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GIS-Enabled Truck–Drone Hybrid Systems for Agricultural Last-Mile Delivery: A Multidisciplinary Review with Insights from a Rural Region

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Highlights

What are the main findings?

- Analyzed 82 studies. Suggested that truck–drone systems can reduce costs by 10% to 50 % and time by 15 % to 40 % through GIS optimization of routing and launch-site placement [1–5].
- Identified seven interconnected research domains that collectively define the technological and policy landscape (Table 3). Smart Agriculture Integration (28 studies), GIS Analytics (21 studies), and Truck–Drone Coordination (15 studies) were most developed. Sustainability assessment (5 studies) and strategic network design (8 studies) remained underexplored.

What is the implication of the main finding?

- Addressing regional challenges such as cold-weather performance, low delivery density, connectivity gaps, and regulatory constraints is essential to realize practical deployment in rural states like North Dakota, USA.
- GIS-guided truck–drone systems can serve as a scalable model for sustainable, data-driven logistics that strengthen agricultural productivity and rural resilience in cold-climate regions.

Abstract

Efficient last-mile delivery remains a critical challenge for rural agricultural logistics, globally, particularly in cold-climate regions with dispersed agricultural operations. This review evaluates the potential of GIS-enabled truck–drone hybrid systems to overcome infrastructural, environmental, and operational barriers in such settings. This study uses North Dakota, USA as a representative case alongside insights from similar rural regions worldwide. The study conducts a systematic review of 82 high-quality publications. It identifies seven interconnected research domains: GIS analytics, truck–drone coordination, smart agriculture integration, rural implementation, sustainability assessment, strategic design, and data security. The findings stipulate that GIS enhances hybrid logistics through route optimization, launch site planning, and real-time monitoring. Additionally, this study emphasizes the rural, low-density context and identifies specific gaps related to cold-weather performance, restrictions to line-of-sight operations, and economic feasibility in ultra-low-density delivery networks. The study concludes with a roadmap for research and policy development to enable practical deployment in cold-climate agricultural regions.

Keywords: GIS analytics; truck–drone coordination; rural implementation; spatial analysis; cold-weather operations; precision agriculture

1. Introduction

Last-mile delivery is the most expensive and complex stage of agricultural logistics. The challenge is especially severe in vast rural areas. In particular, northern U.S. states like North Dakota, South Dakota, Montana, and Wyoming experience such challenges. Farms in these states are widely dispersed. For example, in North Dakota (ND), farmland covers 38.5 million acres, with an average farm size of more than 1,500 acres and about 26,800 farms in total. South Dakota, Montana, and Wyoming have average farm sizes of 1,495, 2,412, and 2,743 acres, respectively. In these regions, long distances separate production sites from supply centers. Hence, reliance on trucks alone increases costs, extends delivery times, and raises emissions, particularly during critical planting and harvest windows [2].

Hybrid truck–drone systems offer a promising alternative. Trucks provide long-haul capacity, while drones handle fast, short-range deliveries directly to farms. This division of roles reduces delivery times and expands service reach [6]. Drones provide flexible payload capacity from a few pounds to several thousand pounds, depending on their size [7]. Yet their deployment remains constrained by regulations and operational limitations in inclement weather [8]. Restrictions on beyond-visual-line-of-sight (BVLOS) operations by government agencies, combined with ND's harsh winter conditions, require new strategies to ensure operational reliability.

Geographic information systems (GIS) are central to these strategies. GIS enables route optimization, strategic network design, and real-time monitoring by integrating maps of farm locations, road networks, and field boundaries. GIS identifies suitable launch and landing sites, designs recharge infrastructure, and fuses environmental data into dynamic delivery planning [9]. In agriculture, GIS demonstrates its versatility through the support of soil and crop suitability mapping, irrigation planning, and precision farming [10].

The convergence of drones and GIS extends this potential. Smart farming platforms, based on Internet-of-Things (IoT) technologies, now integrate sensors, cloud analytics, and autonomous machinery to monitor conditions and automate inputs [11]. When combined with drones and GIS, these systems strengthen logistics by linking delivery operations with real-time farm needs. Such integration advances both efficiency and sustainability [12].

The **goal** of this study is to examine how GIS-enabled truck–drone hybrid systems can enhance agricultural last-mile delivery in regions characterized by dispersed farms and extreme environmental conditions. The study uses ND as a representative case. The review evaluates the role of GIS in supporting routing, scheduling, monitoring, and spatial network design. It integrates insights from seven interrelated domains: GIS analytics, smart agriculture integration, truck–drone coordination, rural implementation, sustainability assessment, strategic network design, and data security. It further identifies key technological, operational, and regulatory challenges, assesses economic and environmental outcomes, and explores how these systems can strengthen rural resilience and long-term agricultural sustainability. This includes support from robust cybersecurity and policy frameworks [13].

To address these objectives, the study integrates insights from multidisciplinary research at the intersection of geospatial analytics, intelligent transportation systems, and precision agriculture. It emphasizes how emerging technologies collectively shape the development of resilient hybrid logistics networks. These technologies include IoT connectivity, AI-driven routing algorithms, edge computing, and data security frameworks. The analysis draws on both global literature and regional considerations to identify opportunities and barriers relevant to cold-climate rural contexts like ND. Accordingly, the study is guided by three central questions:

1. How can GIS specifically enhance coordination, routing, and strategic network design in truck–drone hybrid systems for rural agriculture?
2. What technological, regulatory, and environmental constraints impact the deployment of such systems in cold-climate and low-density regions like ND?
3. What specific sustainable benefits have been demonstrated for truck–drone hybrid systems in cold-climate agricultural settings?

The remainder of the paper presents the methodology for the review (section 2), synthesizes findings in the results (section 3), extrapolates implications in the discussion (section 4), concludes the study (section 5) with policy and practice recommendations, and finally outlines research priorities (section 6).

2. Methodology

This study employed a systematic and multidisciplinary literature review, combined with a thematic analysis, to synthesize knowledge at the intersection of geoinformatics, intelligent transportation systems, precision agriculture, and rural logistics. The primary objective was to assess how geospatial technologies and hybrid truck–drone delivery models collectively address infrastructural, environmental, and operational challenges in agriculture.

The structured bibliographic search strategy illustrated in Figure 1 guided the review process. It follows the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines, widely recognized by scholars for its transparency, rigor, and replicability [14]. The search queried four major academic databases: Scopus, Web of Science, ScienceDirect, and SpringerLink. The query command utilized a Boolean search with the following logic:

```
("truck-drone*" OR "UAV" OR "GIS" OR "geographic information systems" OR
"IoT") AND ("last mile" OR "logistics" OR "delivery") AND "agricult*" AND
"rural"
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where the wild-card character "*" represents any alternative ending. To capture recent developments, the review focused on peer-reviewed English language publications from the last decade.

The initial search retrieved 519 records: 372 from Web-of-Science, 99 from Scopus, and 48 from ScienceDirect and SpringerLink combined. The search excluded studies (exclusion criteria) that were not written in English and documents that was not peer-reviewed. The duplicate removal process then reduced those to 482 unique studies. A two-stage screening process followed. The first stage applied inclusion and exclusion criteria to titles and abstracts. The process retained studies (inclusion criteria) if they addressed two core themes from among the following: (1) GIS applications in agriculture, (2) hybrid truck–drone logistics, (3) spatial data analysis for route optimization, or (4) integration of digital agriculture technologies in rural delivery systems. This step produced a refined set of 203 articles.

The second stage applied a quality appraisal protocol (QAP) to evaluate methodological rigor and relevance. The QAP employed eight assessment criteria, as summarized in Table 1. These criteria were GIS integration, hybrid truck–drone technology, last-mile delivery to support agriculture, spatial optimization, use of empirical or quantitative methods, rural contexts, sustainability metrics, and integration of IoT or digital agriculture tools. Two reviewers independently screened all records and resolved disagreements through consensus. The reviewers retained studies that scored at least 5 out of 8 across the criteria. This step retained 82 high-quality publications for full-text reviews.

The reviewers adopted a thematic coding framework, combining inductive and deductive approaches, to classify the studies into the five thematic domains, as summarized in Table 2. These were (1) GIS applications and spatial analytics, (2) truck–drone system coordination, (3) smart agriculture technology integration, (4) rural infrastructure and implementation, and (5) sustainability and economic impact assessment. This framework enabled structured synthesis and facilitated cross-comparison of strategies, models, and outcomes across different regions and technological ecosystems.

To complement the review, this study conducted a term co-occurrence analysis using the tool VOSviewer version 1.6.20 [15]. The tool extracted key terms from titles and abstracts of the selected publications and mapped their relationships based on frequency and co-occurrence strength. The resulting network visualization organized terms into color-coded clusters. The size of each node in the network reflects term frequency, and the thickness of lines connecting nodes indicates the strength of association. This network visualization highlights dominant themes and shows how they interconnect across disciplinary boundaries. By identifying thematic clusters and cross-linkages, the co-occurrence analysis provided insights into the intellectual structure of research on GIS-enabled truck–drone hybrid systems and highlighted the areas where technological, environmental, and operational considerations converge in agricultural logistics. 1

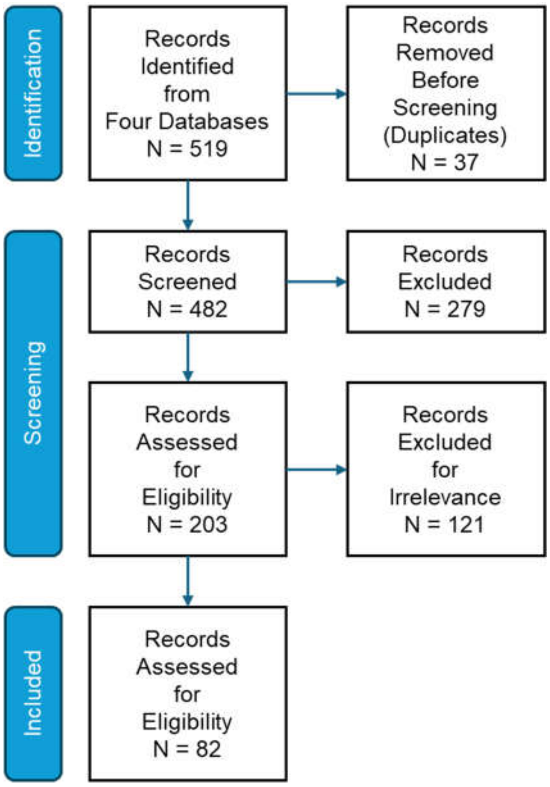

Figure 1. Article filtering following the PRISMA guidelines.

Table 1. Quality appraisal protocol to guide article selection.

Assessment Criteria	Quality Evaluation
GIS Integration in Agricultural Systems	Specifically integrated GIS for agricultural applications, route optimization, or strategic network design.
Hybrid Truck-Drone Technology	Addressed hybrid delivery systems that combine truck and drone technologies for logistics.
Last-Mile Delivery in Agricultural	Explicitly examined delivery challenges and solutions in last-mile deliveries with an agricultural context.
Route Optimization and Spatial Analysis	Investigated spatial optimization algorithms, delivery routing, or site selection methodologies.
Empirical Data and Quantitative Methods	Utilized robust datasets, statistical analysis, or quantitative research methodologies.
Rural Infrastructure Considerations	Addressed challenges specific to rural environments, including terrain, weather, and accessibility factors.
Sustainability and Efficiency Metrics	Evaluated environmental impact, energy efficiency, or cost-effectiveness of delivery systems.
Technological Integration and IoT	Incorporated smart agriculture technologies, IoT sensors, or real-time monitoring systems.

Table 2. Thematic classification of the studies.

Classification	Description
GIS Applications and Spatial Analytics	Focused on geospatial modeling, spatial data analysis, land use classification, remote sensing integration, and GIS-enabled route optimization for agricultural logistics.
Truck-Drone Hybrid System Coordination	Examined vehicle coordination algorithms, launch-and-recovery models, payload optimization, route planning heuristics, and operational efficiency of hybrid delivery systems
Smart Agriculture Technology Integration	Addressed IoT-enabled sensor networks, edge computing, autonomous farm monitoring systems, precision agriculture applications, and data-driven decision making.
Rural Infrastructure and Implementation	Focused on infrastructure limitations, last-mile accessibility challenges in rural areas, regulatory compliance, and deployment strategies for remote agricultural regions
Sustainability and Economic Impact Assessment	Evaluated carbon emissions reduction, energy efficiency optimization, cost-benefit analysis, and environmental externalities of drone-assisted agricultural delivery systems

3. Results

The approach of combining systematic search protocols, multi-criteria evaluation, and thematic categorization, including a term co-occurrence network and clustering, ensured a rigorous review process with multidisciplinary contexts. The outcome was a comprehensive foundation that distilled both strategic insights and technical considerations relevant to researchers, policymakers, and agricultural practitioners seeking to advance GIS-enabled truck–drone logistics. The review identified the seven interrelated domains summarized in Table 3. They were GIS analytics, smart agriculture integration, truck–drone coordination, rural implementation, sustainability assessment, strategic network design, and data security. These domains collectively define the research landscape of hybrid truck-drone delivery systems. Across these domains, the findings reveal how geospatial technologies enhance route optimization, system coordination, and strategic network design while exposing persistent challenges related to cold-weather performance, regulatory constraints, and data security. The following subsections synthesize these insights to establish the technical and contextual foundation for the subsequent discussion.

Table 3. Literature categorization by domain identified.

Domain	Articles
GIS Analytics	[3,4,9,10,16–32].
Smart Agriculture Integration	[6,11,12,33,34,35,36,37,38,39,40,41,42,43,44,45,46,47,48,49,50,51,52,53,54,55,56,57].
Truck–Drone Coordination	[2,53,58,59,60,61,62,63,64,65,66,67,68,69,70].
Rural Implementation	[2,5,58,65,66,67,69,71,72,73,74,75,76,77].
Sustainability Assessment	[61,71,72,74,75].
Strategic Network Design	[59,62,65,66,67,69,76,78].
Data Security	[13,45,48,49,50,51,52,79,80,81,82,83,84,85].

Figure 2 complements the topic categorization by showing a term co-occurrence network that highlights the main research themes linking GIS, drones, and agricultural logistics. The network shows 44 terms that had at least five co-occurrences across the corpus, forming six clusters. The green cluster centers on the term “drone” with occurrences in 54 articles and 26 links to central terms such as delivery, last-mile delivery, emission, cost, demand, and medical supply. These connections reflect operational and environmental aspects of drone-based logistics. The red cluster centers on the term “GIS” with occurrences in 33 articles and 24 links to terms like “geospatial technology,” “information,” “management,” “soil,” and “decision making.” This cluster highlights the role of spatial analysis and data-driven planning. The dark blue cluster focuses on the term “data” with occurrences in 44 articles and links [6,11,12,33–57to 38 terms like “field,” “environment,” “land,” and “performance.” These indicate strong connections between geospatial datasets, environmental monitoring, and precision farming. The purple cluster centers on the term “internet” with occurrences in 24 articles and 25 links to terms like “smart farming,” “communication technology,” and “UAV.”

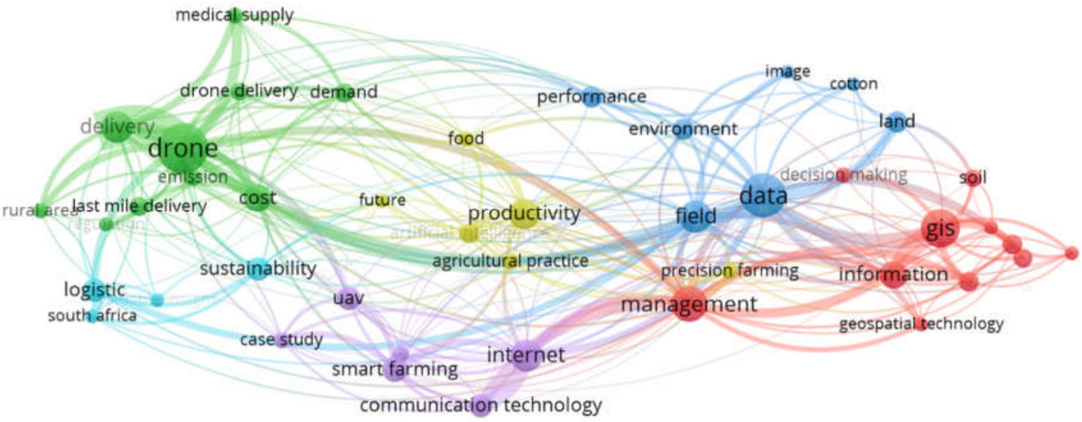

Figure 2. Term co-occurrence and thematic clustering.

These relationships highlight the integration of IoT and connectivity tools with drone applications. The yellow cluster centers on the term “productivity” with occurrences in 22 articles and 32 links to terms like “agricultural practice,” “future,” “food,” “artificial intelligence,” and “precision farming.” These relationships reflect how current and emerging technologies are influencing farm productivity and resource use. The light blue cluster focuses on the term “sustainability” with a strong connection to the term “logistic” as well as cross-links to terms in other clusters such as “field,” “data,” “internet,” and “management.” These cross-connections highlight the leading role of sustainability as a concept bridging operational logistics, technological integration, and data-driven strategic network design. Together, the clusters reveal that research converges on combining drones, GIS, and smart technologies to improve sustainability, efficiency, and strategic network design in agricultural logistics. The subsections that follow provide further insights into the main topics of the categorized literature.

3.1. GIS Analytics for Hybrid Logistics Systems

GIS is essential for planning, routing, and infrastructure placement across various sectors. It has evolved from basic land mapping to advanced spatial modeling [9,10,24,27], including digital-twin systems and smart transportation networks [9,10,24,27]. In agriculture, GIS supports crop mapping, soil suitability analysis, irrigation design, and water quality monitoring [3,16,17,21,23,32]. Studies have also validated its effec-tiveness in emergency logistics and transportation safety analytics [16,22].

Three core capabilities make GIS particularly valuable for hybrid delivery systems. First, site suitability analysis identifies optimal locations for infrastructure, such as verti-ports located at existing airports and hospital heliports [4]. Second, network optimization enhances route efficiency and facility placement across dispersed networks [9,23,32]. Third, dynamic spatial modeling enables real-time operational adjustments through dig-ital-twin systems that improve traffic management using network-wide optimization [9,10,24,27].

Despite these advancements, a critical research gap persists. That is, GIS applications for truck-drone coordination in rural agricultural settings remain underexplored, particularly under challenging operational constraints. In cold-climate regions, hybrid delivery systems face unique challenges such as extreme temperatures, seasonal road closures, limited connectivity, and dynamic infrastructure availability. While GIS could significantly reduce productivity losses, improve delivery efficiency, and enable rapid route adjustments during disruptions, few studies examine how these systems perform under such conditions year-round. This gap limits current understanding of operational reliability and real-time spatial decision-making capabilities in agricultural regions where these constraints are most acute.

3.2. Smart Agriculture Integration

Studies report rapid convergence of IoT sensors, edge computing, machine learning, and cloud platforms. The convergence of such technologies enables real-time monitoring, automated irrigation, yield estimation, and spatial variability analysis. The studies emphasize how the systems reduce input waste and improve timing of farm operations. Another key insight is that they also increase readiness for autonomous workflows through perception, communications, and analytics.

Analysis of 28 studies pertaining to smart agriculture integration confirmed rapid growth of data-driven farming systems. Technology maturity varied significantly across applications. IoT and machine learning improved irrigation, fertilization, and crop monitoring [34,36,37,39–41,45,52]. For instance, tomato cultivation with soil moisture prediction achieved 30 to 40 percent water savings in high evaporation environments [34]. AI reduced chemical use by 20% while improving productivity [51].

Studies examined IoT, AI, and ML integration across farming systems [54]. Three distinct technology maturity levels emerged from the literature. The first is recording technologies for crop and soil scouting. These are commercially deployed with higher adoption readiness. The second is actuation systems for precision applications. These are transitioning from research to commercial products. The third is robotics and fully autonomous workflows. However, these remain primarily in research and experimental stages due to regulatory and safety barriers [39,41,45].

Critical research gaps constrain deployment in cold-weather regions. However, all implementations assumed reliable broadband connectivity. Only three studies addressed low-connectivity scenarios. They focused on delayed data uploads rather than real-time decisions under intermittent network access [34,55,63]. None of the studies quantified cold-weather sensor reliability or provided winterization protocols. Several UAV technical studies mentioned weather dependency. This included battery life limitations, payload constraints, reduced flight range, and weather sensitivity. However, the studies did not provide details such as temperature thresholds, cancellation rates, or performance curves for extreme conditions. No study examined how seasonal connectivity breaks affect machine learning accuracy or winter dormancy data storage policies.

Five major adoption barriers remain. First, sensor data formats are incompatible, and the absence of standardized protocols forces custom integration. Second, farmers lack training to interpret system outputs and resolve technical issues, while extension services lag behind technology development. Third, high initial costs and uncertain economic feasibility exclude many smallholder farmers despite the long-term benefits. Fourth, unclear data-ownership rules and weak privacy protections discourage the data sharing needed for regional optimization. Fifth, policies governing autonomous systems, data rights, and airspace remain fragmented. These barriers are especially severe in cold-climate agricultural regions, where limited connectivity and extreme temperatures create fundamental operational challenges.

3.3. Truck–Drone Coordination

Hybrid truck-drone systems reduce delivery time by assigning long hauls to trucks and final legs to drones. This approach expands service reach in low-density and hard-to-access rural areas [2,58,59]. The literature review identified four major delivery tracks. These were synchronized delivery where truck and drone coordinate closely, parallel delivery with independent operations, truck-assisted delivery where trucks support drone operations, and drone-assisted delivery which emerged recently [62]. Nearly all studies focused on underlying decision and optimization problems with goals to reduce delivery times or costs compared to truck-only or drone-only systems [62]. One study investigated wind impact on drone-based delivery [61]. It proposed a minimum-energy drone-trajectory problem that optimized round-trip trajectories from trucks by adapting drone paths to exploit tailwinds between truck routes and delivery points. The study evaluated this wind-aware trajectory using synthetic and real data with flight simulations in BlueSky simulator.

Routes, drone flights, and battery limits are coordinated using optimization algorithms. For instance, one study applied Mixed-Integer Linear Programming based on authentic Amazon logistics data . The study demonstrated observable decreases in delivery time and cost [65]. Sensitivity analysis revealed how adjustments to important factors such as volume of consumers, number of trucks, and drone usage affect delivery system effectiveness.

One study categorized policy challenges for coordinated drone-truck delivery into six areas: airspace safety and security, zone planning and integration, liability and risk assessment, interoperability and standards, societal challenges and equity, and environment and sustainability [62]. Studies relating to policy challenges emphasized the need for policymakers, operators, and researchers to work in orchestrated manner to achieve sustainable combined drone-truck delivery. In agriculture, drones assist with monitoring, spraying, and crop management by providing real-time high-resolution data collection to enable informed decisions on irrigation, fertilization, and pest management [63,67,69]. Drones offer precision spraying and application of agricultural inputs to minimize chemical wastage and optimize resource utilization. Drones also provide access to areas difficult to reach [67]. This capability reduces manual labor and increases operational efficiency. Therefore, the literature suggests that drones can enhance efficiency across rural landscapes.

3.4. Rural Implementation

However, operational reliability under adverse conditions represents a critical constraint. Wind conditions directly affect flight stability and energy consumption [69]. Aerodynamic planning reduces energy expenditure when wind patterns are incorporated [61]. Temperature extremes influence battery discharge and internal resistance [69]. Path planning algorithms must account for environmental factors [78]. Structural resilience testing under combined cold, wind, and precipitation remains absent from agricultural studies. This gap limits assessment of year-round reliability in cold-climate regions. Although several studies propose aerodynamic optimization [61], multimodal coordination [66], and heavy-lift drone designs [67], these advancements are discussed here primarily to contextualize their relevance to rural agricultural delivery rather than as engineering solutions.

Studies emphasize benefits in rural geographies with long distances, variable roads, and harsh climates [2,5,58,65–69,71–77]. Direct aerial paths mitigate poor road access and seasonal closures. GIS-guided site selection improves launch, landing, and recharge placement. These studies suggest that multimodal coordination improves reliability under environmental uncertainty. Case studies in rural healthcare logistics and humanitarian operations demonstrated relevance to sparse networks.

3.5. Sustainability Assessment

Five studies showed that hybrid truck–drone systems reduce emissions, energy use, and delivery costs [61,71,72,74,75]. Life cycle assessments confirmed about 20% lower carbon emissions and up to 30% cost savings when routes and payloads were optimized. Wind-aware planning and proper drone sizing further improved efficiency [61,71]. One study reported that large drones have lower emissions than diesel trucks for deliveries in rural areas. However, drones do not compete effectively with electric trucks due to high energy demand required for take-off and landing for each delivery [71]. Nevertheless, electric drones are economically more cost-effective than road-bound transport modes due to a high degree of automation and faster delivery times [71]. In addition, electric drones produce less emissions than diesel trucks, especially in rural areas [72]. Empirical testing of 188 quadcopter flights combined with first-principles analysis showed that electric quadcopter drone with 0.5-kilogram package consumes approximately 0.08 megajoules per kilometer [75]. This resulted in 70 grams of carbon dioxide equivalent per package in the United States. Energy per package delivered by drones of 0.33 megajoules can be up to 94 percent lower than conventional transportation modes [75]. Only electric cargo bicycles provide lower greenhouse gas emissions per package. For emission-friendly operations, it is necessary to determine the optimal drone size, particularly for urban use cases [72]. This avoids exceptionally low landings for deliveries and prioritizes home deliveries instead of pick-up points.

A structured review of 59 academic articles examined environmental implications of drone-based delivery systems [74]. Sustainability strategies for small-scale farmers incorporated IoT devices for real-time tracking and machine learning algorithms for green compliance [73]. Overall, studies suggest that these systems support cleaner, faster, and more cost-efficient logistics. They can cut truck trips and strengthen sustainability in rural transport networks. In states like ND, reducing the number of truck trips and promoting safe, efficient last-mile delivery through drones can significantly reduce overall emissions and enhance sustainability in the region.

3.6. Strategic Network Design

Network designs for hybrid truck–drone systems are enhanced through the use of GIS layers, remote sensing, and digital twins. Research emphasized design factors such as moving-hub trucks, in-route resupply, battery swapping, and multi-drone coordination [58,61,64–66,68,75,78]. Efficient routing and scheduling have been achieved using optimization algorithms that reduce delivery time and cost [58,64]. Policy-oriented studies addressed coordination and regulatory challenges for safe deployment of truck–drone systems [61,65].

In agriculture, UAVs enable precision spraying, crop monitoring, and mapping [66]. These applications improve input efficiency and sustainability [68]. AI-based systems enhance route optimization and real-time tracking. They support secure and faster deliver [75]. Advanced path-planning techniques further improve energy efficiency and operational safety [78]. These technologies can modernize the agricultural supply chain, making it faster, cost-effective, and resilient.

3.7. Data Security

Data security is a core requirement for GIS-enabled truck–drone logistics because these systems depend on continuous exchange of spatial, operational, and sensor data. The reviewed studies show that smart-farm and UAV ecosystems face vulnerabilities in communication links, command-and-control channels, edge devices, and cloud platforms [12,55,78,80–82,84,85]. These weaknesses directly affect routing, monitoring, and strategic network design in hybrid systems. Several unresolved challenges apply specifically to GIS-based applications. First, data provenance remains difficult to guarantee because spatial layers originate from heterogeneous sources, including drones, trucks, satellites, and IoT sensors. Prior work highlights this challenge across smart-farm architectures that lack end-to-end verification mechanisms [12,55,84]. Without secure provenance controls, adversaries can inject falsified coordinates or altered layers into routing workflows. Second, location privacy is vulnerable across agricultural contexts. Studies emphasize that smart-farm data streams reveal operational patterns, asset locations, and production activities [12,84]. Continuous geolocation data enables inference of field conditions, inventory levels, and delivery schedules. This increases exposure to surveillance and targeted disruption. Third, GIS workflows remain susceptible to linkage attacks. Smart-farm and IoT reviews note that attackers can cross-reference publicly available imagery, environmental datasets, and sensor metadata to reconstruct sensitive operational details even when identifiers are removed [49,83,84].

More advanced threats include model inversion and adversarial manipulation of spatial layers. Research on UAV security and control-system vulnerabilities shows that attackers can reconstruct sensitive information from machine-learning outputs or alter inputs to mislead system behavior [81,82]. These findings extend directly to GIS-driven hybrid logistics, where adversarial modification of digital elevation models (DEMs), land-use layers, or road-network data could distort route optimization, altitude planning, and launch-site selection.

The potential impact of these threats is significant. UAV cybersecurity reviews show that adversarial control or spoofed coordinates can destabilize flight paths and compromise safety [81,82]. Smart-farm studies report that corrupted data streams can disrupt irrigation, sensing, and automated decision-making [12,55,85]. In GIS-enabled truck–drone logistics, similar attacks could misdirect drones into restricted airspace, route trucks onto unsafe roads, or cause incorrect energy estimates during challenging cold-weather operations [69,77].

Mitigation strategies described in the literature include secure communication protocols, authentication frameworks, privacy-by-design approaches, and local edge processing to minimize exposure to external threats [12,78,80,82,85]. Additional measures needed for GIS-based hybrid logistics include cryptographic tagging of spatial layers, anomaly detection for routing outputs, segmentation of command-and-control networks, and governance frameworks for data ownership and auditability. Without these safeguards, hybrid systems remain exposed to operational disruption, safety hazards, and regulatory risk.

3.8. Regional Research Gaps and Priorities

Systematic comparison of studied contexts with ND requirements reveals substantial research gaps. Hybrid truck-drone studies concentrated on urban and suburban last-mile delivery [57,64,65]. This is in contrast to ND’s dispersed agricultural landscape. Climate modeling addressed typical weather conditions [68], omitting extreme cold (-40°F to -10°F) affecting winter operations. Payload optimization focused on small parcels [43,71,74]. In contrast, agricultural inputs such as seed bags, chemicals, and equipment parts require heavier capacity [66]. Connectivity assumptions presumed cellular or broadband availability [33,38]. This ignores infrastructure limitations in rural areas [54].

These gaps result in three consequences. First, energy consumption models developed for moderate climates substantially underestimate cold-weather battery degradation [60,78]. This renders economic feasibility analysis unreliable for winter operations [77]. Second, routing algorithms [2,58] optimized for concentrated delivery areas fail to address the cost structure of dispersed rural operations where individual farm deliveries span greater distances. Third, regulatory frameworks [61,65] emphasize urban airspace management rather operations across agricultural landscapes where BVLOS restrictions prohibit practical implementation. Overall, existing studies provided foundational concepts but did not validate applicability in contexts combining extreme cold, ultra-low density, heavy payloads, and limited connectivity. This review identifies these gaps and establishes research priorities to enable practical deployment in cold-climate agricultural regions.

Table 4 links these region-specific challenges to findings in the literature, potential benefits of truck-drone systems, and remaining research gaps. Table 5 ranks the most urgent research priorities by their potential impact. Table 6 summarizes the technology gap assessment relative to coverage in the reviewed literature and ND requirements. The authors determined the priority levels in Table 5 based on an integrated assessment of the severity of the operational barrier in ND’s context (e.g., cold temperatures for nearly half the year), the degree that the current literature did not address this issue, and the potential impact on system feasibility, scalability, and cost-effectiveness. The authors scored each factor qualitatively during cross-comparison of the 82 peer-reviewed sources and aligned with stakeholder needs such as yield protection, delivery continuity, and system resilience.

Table 4. ND context: Challenges and GIS-enabled truck–drone solutions.

Challenges	Thematic Category	Truck-Drone Benefits	Remaining Limitations	Proposed Future Research
Sparse population and dispersed farm.	GIS for agricultural logistics.	GIS-enabled route optimization, dynamic hub placement, launch/recovery site selection.	Drone range limitations; rural connectivity gaps.	High-resolution geospatial mapping, dynamic routing algorithms, multi-hub optimization, network coverage modeling.
Time-sensitive delivery.	Truck–drone hybrid performance.	Trucks for bulk long-haul, drones for last-mile delivery.	BVLOS restrictions, payload constraints.	BVLOS operations, hybrid scheduling optimization, payload-capacity modeling, drone-truck coordination algorithms.
Field variability.	Smart agriculture and data systems.	IoT sensors, edge computing, ML-based yield estimation, automated irrigation.	Connectivity gaps, sensor maintenance, data latency.	Edge computing for low-connectivity areas, IoT sensor network design, machine learning for field variability, precision agriculture analytics.
Harsh winter.	Rural and/or cold-weather contexts.	Drones bypass road closures; moving-hub trucks maintain deliveries.	Cold reduces battery efficiency; drone operations are limited by wind and snow.	Cold-weather UAV design, battery performance modeling, weather-adaptive flight planning, environmental risk modeling.
High operational cost and emissions.	Environmental and/or economic outcomes	Hybrid truck-drone reduces truck trips and fuel use.	Large-scale deliveries still depend on trucks.	Life-cycle assessment, energy-efficient UAVs, cost-benefit modeling, sustainable logistics planning.
Low resilience to disruptions.	Operational enablers and design choices	Multi-drone fleets, moving-hub trucks, in-route battery swaps improve flexibility.	Infrastructure failure, power outage, cyber threats remain.	Resilient network design, redundancy modeling, multi-drone dispatch optimization, failure-risk analysis.
Data security and trust.	Security, privacy, and trust	Local edge analytics, privacy-by-design, secure communication protocols.	Cybersecurity threats; adoption hesitancy.	Secure IoT frameworks, privacy-preserving analytics, blockchain for agricultural logistics, trust modeling and adoption studies.

Table 5. Critical research priorities ranked by impact to ND.

Priority	Research Need	Current Gap	Potential Impact	Key Partners	Literature / Evidence	Comments
CRITICAL	Cold-weather battery performance (-40°F to 100°F)	Technology readiness level (TRL) 2-3; zero quantitative studies.	Blocks all winter operations (Nov-Mar = 5 months = 42% of year)	Battery manufacturers; NDSU Materials Science; National labs.	Battery factors; no cold data [78].	71% of studies ignore temperature; winter delivery loss is 42% of revenue.

CRITICAL	Economic models for ultra-low-density delivery.	No studies model fewer than five deliveries per square-kilometer.	Determines financial viability for 26,800 of the farms in the state.	NDSU Agricultural Economics; Farm Bureau; Cooperatives.	Presents costs and suburban density issue [71].	78% of studies assume 10 to 50 times higher density.
HIGH	BVLOS regulatory pathway for agricultural operations.	Generic BVLOS barriers; no agriculture-specific solutions.	Enables operations beyond visual range (> 5 km = 90% of farm delivery needs.)	FAA Great Lakes Region; ND Aeronautics; Congressional delegation.	Policy framework [62]; Identified barrier but no solutions [44].	BVLOS approval unlocks economic viability.
HIGH	Heavy payload (10-50kg) drone design for ag inputs.	Monitoring drones proven; delivery drones 2-10 kg only.	Suitable for actual agricultural input weights such as seed bags, chemical containers, and parts.	Drone manufacturers; NDSU Agriculture Engineering.	Discuss payloads generally [67]; Optimizes for 1 kg [75]; Large drones are inefficient [72].	Current drones are incompatible with ND delivery requirements.
HIGH	Low-connectivity IoT network deployment.	Edge computing proven in labs; deployment costs prohibitive.	Enables real-time monitoring for 40% of farms without broadband.	ND Broadband Office; ISPs; USDA Rural Development.	Demonstrated technology [55]; Requires reliable connectivity [34].	System inoperable for 40% of ND farmland without network.
MEDIUM	Wind-adaptive flight planning for prairie conditions.	Optimization for wind.	Improves safety.	ND UAS Test Site.	Simulations but not real-world [61].	Field testing needed for ND prairie wind patterns.

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Few studies address economic feasibility through cost–benefit analysis, multi-hub networks, or mobile launch strategies [2,4,5]. Heavy-payload drone development (10–50 kg) remains limited. This capability is essential for transporting inputs such as seed bags, fertilizers, and machinery components [44,67,70]. Additional constraints include harsh winters, road closures, high winds [22,61], and poor broadband access. The lack of cellular coverage necessitates alternative satellite-based communications [11]. Focused research in these areas is essential to enable practical and resilient drone delivery systems suited to ND's climate and geography.

Most drone technologies to date have been designed for mild climates, light payloads, and high-density urban or suburban delivery. Consequently, they fall short in addressing cold-weather endurance, heavy-lift logistics, rural connectivity, and large-scale agricultural deployment. The severity of these challenges ranges from critical—such as battery efficiency and thermal management—to moderate issues like wind resistance and farm-scale routing. Accordingly, the top research priorities for drone delivery in ND include cold-weather battery performance, low-density delivery economics, regulatory approval for BVLOS operations, heavy-payload capability, connectivity solutions, and wind-adaptive flight planning. Reliable cold-weather batteries are fundamental to year-round operations. Economic modeling is needed to assess profitability in sparsely populated regions. Expanding flight permissions will be crucial to serve wide farm areas. Redundant communication networks will ensure safe remote operations. Finally, automatic routing adaptation that accounts for strong prairie winds in the region can improve both safety and efficiency. This will advance the practical adoption of drone-based logistics in ND's agricultural landscape.

Although there is limited empirical cost data available specifically for ND, current research often highlights common themes when assessing economic efficiency. Studies show that hybrid truck–drone systems can optimize delivery for last-mile routes in low-density areas. However, this benefit should be weighed against capital and operational costs, including UAV acquisition, maintenance, charging infrastructure, and regulatory compliance. Life-cycle analysis models suggested that cost parity with truck-only models may be achieved when delivery frequency is low, but timeliness is critical (e.g., during planting season). Future modeling should account for delivery density (< 2 per square kilometer), drone lifespan, energy cost, and potential time-based yield increase to determine break-even points for rural agricultural systems.

Table 6. Technology gap assessment.

Technology	Literature Coverage	ND Requirement	Gap Severity
Battery performance	Warm weather only.	-40°F to 100°F operation.	CRITICAL
Payload capacity	1-5 kg parcels.	10-50 kg agricultural inputs.	HIGH
Delivery density	Urban or suburban.	< 5 deliveries per km²	HIGH
Connectivity	Cellular assumed.	Full broadband coverage.	HIGH
Farm scale	Not specified.	1,500+ acre operations.	MEDIUM
Wind conditions	Limited treatment.	Handle 40+ mph wind gusts.	MEDIUM

Table 7 shows a comprehensive review of studies on drone-supported agricultural logistics. It includes truck–drone coordination, rural delivery, smart agriculture, GIS, sustainability, and data security. Several studies show that hybrid truck–drone systems reduce cost and delivery time, especially in rural and sparsely populated areas. They reveal that GIS and spatial analysis are used for farm mapping, site planning, and resource management. Studies discuss how Drones, IoT, and AI support crop monitoring, irrigation, and efficient resources improve productivity. Sustainability studies show reductions in emissions and energy use when drones are combined with trucks. Data security and trust issues are critical for adoption. The literature provides guidance for infrastructure planning, delivery optimization, and policy design. For states with low population density and agriculture-based economies, such as ND, this review shows that farm efficiency can be improved, operational costs can be reduced, sustainability can be enhanced, and rural development can be supported. Hence, this study provides a foundation for future research on drone-assisted agricultural logistics.

Table 7. A unified framework for drone-based agricultural logistics.

Group	Citation	Domain(s)	Study Type	Key Focus	Main Findings	ND Relevance	Limitations
TDC	[1]	Truck–Drone	Modeling	Rural truck–drone system	Cost reduction 10–50%, time reduction 15–40%	High	No cold weather tests
GIS	[2]	GIS	Case	GIS for public services	Useful spatial analysis	Medium	Not agriculture specific
GIS	[3]	GIS	Review	PA GIS overview	GIS essential for precision agriculture (PA)	High	Dated (pre-drone)
RI	[4]	Rural Logistics	Spatial	Rural vertiport siting	Existing sites usable	High	Healthcare focus
SA	[5]	Smart Ag	Review	Drones in PA	Applications summarized	High	Limited logistics
TDC	[6]	Drone Design	Technical	eVTOL efficiency	Payload ranges noted	Medium	Not delivery topic
RI	[7]	Rural Robotics	Review	Last-mile robots	Weather & rules noted	Medium	Ground robots only
GIS	[8]	GIS	Review	Geospatial tech	Digital twins described	High	Broad
GIS	[9]	GIS	Review	GIS applications	General GIS uses	Medium	Not ag/logistics
SA	[10]	Smart Ag	Review	IoT irrigation	Real-time monitoring	High	Connectivity needed
SA	[11]	Smart Ag	Conf.	AI/IoT in PA	Technology potential	Medium	Limited detail
SEC	[12]	Security	Review	Smart-farm threats	Cyber threats listed	Critical	No UAV specifics
GIS	[16]	GIS	Spatial	Crash analysis	Spatial method	Low	Transport-only
GIS	[17]	GIS	Technical	3D digital twin	Twin construction	Medium	Highway-only
GIS	[18]	GIS	Chapter	Policy DSS	DSS framework	Low	Policy focus

GIS	[19]	GIS	Conf.	Disaster planning	Spatial risk mapping	Medium	Disaster-only
GIS	[20]	GIS	Review	GIS in civil engineering	Engineering uses	Low	Dated
GIS	[21]	GIS	Conf.	Geotech GIS	Project planning	Low	Narrow focus
GIS	[22]	GIS	Review	Emergency GIS	Humanitarian lessons	Medium	Emergency focus
GIS	[23]	GIS	Chapter	Water engineering	RS + GIS integration	Low	Water focus
GIS	[24]	GIS	Technical	Canal design	GIS supports design	Medium	Irrigation-only
GIS	[25]	GIS	Chapter	Geospatial education	Education uses	Low	Not operational
GIS	[26]	GIS	Research	Cotton mapping	Spatial extraction	Medium	Crop-specific
GIS	[27]	GIS	Research	Site suitability	Land suitability	Medium	Regional
GIS	[28]	GIS/ICT	Review	African ICT	Adoption review	Low	Non-ND context
GIS	[29]	GIS	Research	Soil suitability	Soil mapping	Medium	Bangladesh crops
GIS	[30]	PA/GIS	Chapter	Data-driven PA	PA data integration	Medium	General
GIS	[31]	GIS	Research	Water quality	RS/GIS for monitoring	Low	Water-only
GIS	[32]	GIS	Research	Irrigation management	Spatial resource management	Medium	Irrigation
SA	[33]	Smart Ag	Conf.	PA risks	Adoption issues	Medium	Russia
SA	[34]	Smart Ag	Research	Smart tomatoes	30–40% water saved	High	Needs connectivity
SA	[35]	Smart Ag	Review	PA in arid regions	Water conservation	Medium	Arid-only
SA	[36]	Smart Ag	Review	PA research	Research overview	Low	Broad
SA	[37]	Smart Ag	Review	AI + IoT	Tech integration	Medium	Limited details
SA	[38]	Smart Ag	Research	Cloud big-data	Cloud analytics	Medium	Cloud reliance
SA	[39]	Smart Ag	Review	IoT overview	High-level benefits	Medium	Conceptual

SA	[40]	Smart Ag	Chapter	IoT & ML	Maturity levels	High	Theoretical
SA	[41]	Smart Ag	Research	UAV–WSN	Advanced monitoring	Medium	Monitoring-only
SA	[42]	Smart Ag	Research	Aerial–ground robots	Multi-system platform	Medium	EU region
SA	[43]	Smart Ag	Conf.	Ag UAS	Early uses	Medium	Dated
SA	[44]	Smart Ag	Review	UAV in ag	BVLOS barriers	High	Regulation limits
SA	[45]	Smart Ag	Research	Edge AI	Low-latency AI	High	Classification-only
SA	[46]	Smart Ag	Review	Tech trends	Economic impacts	Medium	Europe
SA	[47]	Smart Ag	Conf.	Data processing	Processing methods	Low	Narrow
SA	[48]	Smart Ag	Research	YOLOv8 detection	Improved detection	Low	Not delivery
SA	[49]	Smart Ag	Conf.	AI/IoT	General impacts	Low	Limited depth
SA	[50]	Smart Ag	Review	Big data	Adoption barriers	Medium	Conceptual
SA	[51]	Smart Ag	Review	AI in PA	Chemical use ↓ 20%	Medium	India
SA	[52]	Smart Ag	Review	Innovation	Paths to smart farming	Medium	Broad
SA	[53]	Smart Ag	Review	Sustainability tech	Impact assessment	Medium	Broad
SA	[54]	Smart Ag	Review	AI + tech	Recent survey	Medium	Connectivity assumed
SA	[55]	Smart Ag	Review	IoT + UAV	Low-connectivity issues	High	Conceptual
SA	[56]	Smart Ag	Review	IoT + sensors	Hardware review	Medium	Component focus
SA	[57]	Smart Ag	Viewpoint	Sustainability	Policy viewpoint	Low	Opinion
TDC	[58]	Truck–Drone	Systematic	Hybrid LMD	4 delivery tracks	High	Urban examples
TDC	[59]	Truck–Drone	Optimization	Same-day resupply	Resupply improves service	Medium	Urban density
TDC	[60]	Truck–Drone	Review	Resilient LMD	SA resilience issues	Low	Not cold climate

TDC	[61]	Truck–Drone	Optimization	Wind routing	Energy savings	High	Simulation
TDC	[62]	Truck–Drone	Policy	Hybrid logistics policy	6 barrier categories	Critical	Not ag
SA	[63]	Smart Ag + UAV	Pilot	UAV irrigation	Pilot success	Medium	Small scale
SA	[64]	Smart Ag	Review	UAV in PA	Early UAV roles	Medium	Dated
TDC	[65]	Truck–Drone	Optimization	Drone-enabled VRP	Cost/time reduced	High	Urban data
TDC	[66]	Truck–Drone	Review	Multimodal logistics	Trends + issues	High	Limited cold-weather
TDC	[67]	Ag Drones	Review	Drone types	Heavy-lift needs	High	Payload limits
TDC	[68]	Truck–Drone	Strategic	Hybrid model	Performance factors	Medium	Normal weather
TDC	[69]	Ag UAV	Technical	UAV challenges	Weather issues	High	No thresholds
TDC	[70]	Drone Delivery	Review	Delivery methods	Payload limits	Medium	Urban context
SUS	[71]	Sustainability	LCA	Drone–truck system	Emissions decreased by 20%	High	Moderate climate model
SUS	[72]	Sustainability	Comparative	Drone vs truck	Drone cleaner	High	Urban comparison
SUS	[73]	Sustainability	Review	Fresh-produce logistics	Green strategies	Medium	Produce-specific
SUS	[74]	Sustainability	Structured	Drone environment	59-study summary	Medium	Broad
SUS	[75]	Sustainability	Empirical	Drone emissions	94% GHG ↓	High	Small package
RI	[76]	Rural Delivery	Optimization	Speed–safety	Balanced routing	Medium	General
RI	[77]	Rural Delivery	Field	Medical drone	Rural lessons	High	Medical-only
SA	[78]	Decision-Making	Review	Path planning	Energy + battery issues	High	No cold-weather
SEC	[79]	IoT Security	Conf.	Animal monitoring	Basic security issues	Low	Not ag logistics
SEC	[80]	Smart Ag	Conf.	Philippine IoT	Innovation suggestions	Low	Regional

SEC	[81]	Drone Security	Optimization	Medical UAV MDP	Security decisions	Medium	Medical
SEC	[82]	Drone Security	Research	UAV cyber threats	Drone-specific risks	Critical	No protocols
SEC	[83]	Trust	Qualitative	Trust + transparency	Trust needs identified	High	Australian

(Groups: TDC = Truck–Drone Coordination, RI = Rural Implementation, SUS = Sustainability, GIS = GIS/Spatial, SA = Smart Agriculture/IoT/AI, SEC = Security/Privacy).

4. Discussion

While many prior works emphasized drone routing in urban environments, few addressed the operational challenges in ultra-low-density regions [68,76,77]. This review integrates insights into technological, regulatory, and environmental domains to produce a multidisciplinary perspective on hybrid agricultural logistics. The findings confirm that GIS plays a pivotal role in enabling truck–drone hybrid systems by providing the spatial intelligence needed for routing, launch site selection, and monitoring. These capabilities are particularly valuable for states such as ND, where long travel distances, low population density, and severe winters challenge conventional truck-based logistics. Studies in this review consistently show that hybrid systems shorten delivery times, extend service coverage, and improve operational flexibility compared with truck-only methods.

Integrating IoT, AI, and edge computing with GIS further strengthens system adaptability. Real-time sensing and predictive analytics allow delivery routes to adjust dynamically to weather, road closures, and farm demands. These technologies also support precise timing of input deliveries during critical planting and harvest windows. This reduces waste and increases productivity. GIS-enabled positioning for drone launch and recharge infrastructure ensures continuity of operations even under harsh environmental conditions.

From an economic perspective, hybrid systems demonstrate measurable advantages. Evidence from life cycle and operational studies in this review shows that drones can reduce fuel consumption and emissions for small, urgent deliveries while enhancing the efficiency of truck operations. Faster and more predictable delivery during peak agricultural seasons translates into higher yields and cost savings. This validates the potential of truck-drone systems to improve both sustainability and profitability in rural logistics. Moreover, life cycle assessments reviewed suggest that hybrid truck–drone systems can reduce delivery times by 25–40% and fuel consumption by up to 30% for short-range, high-priority deliveries [70,71,74]. These gains are especially relevant during peak agricultural seasons when timely input delivery affects yield outcomes and operational scheduling. Studies emphasize that drones are particularly effective for time-sensitive de-liveries where quick access is critical and road conditions may impede traditional truck routes [59,77].

The review also highlights persistent technical, regulatory, and security challenges. Coordinating drones with moving trucks requires precise path planning and robust communication links. Federal restrictions on BVLOS operations remain a major barrier to scaling such systems in the United States. Additionally, battery limitations, payload constraints, and cold-weather performance issues reduce operational reliability. Cybersecurity risks, particularly those affecting communication networks and data exchange, could compromise both safety and farmer trust if not mitigated through secure and transparent governance frameworks.

Beyond their technical and operational dimensions, GIS-enabled truck–drone systems offer broader societal value. Use cases in humanitarian aid and healthcare logistics demonstrate their potential to strengthen rural resilience and emergency response. Integration with smart farming platforms aligns agricultural logistics with broader sustainability goals. This bridges data-driven strategic network design and environmental stewardship. Collectively, these insights position truck–drone systems as a foundation for next-generation precision logistics that combine efficiency, sustainability, and equity in service delivery.

Although GIS-enabled truck–drone systems demonstrate potential, significant negative impacts persist that constrain full-scale deployment. First, cold-weather degradation of drone batteries limits operability during almost half of the year in ND. This not only undermines delivery reliability but also leads to revenue loss during peak demand periods. Similarly, regulatory barriers such as BVLOS restrictions prevent efficient route design. This often forces suboptimal launch site placements and reduces delivery radius. Economically, the ultra-low-density delivery environment increases cost per delivery. This challenges the economic viability of systems designed for higher density use cases. Furthermore, the lack of reliable broadband impedes real-time GIS data updates and drone telemetry. This poses risks to both safety and efficiency. These challenges should be addressed in tandem through coordinated regulatory reform, hardware innovation, and rural connectivity initiatives. Emerging alternatives such as autonomous ground vehicles and electric trucks offer efficiency gains but remain limited by terrain accessibility and infrastructure needs. In contrast, hybrid truck–drone systems overcome these barriers through aerial flexibility.

5. Conclusion

This review demonstrates that GIS-enabled truck–drone hybrid systems can improve agricultural last-mile logistics in dispersed and cold-climate regions such as ND. By combining the long-haul efficiency of trucks with the flexibility of drones, these systems can shorten delivery times, lower costs, and extend service reach. GIS provides the spatial intelligence for routing, launch-site selection, and real-time monitoring. Furthermore, integrating GIS with IoT and AI supports predictive scheduling and data-driven strategic network design.

Despite these advances, several unresolved gaps constrain practical deployment. Current drones remain limited by cold-weather battery degradation, heavy-payload capacity, and BVLOS regulatory barriers. Insufficient broadband coverage and evolving cybersecurity requirements further challenge operational reliability. Addressing these deficiencies will require coordinated efforts among technology developers, policymakers, and researchers to design resilient platforms and adequate infrastructure.

The next research directions expand on the needs for field validation of cold-weather drone endurance, GIS-enabled optimization of hub and charging-station networks, evaluation of cost-benefit trade-offs under low-density delivery conditions, and the development of secure, adaptive communication frameworks. Pursuing these priorities will advance safe, efficient, and sustainable hybrid logistics that strengthen agricultural productivity and rural resilience in cold-climate environments.

6. Future Research

ND’s vast and sparsely populated agricultural landscape creates complex logistical challenges that conventional truck-based delivery systems struggle to address. Although GIS-enabled truck–drone hybrid systems present a promising solution, several research directions must be pursued to overcome existing technical, regulatory, and environmental limitations.

The highest priority is obtaining regulatory approval for BVLOS operations. ND’s low population density and limited airspace congestion make it an ideal testbed for agricultural BVLOS frameworks. Future studies should develop and evaluate operational protocols tailored to rural environments through collaborative pilot programs involving federal government agencies, state agencies, and research institutions.

A second major focus should be cold-weather resilience. Extreme winter temperatures between –40°F and –10°F require in-depth studies on battery chemistry, thermal management, and weather-adaptive flight planning. Field experiments across multiple seasons are needed to validate drone endurance and reliability in sub-zero conditions. Partnerships among universities, manufacturers, and national laboratories can accelerate advances in cold-tolerant power systems and components.

Third, GIS-enabled infrastructure optimization will be crucial to guide the placement of launch sites, mobile hubs, and charging stations. Spatial analyses should integrate road access, terrain, and seasonal constraints to design cost-effective and energy-efficient networks. Agricultural vehicles could serve as mobile drone hubs. These should be supported by renewable energy sources such as solar or wind power to improve autonomy and reduce operational costs. With these foundational elements established, future work should extend into four cross-cutting domains:

1. Integration with precision agriculture: Research should link drone logistics with IoT-based soil, crop, and weather monitoring systems. The aim is to synchronize deliveries of inputs such as seed, fertilizer, and spare parts with field conditions in real time. Studies should also address heavy-payload capacity and battery recharging strategies to ensure reliable, year-round drone operations in cold climates.
2. Cybersecurity and data governance: Studies must develop secure communication protocols and privacy-preserving data frameworks to build farmer confidence and protect sensitive operational data.
3. Economic and financial modeling: Economic analyses are needed to assess system viability under low delivery densities. The analysis should evaluate cost savings, productivity gains, and potential business models across farm sizes.
4. Environmental assessment: Life cycle analyses should quantify emissions reduction, energy savings, and road-use benefits compared with conventional transport to substantiate sustainability claims.

Collectively, these research priorities define a roadmap for implementing resilient, economically viable, and environmentally sustainable truck–drone systems in cold-climate agricultural regions. Through interdisciplinary collaboration and data-driven experimentation, ND can serve as a national model for advancing hybrid logistics in rural America.

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