

Review

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Review

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

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Abstract

Efficient last-mile delivery remains a major challenge for agriculture in rural regions such as the state of North Dakota in the United States. In these regions, farms are large, dispersed, and dependent on timely access to inputs. Truck–drone hybrid systems offer a potential solution by combining the long-haul capacity of trucks with the speed and flexibility of drones. Economic studies indicate that such proposed hybrid systems can enable faster, lower-cost, and more sustainable delivery of small, time-critical packages. This research further reviews the role of geographic information systems (GIS) in enabling these systems. A combined systematic and thematic review of 82 high-quality publications identifies five domains: GIS applications, truck–drone coordination, smart agriculture integration, rural implementation, and sustainability impacts. The findings show that GIS supports route optimization, drone launch-site selection, and real-time monitoring. Beyond the capacity of drones to extend reach and reduce delays, integrating IoT and AI platforms enhances decision-making and improves efficiency. However, constraints include federal regulations, payload limits, harsh weather (especially in rural areas), and cybersecurity risks. This review concludes that GIS-enabled truck–drone systems can transform agricultural logistics and rural resilience if providers can address regulatory, technical, and security challenges through coordinated innovation.

Keywords: truck–drone delivery; GIS; agricultural logistics; last-mile delivery; rural transportation; precision agriculture; IoT; smart farming; sustainability; supply chain resilience

1. Introduction

Last-mile delivery is the most expensive and complex stage of agricultural logistics. The challenge is especially severe in vast rural areas like the state of North Dakota in the United States. There, farms spread across 38.5 million acres and average more than 1,500 acres each. With about 26,800 farms, long distances separate production sites from supply centers. Reliance on trucks alone increases costs, extends delivery times, and elevates emissions, particularly during critical planting and harvest windows [1].

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 [2]. Drones provide flexible payload capacity from a few pounds to several thousand pounds, depending on their size [3]. Yet their deployment remains constrained by regulations and operational limitations in inclement weather [4]. Restrictions on beyond-visual-line-of-sight (BVLOS) operations by government agencies, combined with North Dakota's harsh winter conditions, require new strategies to ensure operational reliability.

Geographic information systems (GIS) are central to these strategies. GIS enables route optimization, spatial decision-making, and real-time monitoring by integrating maps of farm locations, road networks, and field boundaries. It identifies suitable launch and landing sites, designs

recharge infrastructure, and fuses environmental data into dynamic delivery planning [5]. In agriculture, GIS demonstrates its versatility through the support of soil and crop suitability mapping, irrigation planning, and precision farming [6].

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 [7]. 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 [8].

This study reviews the role of GIS in enabling truck–drone hybrid systems for agricultural last-mile delivery. It presents North Dakota as a representative case of dispersed farms and harsh rural environments. The review examines how GIS supports routing, scheduling, and monitoring. Furthermore, it identifies technological and operational challenges and evaluates economic and environmental benefits. This work also considers cybersecurity, policy frameworks, and the broader role of these systems in rural resilience [9].

The review addresses the following three guiding questions:

1. How can organizations effectively implement GIS-based truck–drone systems in North Dakota to enhance agricultural logistics?
2. What technological and operational challenges constrain deployment of these systems in dispersed, cold-weather environments?
3. What economic and sustainability benefits can farmers achieve compared with truck-only methods?

In addressing the above questions, this study comprehensively integrates interdisciplinary research situated at the intersection of geospatial analytics, unmanned aerial systems, and agricultural logistics. This includes IoT connectivity, adaptive routing algorithms, spatial infrastructure design, and critically assessing systemic barriers.

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), and outlines research priorities before concluding (section 5) with policy and practice recommendations.

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 [10]. 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:

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("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.

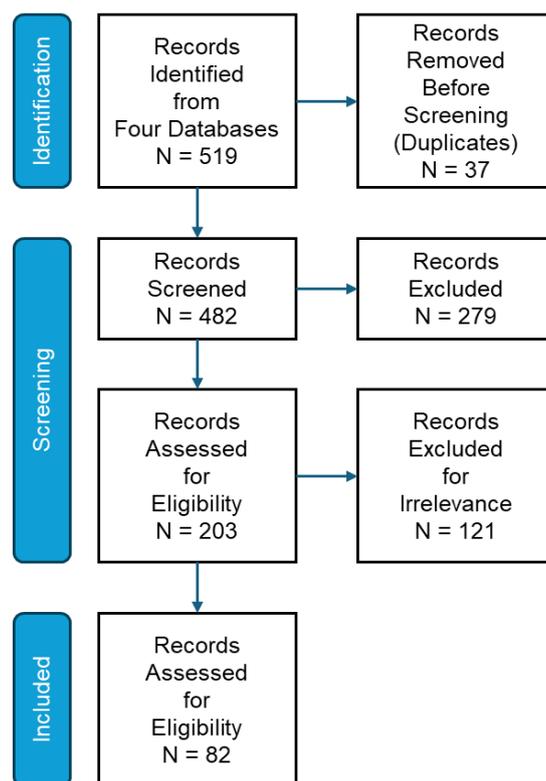


Figure 1. Article filtering following the PRISMA guidelines.

The initial search retrieved 519 records, which the duplicate removal process reduced 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 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. This step retained 82 high-quality publications for reviewing the full text.

A thematic coding framework, combining inductive and deductive approaches, then classified 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.

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 spatial decision-making.
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-based 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	Evaluates carbon emissions reduction, energy efficiency optimization, cost-benefit analysis, and environmental externalities of drone-assisted agricultural delivery systems

To complement the review, this study conducted a term co-occurrence analysis using the tool VOSviewer version 1.6.20 [11]. 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.

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

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 decision-making. Together, the clusters reveal that research converges on combining drones, GIS, and smart technologies to improve sustainability, efficiency, and decision-making in agricultural logistics. The subsections that follow provide further insights into the main topics of the categorized literature.

3.1. GIS Capabilities for Agricultural Logistics

The literature shows that GIS enables route optimization, facility siting, and spatial decision support for dispersed farm networks. It fuses spatial and attribute data, supports geodatabases, and discusses digital-twin workflows. It integrates remote sensing for land-use mapping, crop area extraction, soil suitability, water quality, and irrigation design. Studies emphasize how GIS improves planning at multiple scales and supports emergency and humanitarian logistics. Spatial risk and safety analytics in transportation further validate GIS methods relevant to rural delivery contexts.

3.2. Smart Agriculture and Data Systems

Studies report rapid convergence of IoT sensors, edge computing, machine learning, and cloud platforms. These systems enable 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.

3.3. Truck–Drone Hybrid Performance

Hybrid transport models consistently reduce travel time by delegating long hauls to trucks and final legs to drones. They expand service reach in low-density and hard-to-access places, particularly in large rural areas. Routing and scheduling formulations coordinate truck paths, drone sorties, and battery charging cycles under time windows and range limits. Policy analyses highlight coordination rules and operating constraints. Aerodynamic and wind-aware planning can reduce energy use, as confirmed by feasibility evidence across agriculture and related sectors.

3.4. Rural and Adverse-Weather Contexts

Studies emphasize benefits in rural geographies with long distances, variable roads, and harsh climates. 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. Use cases in rural healthcare logistics and humanitarian operations demonstrated relevance to sparse networks, like those of North Dakota.

3.5. Environmental and Economic Outcomes

Life cycle and operational studies show lower emissions for small, urgent packages and faster service for time-critical deliveries. It was evident that parallel truck–drone systems can reduce cost and lead time when routes and payloads are well matched. The studies suggest that wind-aware flight planning, and prudent drone sizing further improve efficiency.

3.6. Operational Enablers and Design Choices

Results highlight design levers: moving-hub trucks, in-route resupply, battery swapping, and multi-drone fleets. The studies emphasize that path planning must account for terrain, no-fly areas, and recovery on moving platforms. GIS layers, remote sensing products, and digital twins support these decisions.

3.7. Security, Privacy, and Trust

Reviews of smart-farm logistical systems documented threats to communication links, command-and-control, data stores, and edge devices. Those studies recommended authentication, segmentation, and privacy-by-design to protect farm operations and supply chains. They suggested that governance, transparency, and benefit-sharing bolster user trust. Applications also note drone-enabled asset protection, local analytics to cut latency, decision-theoretic dispatch, and perception advances for field safety.

4. Discussion

The results of this comprehensive review confirm that GIS strengthens truck–drone hybrid systems by providing spatial intelligence for routing, siting, and monitoring. This capability validates the technology's relevance in North Dakota. There, farm dispersion and seasonal barriers complicate logistics. The findings were that truck–drone models consistently improve delivery time and coverage. They align with findings from both logistics and agricultural deployments. The hybrid strategy offers a scalable method to bridge the distance between rural depots and farm fields.

The integration of IoT, AI, and edge computing creates opportunities for dynamic operations. Real-time monitoring and predictive analytics reduce waste and support precise input delivery. These capabilities enable decision-making under uncertainty, especially in harsh climates. Studies focused on rural and cold-weather regions demonstrate strong applicability to North Dakota. Direct aerial routing reduces dependence on weak road networks. GIS-based siting of drone launch and recharge stations ensures continuity of service despite environmental constraints.

Economic assessments showed that small-package deliveries by drones cut both emissions and costs when properly integrated with truck fleets. Faster service during planting or harvest seasons directly improves farm productivity. These outcomes validate the system's contribution to both sustainability and profitability.

However, technical and regulatory barriers remain. Coordinating drones with moving trucks requires precise policies, robust sensing, and advanced path planning. FAA restrictions on BVLOS operations continue to limit scalability in the United States. Cybersecurity also emerged as a critical concern. Studies highlighted vulnerabilities in communication, command, and data storage. The adoption of authentication, privacy protection, and transparent governance will be essential for trust. Without these safeguards, farmers may hesitate to adopt smart logistics technologies.

The literature also showed potential broader impacts. Humanitarian and healthcare delivery use cases demonstrated how truck–drone hybrids extend beyond agriculture to rural community resilience. Integration with smart farming platforms further reinforces the role of these systems in future agriculture. Overall, the discussion validates GIS-enabled truck–drone hybrids as both technically feasible and socio-economically valuable. The evidence supports a transition toward precision logistics that is sustainable, data-driven, and resilient. Simultaneously, success depends on advances in regulation, infrastructure, and security.

5. Conclusions

This multidisciplinary and systematic review shows that GIS-enabled truck–drone hybrid systems can transform last-mile agricultural logistics, particularly for rural states like North Dakota. By combining the range of trucks with the precision of drones, these systems reduce costs, shorten delivery times, and expand service to remote farms. GIS strengthens operations by optimized routing, launch-site selection, and real-time monitoring. Integrated IoT and AI platforms further enhance efficiency and sustainability. However, key barriers remain. Federal regulations restrict BVLOS flights, payload and battery limits constrain capacity, and adverse weather poses a challenge to reliability. Cybersecurity and privacy risks also demand stronger safeguards. Addressing these issues requires advances in drone design, resilient infrastructure, and clear policy frameworks. Nevertheless, the broader benefits extend beyond agriculture. Truck–drone systems support

healthcare logistics, disaster response, and rural community resilience. For agriculture, they improve access to time-sensitive inputs, raise productivity, and promote environmental sustainability. Future work should prioritize standardized frameworks, robust cybersecurity, and integration with other smart-farming technologies. Research on scalable models for small farms, renewable energy for drones, and predictive maintenance will strengthen adoption. Coordinated innovation across academia, industry, and policy will be essential to realize the full potential of GIS-informed truck-drone logistics.

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