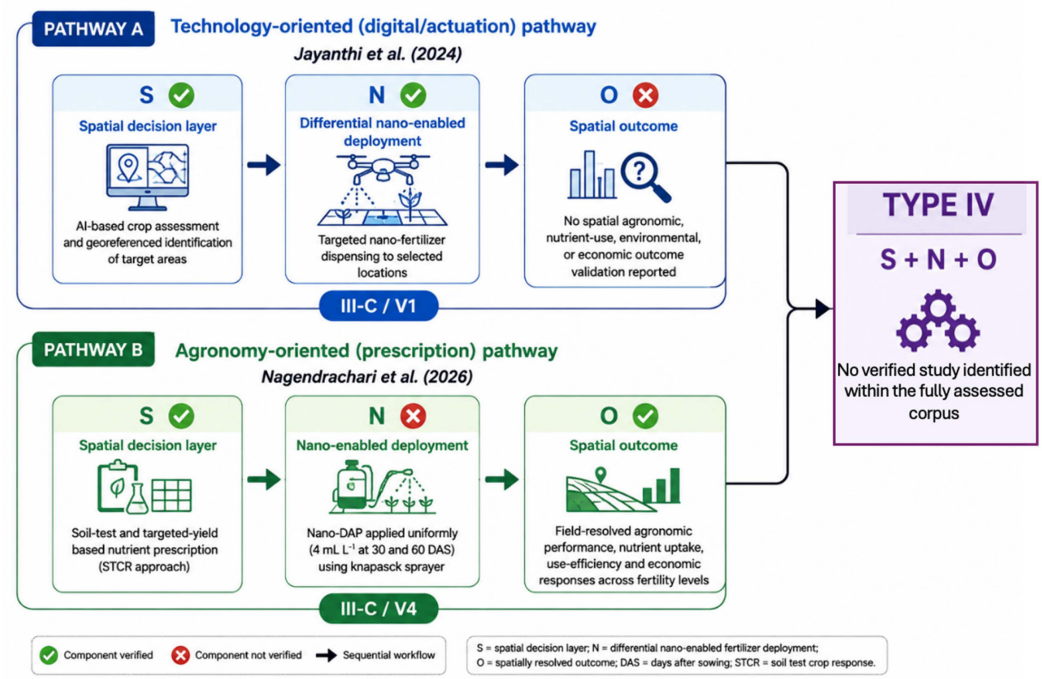


Figure 4. Complementary pathways toward operational convergence identified among Type III-C studies. The technology-oriented pathway demonstrated spatial decision and differential nano-enabled deployment without spatial outcome validation (S-N), whereas the agronomy-oriented pathway demonstrated spatial decision and field-resolved outcomes but retained uniform nano-enabled fertilizer deployment (S-O). Neither pathway fulfilled the complete S-N-O criterion required for Type IV [24,25]. For visual clarity, Pathway A (highlighted in blue) emphasizes the technology-application orientation, while Pathway B (highlighted in green) emphasizes the agriculture and environmental application orientation.

The first pathway was represented by Jayanthi et al. [24], who developed an intelligent agricultural-drone system combining image-based crop assessment, artificial intelligence, georeferenced identification of target areas, and nanofertilizer dispensing. The system used an AI-supported decision architecture to identify crop conditions and direct nano-enabled inputs toward selected areas rather than treating the drone exclusively as a uniform spraying platform. On the basis of the predefined framework, this configuration satisfied S, because a spatially differentiated decision preceded application, and N, because nanofertilizer deployment was linked to the identified target locations. The study therefore represented a substantially closer approximation to operational nano-enabled precision fertilization than studies in which drones simply delivered a predetermined rate uniformly across an experimental area [24].

However, the experimental evidence did not close the outcome component of the workflow. Validation focused predominantly on the technological functionality of the

prototype—specifically, image processing, classification accuracy, target positioning, and dispensing actuation—rather than on spatially resolved agronomic, environmental, or economic consequences across the treated area. The study was therefore coded as Type III-C/V1, indicating that operational coupling between spatial diagnosis and nanofertilizer deployment was demonstrated at the prototype level, but outcome closure under field conditions was not achieved: spatial decision (S) → differential nano-enabled deployment (N) → spatial outcome not verified (O−).

The second pathway was represented by Nagendrachari et al. [25], who integrated nano-DAP into a Soil Test Crop Response (STCR) targeted-yield framework for maize in Alfisols of Karnataka. Their experimental design incorporated fertility-gradient development, soil-test-based fertilizer prescription equations, targeted maize yields, and verification trials across low-, medium-, and high-fertility environments. The STCR approach explicitly adjusted conventional nutrient requirements according to soil-test values and yield targets, while agronomic performance, nutrient uptake, nutrient-use-efficiency indices, and economic responses were evaluated across contrasting fertility conditions [25].

This study therefore provided strong evidence for S, through soil-specific nutrient prescription, and O, through field validation across differentiated soil-fertility environments. Nevertheless, examination of the application protocol showed that nano-DAP itself was applied at a fixed concentration of 4 mL L^{-1} at 30 and 60 days after sowing and sprayed uniformly using a knapsack sprayer. Thus, although the conventional fertilizer component responded to soil-test and targeted-yield information, the nano-enabled component did not change spatially according to that decision.

Accordingly, the nanofertilizer deployment criterion N was not satisfied. The study was classified as Type III-C/V4, reflecting comparatively mature field validation but incomplete operational coupling: spatial decision (S) → uniform nano-enabled deployment (N−) → spatially differentiated field outcomes (O).

The contrast between these two Type III-C studies is particularly informative. Jayanthi et al. [24] approached convergence from the digital-engineering and robotics perspective, establishing the S → N link at the prototype level but omitting spatial field validation. In contrast, Nagendrachari et al. [25] approached convergence from the agronomic prescription side, demonstrating site-specific decision making and mature field validation while leaving the nano-enabled component spatially invariant. The two studies therefore occupied complementary positions immediately below Type IV rather than representing different degrees of the same implementation pathway.

Neither study simultaneously demonstrated a spatial decision layer, differential nano-enabled fertilizer deployment governed by that decision, and spatially resolved outcome validation. Thus, no verified Type IV study was identified in the final evidence base. The complete S–N–O classifications and validation levels are reported in Supplementary Data S1, Table S3.

3.4. Validation Maturity and the Absence of Type IV Evidence

The distribution of validation levels revealed a strong imbalance between the conceptual maturity of the field and the empirical maturity of operational integration. Of the 59 unique studies/evidence units, 52 studies (88.1%) were classified as V0, corresponding to reviews, perspectives, conceptual frameworks, or other forms of non-empirical evidence. No included study was classified as V2, V5, or V6. Empirical evidence was therefore concentrated in a small number of prototype- and field-level studies.

Among the five Type III-B studies, two were classified as V3 and three as V4, indicating that several technological combinations of nano-enabled fertilization with UAVs, drones, remote sensing, or digital decision-support tools have already progressed to field

experimentation and, in some cases, multi-season validation. However, greater validation maturity did not necessarily correspond to greater operational integration. Field-tested systems frequently retained fixed nanofertilizer treatments, used spatial technologies primarily for monitoring, or evaluated precision-management and nano-enabled strategies without directly coupling the decision and deployment components.

This distinction became particularly clear in the two Type III-C studies. The technology-oriented system developed by Jayanthi et al. [24] reached only V1, because its principal validation consisted of laboratory or controlled prototype testing.

By contrast, Nagendrachari et al. [25] reached V4 through replicated field experimentation involving soil-test-based nutrient prescription, contrasting fertility environments, agronomic responses, nutrient-use indicators, and economic evaluation. Despite this substantially higher validation maturity, the nano-DAP component remained uniformly applied and therefore did not satisfy N. The study consequently demonstrated S-O rather than complete S-N-O integration.

Thus, the evidence map shows that validation maturity and operational convergence are not interchangeable. A system may reach field-scale or multi-season validation without spatially differentiating the nano-enabled input, whereas a technologically advanced decision–actuation system may demonstrate operational coupling at prototype level without closing the agronomic outcome loop.

This relationship is summarized in Figure 5, which maps integration class against validation maturity. The evidence is highly concentrated at III-A/V0, while the small empirical tail extends toward III-B/V3–V4 and two distinct III-C positions: III-C/V1 and III-C/V4. No evidence occupied the Type IV column at any validation level.

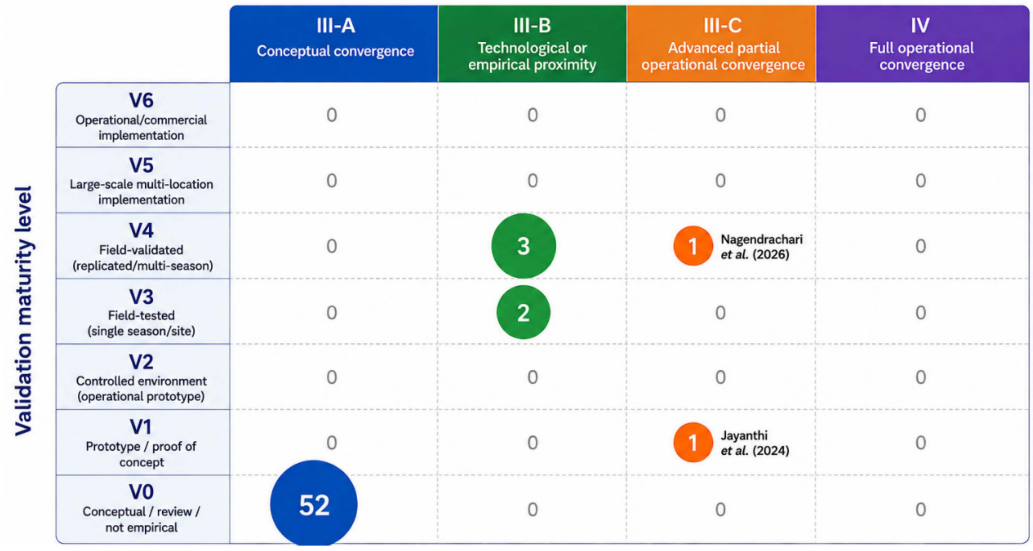


Figure 5. Distribution of the included evidence across operational integration levels and validation maturity. Circle size represents the number of unique studies/evidence units within each integration–validation combination. Integration level and validation maturity were coded independently. The two Type III-C studies occupied distinct maturity levels (V1 and V4), whereas no study reached Type IV at any validation level [24,25]. Specifically, the numerical values within the bubbles denote the exact count of publications mapping to each intersection, illustrating a heavy concentration of the literature in conceptual frameworks (52 studies at III-A/V0). Conversely, a restricted transition toward empirical testing is observed, with few works advancing to single-site field testing (2 studies at III-B/V3), replicated field validation (3 studies at III-B/V4), or advanced partial operational integration (represented by single studies at III-C/V1 and III-C/V4).

The absence of Type IV evidence is therefore not attributable solely to insufficient field validation. Rather, it reflects a more specific structural gap: studies that have advanced toward field maturity have generally not differentiated the nano-enabled fertilizer according to the spatial decision, while studies that have approached automated differential nano deployment have not yet demonstrated spatially resolved agronomic, environmental, or economic outcomes. No included study simultaneously verified S, N, and O, and no operational or commercial-farm implementation (V6) of such a closed-loop system was identified. The complete study-level integration and validation coding is provided in Supplementary Data S1, Table S3.

3.5. Evidence-Translation and Citation-Traceability Gap

Claim-level citation tracing revealed an additional pattern within the convergence literature: the operational maturity implied by some secondary-source statements was not always matched by the evidence supporting those statements. Ten claims involving site-specific nano-delivery, AI-assisted fertilization, closed-loop management, or quantified resource-use benefits were therefore examined in greater detail. The complete audit is provided in Supplementary Data S1, Table S5.

One of the clearest examples was found in the review by Sharma et al. [26]. The abstract states that integration of nanosensors and smart delivery systems within precision agriculture can reduce water use by 20–30%, decrease chemical fertilizer application by 15–25%, and increase crop yields by 10–15%. These values create the impression that the performance of an integrated nano-enabled precision-management system has already been quantitatively demonstrated. However, citation-level examination did not identify a corresponding primary field study in which a spatial decision layer, differential nano-enabled fertilizer deployment, and spatially resolved outcomes were simultaneously evaluated. Instead, the review synthesizes evidence on nano-input performance, sensing technologies, and precision-agriculture concepts across separate evidence streams [26].

A similar pattern was observed in the more recent AI–nanofertilizer literature. Sadiq et al. [27] stated that AI-driven decision-support systems combined with nanofertilizer programs had reduced fertilizer use by 15–20% while sustaining yield. The statement is explicitly presented as an example of emerging AI–nano integration. However, tracing the references supporting this quantitative claim did not resolve to a primary field experiment demonstrating the complete S–N–O sequence. Rather, the supporting literature represented broader AI-based fertilizer optimization and nanotechnology-related evidence. The same article subsequently frames AI–nanotechnology convergence as a future trajectory requiring further field validation, illustrating the distinction between prospective system architecture and demonstrated operational performance [27].

Evidence amplification was also apparent when prototype studies were subsequently cited by broader reviews. Zaman et al. [28] stated that drones equipped with nanomaterial delivery systems can apply fertilizers and other inputs "precisely where needed" and cited the intelligent agricultural-drone system of Jayanthi et al. [24] as supporting evidence. As shown in Section 3.3, however, the underlying study demonstrated a promising S-N prototype-level configuration (III-C/V1) but did not provide spatially resolved agronomic, environmental, or economic outcome validation. Thus, the secondary statement represents a broader interpretation of a system whose operational closure remains incomplete.

These examples were not treated as evidence of poor scientific quality; rather, they reveal an evidence-translation gap that becomes important in a rapidly emerging interdisciplinary field. Terms such as precision delivery, targeted application, AI-driven fertilization, and closed-loop management can refer to substantially different levels of technological integration. In particular, a claim may be scientifically reasonable as a technological

projection while remaining unsupported as evidence of an already validated field-scale S–N–O system.

Accordingly, secondary-source claims were retained as conceptual convergence evidence when they contributed to the development of the field, but quantitative or operational statements were not used to establish Type III-C or Type IV unless their underlying evidence independently satisfied the predefined criteria. This verification step helped prevent conceptual architectures, prototype systems, and independent technology streams from being interpreted as completed operational integration.

Taken together with the integration and validation maps, the citation-traceability analysis indicates that the apparent convergence of nanofertilizers, sensing, AI, and precision agriculture is more mature at the level of scientific discourse and system conceptualization than at the level of empirically closed field implementation.

4. Discussion

4.1. Conceptual Convergence Has Outpaced Operational Integration

The central finding of this review is that the convergence between nano-enabled fertilization and precision agriculture is substantially more advanced at the conceptual level than at the operational level. Although the literature increasingly presents nanofertilizers, nanosensors, artificial intelligence, remote sensing, UAVs, and digital decision-support systems as components of a common precision-agriculture architecture, the evidence map showed a pronounced concentration at Type III-A and a progressive collapse in the number of studies as stricter operational requirements were applied. Of the 59 unique studies/evidence units, 52 were conceptual, five demonstrated technological or empirical proximity, only two reached advanced partial operational convergence, and none verified the complete S–N–O sequence.

This pattern is consistent with the direction proposed in several influential reviews. Zhang et al. [10] positioned the convergence of nanotechnology and artificial intelligence as a pathway toward more sustainable and precise agricultural systems, while Zain et al. [11] similarly described nanotechnology as a potentially transformative component of precision agriculture. In both cases, the conceptual architecture is compelling: spatial sensing and digital decision support can identify crop or soil heterogeneity, while nano-enabled carriers could theoretically deliver nutrients with improved efficiency, controlled release, or greater physiological specificity. However, the present review indicates that these two technological streams have largely developed in parallel rather than as a closed operational system.

Within nanotechnology, precision often refers to controlled release, improved nutrient targeting, stimulus responsiveness, or delivery to particular plant tissues or physiological compartments. Lowry et al. [9], for example, use the concept of nano-enabled precision delivery primarily in relation to the transport of active agents within plants. In precision agriculture, by contrast, precision generally refers to managing spatial and temporal variability using georeferenced information, sensing, prescription maps, management zones, or variable-rate technologies. These forms of precision are complementary but are not equivalent.

As established in the conceptual framework, functional and spatial precision operate at different scales and should not be treated as equivalent. Functional precision concerns the behavior of the nano-enabled nutrient-delivery system, whereas spatial precision concerns the management of field variability through spatially resolved information and differentiated intervention. The evidence map shows that the principal unresolved challenge is not the conceptual compatibility of these dimensions, but the establishment of a causal management chain in which spatial diagnosis generates a prescription, that prescription

modifies nano-enabled fertilizer deployment, and the resulting effects are evaluated at an appropriate spatial resolution. This sequence is formalized by the S–N–O framework.

The absence of Type IV studies does not imply that either parent technology is immature. On the contrary, conventional precision nutrient management has already progressed through management-zone delineation, sensor-based diagnosis, geospatial soil mapping, and variable-rate fertilization, while nano-enabled fertilizers have advanced from material synthesis and controlled-release characterization to replicated agronomic field trials [2,4,7,9]. The unresolved problem is the operational bridge between these domains.

This interpretation is reinforced by recent reviews that increasingly describe closed-loop or AI-assisted nanoagriculture as a desirable next stage while simultaneously acknowledging that large-scale field validation remains limited. Sun et al. [13], for instance, proposed an AI-assisted plant-nanotechnology framework progressing from decision support toward semi-automation and ultimately closed-loop automation. Ma et al. [12] likewise discussed future integration of nanotechnology, sensors, autonomous decision algorithms, and precision-agriculture infrastructure, while emphasizing the gap between controlled efficacy and field-scale implementation. These studies suggest that the scientific community has already articulated the architecture of the integrated system, but the experimental literature has not yet demonstrated its full operational closure.

The evidence therefore supports a more nuanced interpretation than simply stating that nano-enabled precision fertilization is "emerging." The field appears to be in a transitional stage characterized by extensive conceptual convergence, partial technological assembly, and very limited operational closure. The two Type III-C evidence units nevertheless indicate that partial operational coupling is emerging through complementary but incomplete pathways.

From this perspective, the main bottleneck is no longer conceptual feasibility. Rather, it is the development and validation of systems capable of connecting spatial diagnosis, differential nano-enabled actuation, and spatially resolved response assessment within the same experimental workflow.

4.2. Why Current Systems Stop Short of Type IV: The Missing Operational Links

The absence of Type IV evidence can be understood more precisely by examining where the S–N–O sequence breaks down. Across the empirical literature, the limiting factor was rarely the absence of technological capability in general. Instead, current systems tended to fail at one of two interfaces: translating spatial information into differential nano-enabled actuation (S → N) or linking that actuation to spatially resolved agronomic and environmental validation (N → O).

The first bottleneck concerns the S → N transition. Precision-agriculture technologies can already identify spatial heterogeneity through remote sensing, management zones, georeferenced soil information, or crop-sensing platforms, but this information is not yet routinely converted into spatially differentiated nanofertilizer prescriptions. For example, Sinde-González et al. [19] demonstrated that UAV multispectral imagery and spectral sensing could discriminate crop responses under nanofertilizer treatments, yet the sensing system was used primarily to characterize plant response rather than to generate a variable nanofertilizer prescription. Likewise, Sahni et al. [22] showed that drone-based nano-urea spraying can substantially reduce water use and provide agronomic performance comparable to conventional spraying, but both application systems delivered predetermined nutrient inputs rather than a spatially varying nano-urea dose. In these cases, sensing and automated application are technically available, but the prescriptive link between diagnosis and nano-enabled deployment remains absent.

The Nagendrachari et al. [25] study provides an even clearer illustration of this bottleneck. Their STCR-based framework generated soil-test- and target-yield-specific nutrient prescriptions and validated performance across contrasting fertility environments, thereby demonstrating a mature spatial/agronomic decision architecture. However, the nano-DAP component itself remained uniformly applied. This indicates that integrating a nanofertilizer into a site-specific nutrient-management experiment is not sufficient to achieve operational convergence; the nano-enabled component must itself become responsive to the spatial prescription.

The second bottleneck lies in the N → O transition. Prototype-level systems can increasingly connect sensing or AI-supported decisions with targeted nano-enabled application, but agronomic validation of those differentiated interventions remains limited. The Jayanthi et al. [24] system represents this pathway: spatially identified target areas were linked to nanofertilizer dispensing, but the study did not demonstrate spatially resolved nutrient-use, yield, environmental, or economic outcomes. Consequently, the technological actuation loop was more advanced than the biological and agronomic validation loop.

This asymmetry between digital actuation and field validation is consistent with broader assessments of nano-enabled agriculture. Recent reviews emphasize that nano-enabled precision systems still face substantial challenges in translating laboratory or prototype performance into realistic field conditions, including environmental heterogeneity, variable canopy structure, spray interception, wind and rainfall effects, soil complexity, and uncertainty regarding environmental fate and non-target impacts [9,12]. Lowry et al. [9], for instance, emphasize that nano-enabled precision delivery still faces major scientific and societal barriers, while Ma et al. [12] explicitly highlight the discrepancy between experimental efficacy and actual field exposure conditions.

A further barrier is system interoperability. Full Type IV implementation requires spatial diagnosis, decision algorithms, fertilizer formulation, actuation hardware, and outcome monitoring to operate as one coordinated system. Yet these components are typically developed in separate disciplinary domains. Agronomic sensing platforms are optimized to diagnose crop variability, drone systems are optimized for efficient application, and nanofertilizer research is often focused on formulation, release kinetics, uptake, or physiological response. Connecting these systems requires compatible data structures, prescription algorithms, application hardware capable of variable nano-input delivery, and agronomic rules that define how spatial information should alter nanofertilizer rate, formulation, timing, or placement.

This issue is especially important because precision of application is not equivalent to precision of nutrient decision. UAV spraying can improve coverage, reduce labor, lower water consumption, and automate application while still applying the same fertilizer rate across the entire field. Sahni et al. [22], for example, demonstrated strong operational advantages of drone-based nano-urea application, including markedly reduced water use, but the experiment was intentionally designed to compare two delivery platforms under identical nano-urea inputs. Such studies represent important progress in application technology, but they do not yet establish the spatial decision-controlled actuation required for Type IV.

A final limitation concerns the type of outcome evidence used to validate integration. Many nano-enabled fertilizer studies focus on yield, nutrient uptake, chlorophyll indices, or biomass averaged across experimental treatments. These outcomes are valuable for establishing agronomic efficacy, but full operational convergence requires demonstrating that spatial differentiation produced a meaningful spatial response. This may include yield or nutrient-use efficiency by management zone, spatial reductions in nutrient loss, differential environmental exposure, or economic returns linked to the prescription unit. Without

this resolution, the response cannot be causally connected to the spatially differentiated nano-enabled intervention.

The immediate challenge is therefore to connect spatial diagnosis, nano-enabled actuation, and spatially resolved validation within the same experimental workflow. Future studies should move beyond demonstrations in which nanofertilizers, sensors, AI, and UAVs merely coexist and instead test complete workflows in which spatial diagnosis → prescription → differential nano-enabled application → spatially resolved validation are implemented and evaluated within the same field experiment.

The contribution of this evidence map therefore extends beyond documenting the absence of a Type IV study within the assessed corpus. First, it establishes explicit operational criteria that distinguish spatial diagnosis, differential nano-enabled actuation, and spatial outcome validation from the broader co-occurrence of nanofertilizers, sensors, models, or UAVs. Second, it separates operational integration from validation maturity, showing that field testing does not necessarily imply decision-controlled nano-enabled deployment. Third, the two Type III-C configurations reveal complementary translational pathways: one closes the S–N interface without closing the outcome loop, whereas the other provides spatial decision making and field-resolved outcomes while leaving the nano-enabled input spatially uniform. Finally, the citation-traceability analysis identifies how prospective or component-level evidence can be interpreted as complete operational integration. Together, these findings convert a general statement of limited integration into a set of explicit, testable interfaces for future research.

4.3. From Double Precision to Closed-Loop Nano-Enabled Nutrient Management

The findings of this review support the use of double precision as a conceptual lens for distinguishing the technological roles of nano-enabled nutrient delivery and spatial nutrient management. Spatial precision concerns where, when, and how much nutrients should be supplied according to spatial or temporally resolved variability in soil and crop requirements. Functional precision concerns how the nutrient-delivery system behaves after application, including controlled or stimulus-responsive release, nutrient protection, modified availability, enhanced uptake, transport, or biological targeting. These dimensions are complementary but operate at different scales and have often been grouped under the broad terminology of precision agriculture without demonstrating that they are operationally connected.

Functional precision has historically been one of the principal rationales for agricultural nanotechnology. Raliya et al. [7] highlighted controlled release and targeted delivery as potential mechanisms through which nanofertilizers could contribute to sustainable and precision agriculture. More recently, Lowry et al. [9] substantially refined this concept by emphasizing how nanocarrier properties can be designed to influence transport, uptake, transformation, release, and delivery to specific locations within plants. In this sense, nanotechnology provides a means of engineering the behavior of the nutrient-delivery system itself.

Representative primary studies illustrate the substantial development of this material foundation. Early work incorporated NPK nutrients into chitosan nanoparticles, while nano-hydroxyapatite was investigated as a phosphorus source for soybean. Urea–hydroxyapatite nanohybrids subsequently demonstrated a controlled-release route for nitrogen delivery. However, results obtained under agriculturally realistic conditions have not always reproduced the expected agronomic benefits of nano-hydroxyapatite, underscoring the importance of formulation, dose, matrix, and exposure conditions. More recent field experiments with a chitosan-based NPK nanostructure further indicate progression from formulation development toward multi-season agronomic evaluation. These studies establish important

Type I material and agronomic foundations, but they do not by themselves demonstrate spatially differentiated nano-enabled fertilization; operational convergence additionally requires the S–N–O links defined in this review [5–8,29–33].

Spatial precision operates at a different scale. It requires recognition of heterogeneity across the field and conversion of that heterogeneity into differentiated management decisions. Sensors, proximal and remote sensing, geospatial information, management zones, prescription maps, variable-rate technologies, and increasingly AI-based decision systems provide the technical basis for this dimension. Zhang et al. [10] anticipated the potential value of combining such precision-agriculture capabilities with nanotechnology and AI, including the coupling of nutrient and crop models with nanoinformatics to optimize the behavior and targeting of nanoscale agricultural inputs.

The key implication of the present evidence map is that neither form of precision alone constitutes nano-enabled precision fertilization in the operational sense. A highly sophisticated controlled-release nanofertilizer applied uniformly to an entire field achieves functional precision but not spatial precision. Conversely, a detailed prescription map used to vary conventional fertilizer rates achieves spatial precision without exploiting the functional properties of nano-enabled nutrient delivery. Even applying the same nanofertilizer uniformly across spatial management zones does not fully combine the two dimensions because the nano-enabled component remains disconnected from the spatial prescription.

Under the double-precision concept, full convergence therefore requires the two forms of precision to become causally coupled. Spatial information should determine not only whether fertilizer is required, but also how the nano-enabled input should be deployed. Depending on the system, this may involve spatial adjustment of the nanofertilizer rate, formulation, carrier characteristics, release profile, timing, placement, or combinations thereof. The functional advantages of the nano-enabled material would consequently be deployed in response to spatially diagnosed nutrient requirements rather than applied uniformly.

Beyond this initial operational convergence, a subsequent developmental stage would involve closed-loop nano-enabled nutrient management rather than the simultaneous use of nanofertilizers and digital technologies alone. In its minimal form, such a closed-loop system would comprise four connected functions: sense and map → decide and prescribe → differentially deploy → verify and update.

The first stage characterizes spatial variability in crop or soil nutrient status. The second transforms that information into a spatial prescription. The third executes the prescription through differential nano-enabled deployment. The fourth quantifies spatial agronomic, environmental, and economic responses and feeds those observations back into subsequent decisions. This feedback component is especially important because nutrient demand, environmental conditions, and nano–soil–plant interactions are dynamic rather than fixed.

Such a closed-loop architecture is consistent with the broader convergence anticipated by Zhang et al. [10], who argued that combining nanotechnology, informatics, and AI could enable more sustainable and precise agricultural management. However, our evidence map indicates that the literature has so far developed the individual components considerably further than their operational coupling. The distinction is important: a conceptual closed loop should not be interpreted as an experimentally validated closed loop.

The double-precision perspective also implies that future research should move beyond asking whether nanofertilizers outperform conventional fertilizers under uniform experimental treatments. That question remains relevant for material efficacy and safety, but it does not test the added value of operational convergence. A more informative experimental

question is whether spatially differentiated nano-enabled fertilization produces measurable advantages over both uniform nanofertilizer application and conventional site-specific nutrient management. Such comparisons would allow the contribution of spatial precision, functional precision, and their interaction to be separated experimentally.

An appropriate field design could therefore include at least four management strategies: conventional uniform fertilization, spatially differentiated conventional fertilization, uniform nano-enabled fertilization, and spatially differentiated nano-enabled fertilization. The fourth treatment is the crucial Type IV condition. Spatially resolved yield, nutrient-use efficiency, nutrient losses, environmental exposure, operational costs, and economic returns could then determine whether combining spatial and functional precision generates an advantage greater than either strategy independently.

This requirement is particularly relevant because nano-enabled delivery introduces additional variables that conventional variable-rate fertilizer systems do not normally address. Particle or carrier characteristics, concentration, suspension stability, release kinetics, interaction with water quality, sprayability, nozzle compatibility, foliar retention, soil transformation, and environmental fate may all interact with the prescription and application system. Lowry et al. [9] emphasize that nanocarrier behavior depends strongly on both material properties and biological/environmental conditions, reinforcing the need to integrate material design with realistic deployment contexts rather than optimize these dimensions independently.

The conceptual progression identified in this review can therefore be summarized as:

functional precision + spatial precision → operational double precision → closed-loop validation.

This formulation shifts the focus from technological accumulation toward system integration. The critical scientific question is no longer whether nanotechnology, sensors, drones, AI, and variable-rate management can individually contribute to precision agriculture; substantial evidence already supports those individual capabilities. The unresolved question is whether they can be connected in a reproducible, agronomically effective, environmentally responsible, and economically viable nutrient-management workflow.

4.4. Research Roadmap for Achieving Type IV Operational Convergence

The identified S–N and N–O discontinuities define an eight-part research roadmap for progression toward Type IV operational convergence: (i) conversion of spatial diagnosis into an explicit nano-enabled fertilizer prescription; (ii) reliable differential deployment of the nano-enabled input; (iii) engineering compatibility between nanoformulations and variable-rate application systems; (iv) spatially matched agronomic, environmental, and economic outcome validation; (v) experimental controls that separate the effects of spatial and functional precision; (vi) feedback-based updating of subsequent prescriptions; (vii) multi-season and multi-location validation under operationally relevant conditions; and (viii) explicit assessment of economic and operational viability [7,9,12]. These requirements are interdependent, because progress in one component cannot compensate for the absence of another within the same workflow. The following paragraphs define the minimum experimental requirements associated with this roadmap, which are summarized in Table 2.

Table 2. Research priorities for progressing from partial to full operational convergence.

Research Priority	Current Evidence Gap	Minimum Requirement for Future Studies	Relevant S–N–O Component	Expected Advancement
Spatial diagnosis and prescription	Spatial sensing frequently remains descriptive	Convert georeferenced soil/crop information into explicit nano-enabled fertilizer prescriptions	S	Establish a causal decision layer
Differential nano-enabled deployment	Nano-inputs commonly remain fixed across zones	Vary nano rate, formulation, timing, placement, or location according to S	N	Close the S → N interface
Application-system compatibility	Nano formulations and variable-rate hardware are rarely evaluated together	Validate suspension stability, flow, nozzle compatibility, dose accuracy, and spatial actuation	N	Ensure that prescriptions can be executed reliably
Spatial outcome validation	Outcomes are commonly reported as treatment means	Measure agronomic, environmental, physiological, and/or economic responses by spatial management unit	O	Close the N → O interface
Appropriate experimental controls	Spatial and functional precision effects cannot be separated	Compare uniform conventional, spatial conventional, uniform nano, and spatial nano treatments	S–N–O	Quantify the added value of double precision
Feedback and adaptive management	Most systems remain open-loop	Use post-application sensing/outcomes to update subsequent prescriptions	S–N–O	Progress toward closed-loop management
Multi-season and multi-location validation	No Type IV evidence at V5–V6	Replicate integrated systems across seasons, soils, crops, and locations	S–N–O	Test robustness and transferability
Environmental fate and safety	Local exposure and long-term nano-fate remain insufficiently integrated with precision trials	Quantify spatial fate, nutrient losses, persistence, non-target exposure, and repeated-use effects	O	Demonstrate environmental sustainability
Economic and operational feasibility	Technical performance is rarely evaluated against total implementation cost	Include machinery, sensing, data, application, labor, energy, water, and profitability metrics	O	Determine commercial feasibility
Reporting and traceability	Operational terminology may exceed demonstrated evidence	Report S, N, O and validation level explicitly and distinguish demonstrated from proposed integration	Cross-cutting	Improve comparability and prevent evidence inflation

Progress toward Type IV convergence should not be understood as depending on a single disruptive nanofertilizer formulation. The material challenge is instead to develop application-ready nano-enabled nutrient systems whose nutrient loading, release behavior, colloidal stability, dose–response relationship, and environmental safety remain reproducible under realistic soil, water, canopy, and climatic conditions. For nitrogen, phosphorus, and potassium delivery, this requires formulation-specific optimization together with compatibility testing for variable-rate equipment, including suspension stability, flow behavior, nozzle passage, deposition uniformity, and dose accuracy. Accordingly, future breakthroughs should be evaluated not only by their novelty at the nanoscale, but also by whether the formulation can be manufactured consistently, spatially prescribed, differentially applied, and agronomically and environmentally validated within the complete S–N–O workflow.

A first priority is to strengthen the S → N interface. Spatial variability detected through soil mapping, remote sensing, crop sensors, management zones, or AI-assisted diagnosis should be translated into explicit nanofertilizer prescriptions. The prescription should specify how the nano-enabled input changes among spatial units rather than merely indicating whether fertilization is required. Depending on the formulation, this differentiation may involve application rate, concentration, timing, carrier type, release characteristics, placement, or combinations of these variables. The potential value of combining nanoinformatics, artificial intelligence, and precision-agriculture decision systems has already been recognized conceptually [10], but the present evidence indicates that this connection remains largely untested under operational field conditions.

A second priority concerns the technical execution of differential nano-enabled application. Conventional variable-rate fertilizer systems have mainly been developed for granular, liquid, or soluble products and cannot automatically be assumed to perform equivalently with nano-enabled formulations. Suspension stability, aggregation, concentration-dependent viscosity, nozzle compatibility, spray-droplet characteristics, foliar retention, carrier transformations, and interactions with irrigation or spray water may influence whether a spatial prescription can actually be delivered accurately. Lowry et al. [9] emphasize that the environmental and biological behavior of nano-enabled delivery systems depends strongly on material properties and exposure conditions. Therefore, application engineering should be incorporated into future precision-nanofertilizer studies rather than treated as a downstream implementation issue.

Third, the N → O interface requires substantially stronger validation. Future studies should evaluate whether spatial differentiation of the nano-enabled input generates outcomes that are measurable at the same spatial resolution at which the prescription was applied. Relevant outcomes should extend beyond crop yield to include nutrient-use efficiency, nutrient recovery, residual soil fertility, nitrate or phosphate losses, greenhouse-gas emissions where relevant, nano-enabled material fate, non-target exposure, water use, energy demand, and economic return. Without spatially resolved outcome assessment, it remains impossible to determine whether differentiated nano-enabled deployment provides a meaningful advantage over uniform application.

A particularly important experimental requirement is the use of comparators capable of separating spatial and functional precision effects. Many existing nanofertilizer studies compare nano-enabled products with conventional fertilization under uniform treatment conditions. Such designs can assess product efficacy but cannot determine whether nano-enabled precision management provides an additional systems-level advantage. A stronger field design should include, where agronomically appropriate, at least four reference strategies: (1) uniform conventional fertilization; (2) spatially differenti-

ated conventional fertilization; (3) uniform nano-enabled fertilization; and (4) spatially differentiated nano-enabled fertilization.

This factorial logic would permit the effects of spatial precision, nano-enabled nutrient functionality, and their interaction to be distinguished. The fourth strategy represents the operational condition most closely aligned with Type IV.

Longer-term and multi-location validation is also essential. The evidence map contained no Type IV study and no V5 or V6 example of full operational convergence. Yet both spatial nutrient variability and nano–soil–plant interactions are strongly context-dependent. Soil texture, pH, organic matter, mineralogy, crop genotype, weather, irrigation regime, and management history may alter both nutrient demand and nanomaterial behavior. Field evaluation across multiple seasons and environments is therefore necessary before integrated systems can be considered robust or transferable [9,12].

A fifth priority is the development of closed-loop decision systems rather than one-way prescriptions. Initial Type IV experiments do not necessarily require full autonomy, but they should include a feedback mechanism capable of testing whether the spatial intervention produced the expected response. In practice, this means connecting post-application sensing and outcome assessment to subsequent nutrient-management decisions. The staged transition from decision support to semi-automation and ultimately closed-loop management proposed in recent AI–nanotechnology frameworks provides a useful developmental trajectory [13]. Importantly, however, each stage should be validated empirically before being described as an operationally integrated system.

Environmental and regulatory evaluation should be embedded within this development pathway rather than added only after agronomic efficacy has been demonstrated. Nano-enabled fertilizers may reduce total nutrient application or improve uptake efficiency, but spatially differentiated application also changes local exposure patterns. Consequently, environmental assessment should consider not only total application rate but also where the nano-enabled material accumulates, transforms, moves, or persists. Long-term fate, repeated application, effects on soil microbial communities, off-target transport, and crop-residue implications remain particularly relevant for any transition toward routine field deployment [9,12].

Finally, economic and operational viability must be evaluated explicitly. A technically successful Type IV system may still be impractical if the costs of sensing, prescription generation, nano-formulation, variable-rate application, data processing, and equipment adaptation exceed the agronomic or environmental benefits. Economic assessment should therefore extend beyond fertilizer cost alone and incorporate labor, energy, water, equipment depreciation, sensing and analytics costs, application efficiency, yield variability, and potential savings from reduced nutrient losses. This will be particularly important when evaluating whether integrated systems can progress from replicated field trials toward V5 multi-location validation and V6 operational-farm implementation.

These priorities are summarized in Table 2. Collectively, they indicate that the next generation of research should be designed around system closure rather than technology accumulation. A study should not be considered a demonstration of nano-enabled precision fertilization merely because it includes a nanofertilizer, a sensor, and a drone. The decisive test is whether spatial information changes nano-enabled deployment and whether that differentiated intervention produces spatially verified agronomic, environmental, and economic outcomes.

4.5. Implications of the Evidence-Translation Gap

The citation-traceability analysis identified a second challenge for the development of nano-enabled precision fertilization: the language used to describe technological convergence sometimes advances faster than the primary evidence demonstrating that convergence. This does not necessarily reflect inaccurate scholarship. Rather, it appears to arise from the rapid interaction of several research domains—nanotechnology, remote sensing, artificial intelligence, robotics, and precision nutrient management—whose individual advances can readily be assembled into plausible integrated architectures before those architectures have been tested as complete systems.

This distinction is particularly important for terms such as precision delivery, targeted fertilization, smart application, AI-guided nutrient management, and closed-loop agriculture. These expressions can describe substantially different levels of evidence. For example, targeted delivery may refer to controlled release or biological targeting at the material or plant level, whereas site-specific application implies that georeferenced variability has altered the field-scale management decision. Similarly, a drone may deliver a nano-enabled fertilizer accurately along a predefined flight path without performing variable-rate fertilization, and post-treatment UAV imagery may provide highly resolved crop information without having contributed to the fertilizer prescription.

The S–N–O classification therefore provides not only a framework for organizing the literature but also a means of improving claim precision. Statements of operational integration should ideally identify which components have actually been demonstrated. Evidence of spatial diagnosis alone supports S; evidence that this diagnosis altered the nano-enabled treatment supports N; and evidence that the resulting intervention was evaluated at an appropriate spatial resolution supports O. Only demonstration of all three components supports a claim of complete operational convergence.

The claim-level examples presented in Section 3.5 reveal two recurrent mechanisms of evidence amplification: prototype capabilities being described as complete operational systems, and quantitative benefits derived from parallel nano-enabled and precision-agriculture evidence being attributed to their untested integration. These mechanisms can inflate perceived technology readiness and obscure whether S, N, and O were demonstrated within the same study.

The implications extend beyond terminology. Evidence inflation can affect technology-readiness assessment. If conceptual frameworks, prototypes, fixed-rate drone applications, and fully closed spatial decision–actuation systems are described using the same operational vocabulary, it becomes difficult to determine which technologies are genuinely ready for field scaling. This may obscure the specific engineering or agronomic barriers that remain unresolved and can lead to overly optimistic interpretations of deployment readiness.

A second implication concerns the design of future reviews. In rapidly converging fields, conventional article-level inclusion alone may be insufficient when strong operational or quantitative claims form the basis of major conclusions. Targeted citation verification, as used in the present review and supported methodologically by citation-searching guidance such as TARCiS [18], provides an additional means of distinguishing evidence that is directly demonstrated from evidence that is extrapolated, synthesized, or proposed. This is particularly valuable when terminology is evolving faster than standardized reporting practices.

A third implication is the need for explicit reporting of integration status in primary studies. Future work could improve transparency by stating whether sensing data were used for diagnosis only or directly informed application; whether nano-enabled fertilizer deployment was uniform or spatially differentiated; whether spatial outcomes were measured; and at what validation scale the system was tested. Reporting these features would

make it substantially easier to compare studies and would reduce ambiguity in subsequent reviews and technology assessments.

The evidence-translation gap should not be interpreted as indicating that nano-enabled precision fertilization is technically implausible. Rather, it shows that conceptual architecture, component demonstration, operational coupling, field validation, and commercial implementation represent distinct stages that should not be treated as interchangeable. The absence of verified Type IV studies is therefore consistent with an emerging field in which compatible enabling technologies exist, but their complete operational coupling remains unverified.

4.6. Limitations of the Review

Several limitations should be considered when interpreting the findings of this review. First, the structured database search was limited to Scopus and WoSCC. Although these multidisciplinary databases cover the principal subject areas relevant to this review and were complemented by backward and forward citation searching, they do not provide exhaustive coverage of all the agricultural, regional, conference, or non-journal literature. In particular, the absence of an agriculture-specific database such as CAB Abstracts may have reduced retrieval of records indexed primarily within specialist agricultural sources. ScienceDirect and Google Scholar could also identify additional records through full-text or broad web-based discovery, although they differ from structured bibliographic databases in coverage, search functionality, and reproducibility [34]. Consequently, some relevant reports may not have been captured, and the evidence map and Type IV absence finding should be interpreted as applying to the sources, search methods, and fully assessed corpus defined in this review. Future updates should consider adding CAB Abstracts and other complementary sources while preserving transparent, source-specific search documentation. This limitation is particularly relevant because highly applied work involving agricultural robotics, UAVs, embedded systems, and prototype development may appear first in engineering conference proceedings rather than conventional agronomic journals.

Second, 35 of the 96 reports sought for full-text assessment (36.5%) could not be retrieved. These records were not excluded following a substantive assessment of the full text; instead, they remained unclassified because titles and abstracts did not provide sufficient information to verify the S, N, and O components, the relationship between spatial diagnosis and nano-enabled deployment, or the spatial resolution of the reported outcomes. Their non-retrieval introduces potential availability bias and limits the completeness and representativeness of the evidence map. It remains possible that one or more non-retrieved reports contained additional evidence of partial or complete operational convergence. Accordingly, the absence finding is restricted to the included and fully assessed corpus and should not be interpreted as definitive proof that no Type IV study existed in the broader literature at the time of the search.

Third, the search strategy necessarily operated within an evolving and inconsistent terminology. Nano-enabled fertilizers may be described using terms such as *nanofertilizer*, *nano-urea*, *nano-DAP*, *nano-NPK*, *nanoformulation*, or *nano-enabled nutrient delivery*, whereas spatial nutrient management is reported using terms including *precision agriculture*, *site-specific management*, *variable-rate application*, *smart farming*, *digital agriculture*, and *UAV-based application*. Conversely, terms such as *precision delivery* or *targeted fertilization* are also used in nanotechnology to describe controlled release or physiological targeting without any geospatial management component. No search strategy can completely resolve this semantic overlap. The two complementary search sets and subsequent citation searching were designed to reduce this problem, but some relevant studies may remain outside the captured corpus.

Fourth, citation searching was targeted rather than exhaustive across every included reference list and citing network. Backward and forward citation searches were concentrated on studies positioned closest to operational convergence and on reviews or frameworks containing strong claims about integrated nano-enabled precision systems. This approach was appropriate for identifying potential bridge studies that terminology-based database searches might miss and was reported separately from the database arm, consistent with transparent citation-searching principles [18]. However, it should not be interpreted as a complete citation-network census of the two parent literatures.

A fifth limitation arises from the composition of the evidence base itself. Fifty-two of the 59 included unique studies/evidence units were classified as III-A/V0, meaning that the synthesis was dominated by the conceptual or review-level literature. Only seven evidence units provided empirical validation beyond V0. This asymmetry limits the extent to which quantitative comparisons can be made among integrated systems and explains why meta-analysis was neither appropriate nor attempted. The central conclusions are therefore based primarily on evidence mapping and verification of operational components, rather than pooled estimates of agronomic effectiveness. Relatedly, the review did not apply a conventional intervention-level risk-of-bias instrument across the entire corpus. Such tools are poorly suited to an evidence base combining reviews, conceptual frameworks, engineering prototypes, field experiments, remote-sensing studies, and agronomic trials. Consistent with the purpose of a critical scoping review, the principal analytical question was not whether a specific fertilizer treatment produced a pooled effect size, but whether the published evidence demonstrated the predefined components of operational convergence. Accordingly, methodological appraisal focused on claim verification, S–N–O traceability, evidence role, and validation maturity rather than a single standardized risk-of-bias score [14,15].

The limited empirical corpus also constrains the inferences that can be drawn from the identified configurations. In particular, the two Type III-C studies do not provide a sufficient basis for estimating comparative agronomic effectiveness, environmental performance, scalability, or commercial feasibility. The S–N and N–O discontinuities identified in this review should therefore be interpreted as documented gaps in the available operational evidence and as candidate translational bottlenecks, rather than as statistically established causal determinants of implementation failure. Their value lies in defining the interfaces that future studies must test directly.

The S–N–O framework itself also imposes a deliberately stringent definition of convergence. Studies using temporally responsive tools such as SPAD- or leaf-colour-chart-guided fertilization, fixed-rate drone application, or post-treatment UAV sensing were not considered spatially integrated unless the technology generated or implemented a spatially differentiated nano-enabled prescription. A broader definition of "precision" would therefore produce a larger number of apparently integrated studies. However, relaxing this requirement would undermine the central distinction between functional precision, application automation, and spatially explicit nutrient management. The strict criterion was therefore considered necessary to avoid classifying technological co-occurrence as operational coupling.

Finally, the review represents the evidence available up to the database searches conducted in August 2026. The field is developing rapidly, particularly at the intersection of AI, autonomous platforms, nano-enabled delivery, and digital agriculture. The absence of verified Type IV evidence should consequently be interpreted as a state-of-the-evidence conclusion for the reviewed period, not as evidence that such systems are technically impossible or will remain absent. Indeed, the identification of two complementary Type

III-C pathways suggests that some of the components required for full convergence are already emerging.

Taken together, these limitations qualify but do not invalidate the principal finding within the assessed evidence base. Even after complementary database searches, full-text assessment of all retrievable records, targeted citation searching, study-family consolidation, and claim-level traceability assessment, none of the included studies simultaneously demonstrated a spatial decision layer, differentiated nano-enabled fertilizer deployment, and spatially resolved outcome validation. The available evidence therefore indicates that full operational closure remains unverified within the reviewed corpus, while also defining the components that future studies would need to demonstrate to satisfy the Type IV criterion.

5. Conclusions

This critical scoping review examined whether nano-enabled fertilizers have moved beyond conceptual association with precision agriculture toward operational integration in spatially explicit nutrient-management systems. The evidence shows a clear progression, but also a marked contraction as stricter integration criteria are applied. Among the 59 unique studies/evidence units, 52 were classified as conceptual convergence (III-A), five as technological or empirical proximity (III-B), two as advanced partial operational convergence (III-C), and none as full operational convergence (Type IV).

The principal finding is not that nano-enabled precision fertilization lacks technological foundations, but that its enabling components remain insufficiently coupled within the same field-management workflow. The two Type III-C evidence units followed complementary but incomplete pathways, indicating that individual components of convergence are emerging while complete S–N–O closure remained unverified within the included and fully assessed corpus. Because the empirical corpus was small and heterogeneous, these findings do not establish the comparative agronomic effectiveness, environmental performance, scalability, or commercial feasibility of fully integrated systems.

These findings support double precision as a useful conceptual framework for distinguishing spatial nutrient management from the functional behavior of nano-enabled nutrient-delivery systems. The present S–N–O framework does not comparatively rank the degree of functional precision achieved by individual formulations; rather, it evaluates whether a reported nano-enabled fertilizer component becomes operationally connected to spatially differentiated nutrient management. Spatial precision determines where nutrient management should differ, whereas nano-enabled nutrient functionality determines how the nutrient-delivery system behaves. Full nano-enabled precision fertilization requires these dimensions to be causally connected rather than simply present within the same experiment. Future Type IV studies should therefore test complete workflows in which spatial diagnosis generates a prescription, the prescription directly alters nano-enabled fertilizer rate, formulation, timing, or placement, and the resulting intervention is evaluated using spatially resolved agronomic, environmental, and economic outcomes.

The review also identified an evidence-translation gap between the increasingly integrated language used in the secondary literature and the more fragmented primary evidence supporting some operational claims. This reinforces the need to distinguish clearly among conceptual convergence, technological co-occurrence, partial operational coupling, and fully validated integration.

Overall, the literature reflects extensive conceptual convergence but limited operational closure. The next advance will depend less on adding new technologies to already complex systems and more on experimentally closing the interfaces between spatial diagnosis, nano-enabled actuation, and outcome verification. Until complete S–N–O workflows

are demonstrated and validated across seasons, locations, and operational farm conditions, nano-enabled precision fertilization should be regarded as a promising research direction whose comparative agronomic, environmental, and economic value remains to be established.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/agrochemicals5040050/s1, Table S1: Complete database search strategies; Table S2: Operational coding rules, boundary cases, and validation maturity scale; Table S3: Study-level evidence matrix of the 59 included studies/evidence units; Table S4: Backward, forward, and directed citation-searching audit; Table S5: Claim-level citation traceability audit. Supplementary Data S1: Table S6 Supplementary_References: dataset retrieved via our Machine Learning algorithm and the PRISMA methodology.

Author Contributions: Conceptualization, J.M.R.-D., E.Z.-L. and R.T.-C.; methodology, J.M.R.-D., E.Z.-L. and R.T.-C.; software, R.T.-C., C.Z.-L. and A.J.G.-G.; validation, J.M.R.-D., E.Z.-L., L.G.-R., F.R.-G., P.E.M.M. and I.B.P.-A.; formal analysis, R.T.-C., E.Z.-L., J.M.R.-D. and L.G.-R.; investigation, R.T.-C., E.Z.-L. and J.M.R.-D.; resources, J.M.R.-D. and E.Z.-L.; data curation, R.T.-C., C.Z.-L., F.R.-G. and P.E.M.M.; writing—original draft preparation, R.T.-C., E.Z.-L. and J.M.R.-D.; writing—review and editing, J.M.R.-D., E.Z.-L., L.G.-R., C.Z.-L., F.R.-G., P.E.M.M., I.B.P.-A. and A.J.G.-G.; visualization, R.T.-C., C.Z.-L. and A.J.G.-G.; supervision, J.M.R.-D. and E.Z.-L.; project administration, J.M.R.-D. and E.Z.-L.; funding acquisition, J.M.R.-D. and E.Z.-L. All authors have read and agreed to the published version of the manuscript.

Funding: This research was partially funded by the United Nations Development Programme (UNDP), the Ministry of Environment, Water and Ecological Transition of Ecuador (MAATE), and the Ministry of Agriculture and Livestock of Ecuador (MAG) through the FARM Ecuador Project (Financing Agrochemical Reduction and Management) and the "AgroConCiencia" competitive research grant fund, supporting the project "Aplicación de bio-nano formulados y agricultura de precisión para reducir agrotóxicos en sistemas productivos de maíz de la costa ecuatoriana" (BIONANO-F-AGRO), led by Universidad Técnica de Manabí (UTM). The funding partially supported research personnel and academic activities necessary to conduct this review.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The original contributions presented in this study are included in the article/Supplementary Material. Further inquiries can be directed to the corresponding authors.

Conflicts of Interest: The authors declare no conflicts of interest.

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