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Original Research Paper

Application of GIS-Based UAV Systems for Mapping and Monitoring Agricultural Land

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Abstract: Bangladesh faces serious challenges in agricultural mapping and monitoring due to urbanization, climate change, and the limitations of manual methods. This research aims to utilize a Geographic Information System (GIS)-based UAV system for efficient and accurate agricultural mapping and monitoring. The system collects multispectral data on vegetation conditions, soil moisture, and crop growth, and identifies areas affected by drought or pest infestations. The UAV is designed to cover large areas difficult for humans to access, with data integrated into GIS for spatial analysis and precision agriculture-based recommendations. The research methodology employed a quantitative approach with experimental methods and GIS spatial analysis. It was conducted from September to December 2025 in three key agricultural districts: Gazipur, Rajshahi, and Khulna. The multirotor UAV was equipped with a multispectral camera, a high-resolution RGB camera, GPS, and autopilot for coordinate accuracy and automated flight path planning. Image acquisition was conducted two to three times during the growing season, supplemented by soil moisture measurements, weather data, visual observations, and respondent interviews for validation. The results demonstrated that the UAV-GIS system was capable of producing accurate maps of vegetation conditions, soil moisture, and crop stress areas. Field findings indicate that the integration of GIS spatial analysis can detect crop conditions with an accuracy of up to 92%, surpassing conventional methods, which only reach 70%. Furthermore, operational efficiency has increased, with work time reduced from 10 hours to just 2 hours per hectare, and costs reduced from \$25 to \$15. This system aligns with previous studies on the effectiveness of UAVs and GIS in monitoring hard-to-reach areas, supporting precision agriculture practices, and improving productivity and sustainability. Further research could explore fixed-wing UAVs for larger areas, the integration of LiDAR or hyperspectral sensors, the development of AI algorithms for predicting crop stress and disease, and sustainable business models for UAV-GIS adoption in developing countries.

Keywords: Bangladeshi Agriculture, Crop Stress, GIS, Precision Agriculture, UAV

1. Introduction

Bangladesh is in a race against time. A rapid population explosion and massive urbanization are slowly suffocating the availability of productive land, while pressure on natural resources has reached a boiling point. Amid this spatial crisis, the prevailing orthodox agricultural practices are proving inadequate. It's incredibly slow. Monitoring canopy health and soil moisture solely by relying on manual observation is a technical gamble; it places crop productivity squarely at the mercy of extreme weather fluctuations, pest invasions, and overall environmental degradation [1].

We need eyes in the air. The integration of digital technology—particularly Unmanned Aerial Vehicles (UAVs) synergized with Geographic Information Systems (GIS) architecture—is opening the way for executing large-scale land monitoring with astonishing precision. Equipped with multispectral sensor instruments, these drones don't just fly; they "read" the landscape. Crucial metrics such as vegetation index, soil water saturation, and early detection of drought stress in specific areas can be recorded in minutes [2][3]. This abundant raw data is then fed into the spatial analytics kitchen of GIS to produce sharp topographic maps. The result? Precision agriculture recommendations that are no longer based on blind guesswork, but rather on precise calculations for irrigation maneuvers, fertilizer distribution, and crop failure risk mitigation [4].

The presence of UAVs is breaking down the physical boundaries that have held humans hostage. Remote areas can now be mapped in real time with a depth of data that makes traditional survey methods seem archaic. This synergy between aerial hardware and analytical software ultimately empowers farmers to make evidence-based decisions. Decisions are made faster. Financial losses due to weather or pests are minimized [5]. This is the essence of sustainable agriculture: we maximize the land's potential without sacrificing its ecological future [6] [7].

This is where our research takes a definitive stance. Our mission is to engineer the agricultural land mapping system in Bangladesh to be far more aggressive and efficient using a GIS-based UAV ecosystem. The focus of our intervention is very specific: distilling aerial multispectral imagery into concrete data related to vegetation health, water deficits, and growth pattern anomalies in the field. We aim to capture drought stress signals long before the canopy completely dies, especially in large fields that are impossible to monitor on foot. Integrating these aerial images into a GIS spatial analysis framework is expected to provide valid data for formulating irrigation and fertilization strategies. Providing a solid database foundation to support the resilience of precision agriculture is the spirit of this study.

2. Literature Review

2.1. Challenges of Agricultural Management in Bangladesh

Managing agricultural governance in Bangladesh today is like untangling a tangled web. This vital sector is being buffeted by structural obstacles from all sides. Uncontrolled population growth collides directly with land shrinkage due to urbanization and brutal climate shifts. The impact directly impacts productivity. The various literatures on precision agriculture discourse agree on one stark conclusion: conventional methodologies fail to address real-time demands. Human visual limitations make this sector extremely fragile [8]. Their agriculture is vulnerable. The slightest weather anomaly or the emergence of a new pest can lead to massive losses. The more climate change ravages, the more urgent our need for modern monitoring instruments becomes.

Global discourse has loudly positioned UAVs and remote sensing as essential artifacts. The maneuverability of drones in extracting ultra-high-resolution vegetation data has clearly rendered ground-based methods irrelevant [9]. Equipped with thermal and multispectral lenses, these aerial vehicles can detect land variability and canopy quality in the blink of an eye. Plant health diagnoses become sharp and undeniable [10].

These drones cannot operate in isolation. UAV data acquisition necessarily requires a partnership with GIS applications to ensure its spatial narrative is human-readable. This technological marriage produces highly specific zoning maps. Take a recent case study in Bangladesh, for example. GIS interventions combined with satellite profiles data have proven effective in revealing soil, leading to a complete overhaul of how farmers distribute their resources in the field [8].

On the other hand, drones are here to fill the fatal gap left by satellite monitoring. Satellites are vast, but they are rigid. Drones offer flexibility; these fleets can patrol at high frequencies to track crop reactions to environmental stressors day by day [9]. This flexibility is an essential luxury. For developing countries where the weather can change 180 degrees in a matter of days, this micro-observation is a harvest-saving measure.

These aerial sensors are becoming key building blocks for predictive algorithms. By extracting mathematical indices such as NDVI, we can not only map field stress but also project the future of the crop itself [10]. Multispectral sensors can detect nutrient deficits or early insect bites long before the farmer's naked eye notices a problem [11]. Early detection is key. This moment of early intervention is what saves profit margins.

While it may sound revolutionary, the reality on the ground is never as rosy as academic texts. The adoption of this cutting-edge technology is haunted by the looming threat of startup costs. Not to mention the digital literacy crisis and the headache of integrating hardware with software infrastructure. This sophisticated ecosystem demands a radical upgrade of human resource skills, as well as the injection of affirmative policies to ensure long-term survival for small-scale and medium-scale farmers [12]. Isolation from technological access and weaknesses in data processing remain major stumbling blocks of concern.

Looking at future research trends, the fusion of drones, remote sensing, and artificial intelligence (machine learning) will accelerate uncontrollably. Machines are now being taught to crunch thousands of parameters from various sensors to produce incredibly accurate and robust crop prediction models [13]. This integration of complex algorithms is forcing agricultural decision-making to shift to lightning-fast, evidence-based processes.

For Bangladesh, this isn't just a matter of modernization. It's a matter of survival. The integration of UAVs, GIS, and remote sensing is a sledgehammer for breaking down outdated land monitoring constraints, providing spatial intelligence ammunition to turn the tide amidst the increasingly uncertain climate crisis.

The use of drones in precision agriculture is exploding rapidly. The reason is simple: spatial resolution. These tools are capable of capturing layers of detailed data impossible for conventional ground observation. Armed with multispectral sensors, drones capture vital metrics related to soil moisture and canopy vitality to support rational land management [14]. At this point, this technology essentially gives us superhuman eyes. Humans can now peer into the invisible light spectrum, detecting environmental stress from the air even before plants show physical signs of wilting [14].

2.2. The Role of UAVs in Agricultural Land Monitoring and Mapping

These multispectral lenses are adept at tracking vegetation dynamics through the extraction of indices such as NDVI, GNDVI, and SAVI, the parameters that have now become the gold standard for remote sensing. This synergy triggers instant classification, mapping healthy plots and stressed areas across a field [14]. Drones are no longer just mechanical toys. It has evolved into an essential instrument for monitoring growth rates, tracking pest infestations, and even calculating the absolute amount of water and fertilizer needed [14]. This practice is empirically valid. Airborne spectral analysis has been proven to accurately measure nutrient status, biomass accumulation, and even project harvest volumes [14] [15]. We combine low-flying maneuvers with high computing power to produce thematic maps. The process is rapid, far surpassing the slow, capital-intensive, and time-consuming methods of walking surveys [14].

When it comes to maneuverability, satellites are clearly inferior. They are rigid, orbit-bound, and often crippled by thick cloud cover. Drones offer something else. They can hover over the same coordinates repeatedly, whenever time calibration demands it. This fleet is capable of infiltrating vast swaths that have been a logistical nightmare with conventional methods [15]. A monumental breakthrough, especially for the landscapes of developing countries where infrastructure and resources are scarce.

Various literature demonstrates that injecting machine learning into multispectral data streams can radically improve the accuracy of pathogen detection and moisture profiles. This marriage of deep learning and aerial footage has successfully reconstructed land cover classification models with astonishing precision [16]. This is highly relevant, especially when discussing precision agriculture interventions in the tropical belt, where weather anomalies and pest ecosystems fluctuate wildly [15] [16].

Deploying drone operations in the field is fraught with technical friction. There are a number of complex issues: sensor calibration, which often deviates due to fluctuations in sunlight, and a scarcity of talent capable of transforming raw data into analytical intelligence [17] – [19]. Calibration adjustments are non-negotiable. Even the slightest deviation in data can destroy the validity of vegetation parameters throughout the growing season [17]. This technical complexity is slowly becoming a major stumbling block in the smooth adoption of sustainable agriculture in third-world countries [20] - [22].

2.3. Integration of UAVs with GIS for Spatial Analysis and Decision Making

Integrating aerial data into Geographic Information Systems (GIS) architecture is no longer just an option. It's dogma. This is where its computational heart lies: the central furnace where millions of raw pixels are brutally refined into super-sharp, thematic maps [23] [24]. The multispectral lens merely captures light reflections. The GIS does the execution. These algorithms ruthlessly dissect growth anomalies across zones, exploiting metrics like NDVI to reveal the true vitality of the canopy in the field [25].

This intimate connection between the sky's pixels and the analytical engine yields a terrifying spatial acuity. The maps these systems produce are not merely passive visual displays. They are dictated. An empirical, evidence-based mandate for executing irrigation maneuvers, determining fertilizer doses, or launching precision pesticide attacks [26]. In this ecosystem, GIS acts as a stabilizing anchor. It tames the chaotic sea of spatial data and simplifies the complexity of soil fluctuations into models that can be rationally understood by humans.

Limiting oneself to a single camera eye often leads to technical naivety. This is where fusion techniques must take over. Micro-resolution drone imagery is deliberately combined with macro-scale satellite imagery through spatial interpolation [27]. The result? An incredibly sharp monitoring instrument. The agility of the aerial fleet is combined with the breadth of its orbit. Land slowly suffocating from dehydration or beginning to be eaten away by pathogens can be immediately isolated in a matter of hours. Through GIS analysis, these vegetation index records are not simply photographed but sequenced along historical trends dating back to the first seed planted. This provides practitioners with undeniable scientific legitimacy every time they press the micro-irrigation button [28]. Moreover, this fusion has now gone beyond mere cartography. It has transformed into the driving force behind Decision Support Systems (DSS). Once these spatial models are combined with artificial intelligence, the systems can detect past anomalies to project critical land points, long before botanical disasters actually occur [29].

This hybrid approach fundamentally undermines the outdated agricultural paradigm. Sweaty on-foot observations have officially been replaced by instant synchronization from the cloud. Thanks to the power of GIS, a pile of drone pixels can easily be transformed into a highly pragmatic daily command map for maneuvering in the field [30]. The challenge? Purely infrastructure brutality. This sophisticated ecosystem could collapse at any moment if the server fails to crunch big spatial data without crashing, if data overlapping distortions occur, or if the georeferencing accuracy is off by even a few centimeters [26]. But beyond all the technical complexity behind the scenes, the end result is crystal clear. The absolute synergy between UAV instruments and GIS computing offers a mitigation of land logistics risks that has so far been unrivaled; a radical leap that is poised to redefine the face of modern agricultural management in this century [25] [30].

3. Methodology

Our primary tool is a multirotor UAV equipped with a multispectral camera module (RGB, Red, Green, Blue, and Near-Infrared). The entire mission was executed autonomously under very strict technical parameters:

1) The cruise elevation was locked in the range of 80-120 meters, achieving a Ground Sample Distance (GSD) of 5 cm per pixel.
2) Imagery overlap was set at an absolute 75% frontal area and 70% lateral. This was a prerequisite for seamless map mosaic reconstruction.
3) Operation duration was kept at 20–30 minutes per sortie to ensure efficient coverage.
4) All raw data was captured by the drone's internal memory and then instantly injected to a local server via 2.4 GHz radio frequency for analysis.

This raw imagery was then dragged into GIS software. This is where vegetation indices (NDVI and NDRE) were extracted and calculated. This series of metrics served as the demarcation line for classifying plant vitality and isolating stress zones. Aerial imagery alone was, of course, insufficient.

We combined this sky data with ground-based moisture sensor penetration and historical weather data. This cross-fertilization gave birth to the Land Zoning algorithm. Agricultural areas were divided into three definitive classes: Healthy, Moderate, and Critical. The final output of this research was a thematic map sheet, a visual spatial manifesto ready to dictate precise irrigation and fertilizer management systems, based purely on objective diagnoses of each plot of land.

4. Finding and Discussion

4.1. Findings

4.1.1. Land Mapping Results

UAV flight maneuvers and GIS spatial analysis have finally spoken. The raw data has transformed into a topographic map that is not only accurate but also straightforward. This map lays everything bare, from how dense the vegetation canopy is, to how wet the ground is, to detecting the exact coordinates where plants are crying out due to environmental stress.

1) Vegetation Condition Map

By exploiting the NDVI and NDRE index formulations, multispectral imagery successfully filters land cover into three spectrums: healthy, moderate, and critical. The distribution? Very uneven between locations. Just look at Gazipur. This area seems like an agricultural paradise, with 70% of its vegetation growing luxuriantly without flaws. The remainder is mapped as 25% moderate and only 5% with a thin canopy. The biophysical conditions there truly pamper the roots.

Table 1. Distribution of Vegetation Conditions Based on NDVI

Research Location	Healthy Vegetation (%)	Temperate Vegetation (%)	Less vegetation (%)
Gazipur	70	25	5
Rajshahi	55	35	10
Khulna	60	30	10

The reality takes a 180-degree turn when we shift our lens to Rajshahi. The rice paddies there seem to be struggling to withstand the onslaught of a harsh climate. Only 55% of the stands remain in the healthy zone. The moderate vegetation figure swells to 35%, and the remaining 10% is in poor condition. What about Khulna? This region exhibits a completely different pattern. Its ecosystem is complex. The brutal mix of fish ponds and rice paddies results in extreme vegetation variation: 60% healthy, 30% moderate, and 10% vulnerable. This wild variability is precisely the foundation for dictating future precision agriculture strategies.

2) Soil Moisture Map

Soil moisture maps constructed from UAV sensor fusion and ground-based measurement instrument calibration, provide that water availability in these three regions fluctuates significantly. Gazipur once again excels. Irrigated land is moist and stable. Rice paddies average 72% moisture, rain-fed land 65%, and horticultural areas 68%. Ideal.

Table 2. Average Soil Moisture (%) per Location

Research Location	Rice Fields	Rainfed Land	Horticulture
Gazipur	72	65	68
Rajshahi	60	45	50
Khulna	65	55	60

In Rajshahi, the soil is parched. Rice paddies can only absorb 60% moisture. Rain-fed land is far more dire, languishing at 45%, while horticultural areas are stuck at 50%. This severe soil dehydration is a ticking time bomb. It has the potential to trigger systemic stress in crops if irrigation infrastructure is not promptly intervened. Khulna, on the other hand, is in a fluctuating zone with medium to high moisture (Rice 65%, Rain-fed 55%, Horticultural 60%). The anomalous spike in this region is likely driven by water infiltration from nearby fisheries. This data is not just a series of dead numbers; it is the primary compass for executing irrigation precisely without wasting a single drop of water.

3) Identify Plant Stress Area

Sensing stress before plants actually wilt. This is the most crucial function of our system. The combination of a drop in NDVI (below 0.4) and a soil moisture deficit is an absolute indicator of physiological stress. Gazipur is virtually free of this problem. Only about 5% of its horticultural area experiences mild stress. Moderate or severe? A big fat zero.

Table 3. Percentage of Plant Stress Areas per Location

Research Location	Mild Stress (%)	Moderate Stress (%)	Heavy Stress (%)
Gazipur	5	0	0
Rajshahi	4	6	0
Khulna	3	7	0

Moving to Rajshahi, the disaster begins to become clear. A prolonged drought has forced 4% of the land to suffer from mild stress, while another 6% has entered the moderate stress phase. Rice crops there are truly suffering from the drought. Meanwhile, in Khulna, stress comes from a more lethal combination: water fluctuations and soil salinity intrusion. Three percent of this coastal area is diagnosed with mild stress, and another 7% with moderate stress. Early mapping of these diseased areas will become the fundamental basis for formulating land management prescriptions. There should be no more guesswork.

4.1.2. Spatial Analysis and Land Zoning

Aerial imagery without the analytical tool of GIS is merely a meaningless snapshot of the landscape. This is where spatial computing takes control, dividing the land demographic into absolute zoning blocks, providing operational mandates for precision irrigation and fertilization.

1) Distribution Zone

The combination of NDVI and NDRE parameters creates three land demarcation classes: Healthy, Intermediate, and Critical. In Gazipur, green status dominates. Seventy percent of the horticultural landscape rests securely in the healthy class. A quarter of the area falls into the intermediate category, and the remaining 5% struggles in the critical zone. The vitality of the ecosystem here is assured.

Table 4. Percentage of Plant Health Zones per Location

Research Location	Healthy Zone (%)	Medium Zone (%)	Unhealthy Zones (%)
Gazipur	70	25	5
Rajshahi	55	35	10
Khulna	60	30	10

The landscape in Rajshahi, by contrast, is stifling. Only 55% of the rice plots qualified for the healthy zone. The rest were suffering from dehydration; 35% were stranded in the intermediate zone, and 10% were declared critical due to the relentless dry weather. Khulna is back again.

2) Based Zone

This zoning map isn't just a passive visualization tool. It definitively dictates field actions. Spatial analysis dissects the specific needs of each demarcation, revealing what the soil truly requires for root respiration. Routine irrigation and standard fertilizer applications are sufficient interventions to maintain growth momentum. The story is different when we look at the intermediate zones. Land at this point is demand extra water injections and focused fertilization maneuvers to break canopy dormancy.

Table 5. Irrigation and Fertilization Recommendations by Zone

Health Zone	Irrigation Recommendations	Fertilization Recommendations
Healthy	Routine irrigation	Standard fertilization
Medium	Irrigation supplements	Focused fertilization
Unhealthy	Intensive irrigation / adjustment	Optimal fertilization + improved conditions

Front-line interventions are required: overhauling irrigation architecture, repairing soil structure from the grip of salinity, and aggressively calibrating fertilizer doses. With this instructional cartography, land managers are no longer left feeling lost. The direction is completely transparent. Resource allocation becomes razor-sharp, ensuring every drop of water and particle of ammonia falls precisely where it needs to.

4.1.3. Effectiveness of UAV GIS Systems

Bringing this system to the open field is a true proving ground. Does this technology truly disrupt old methodologies? Our field validation results, directly supported by expert respondent testimony, deliver a resounding blow. The UAV-GIS ecosystem ruthlessly crushes orthodox monitoring methods in terms of efficiency, diagnostic precision, and range penetration.

1) Comparison of Time and Cost with Traditional Methods

The use of drones is often debated due to the perceived high initial hardware acquisition costs. But consider the future balance sheet. Manual field monitoring, which takes up to 10 hours per hectare, is a tragedy of inefficiency. It's incredibly slow. UAV-GIS reduces that torturous time to just two hours. This mechanized fleet takes off, scans massive expanses of land in a single maneuver, and then lands with a sea of mature spatial data. Medium-term operational costs plummet, from $25 per hectare using human labor to $15. We radically reduce reliance on ground observers. It's much cheaper, faster, and eliminates the risk of physical exhaustion.

Table 6. Comparison of Land Monitoring Time and Cost

Method	Time per Ha (hours)	Cost per Ha (USD)
Traditional	10	25
UAV-GIS	2	15

2) Improved Monitoring Accuracy

The UAV-GIS system surpassed 92% accuracy, while on-foot observations stalled at 70%. The human eye is often deceived.

Table 7. Comparison of Monitoring Accuracy

Method	Condition Detection Accuracy (%)
Traditional	70
UAV-GIS	92

They often fail to notice minor anomalies in the canopy or fluctuations in soil moisture before the symptoms become visible. In contrast, these sky sensors detect stress from the first day of wilt. This diagnostic precision gives farmers the luxury of time to trigger an intervention alarm before an ecological crisis consumes half their fields.

3) Ability to Reach Hard to Reach Areas

Agriculture isn't always a welcoming, flat landscape. Sometimes, dense irrigation canopies, foot-sucking swamps, or stretches of salty soil create physical barriers for observers. These blind spots hinder manual penetration. They can only map 75% of the total area. The rest is left untamed and unsupervised. The deployment of UAVs is a tangible manifestation of the accessibility revolution. These drones don't care how thick the mud beneath them is. Flying above geographic limitations, this system successfully achieved absolute coverage of up to 100%. Not a single centimeter of land was overlooked by the analytical scan. Our data integrity was ultimately uncompromised.

Table 8. Area Coverage

Method	Percentage of Area Covered (%)
Traditional	75
UAV-GIS	100

4.2. Discussion

This experiment confirmed a quantum leap in the quality of agricultural information in Bangladesh. The UAV-GIS system doesn't simply summarize data; it dissects reality. Based on the representation in Table 1, the dominance of 70% healthy vegetation in the Gazipur region absolutely correlates with the hydrological stability of its irrigated land, which is able to lock moisture at an optimal level of 72% (Table 2). Nutrients and water are distributed perfectly. Without the support of multispectral data, these subtle variations at the canopy level would be impossible to detect with the naked eye before permanent physical damage to the plants becomes permanent.

The contrasting reality hit Rajshahi. The arid microclimate massively depressed plant biophysical parameters. The decrease in soil moisture to a nadir of 45% in rainfed land directly impacted the increase in the percentage of moderate (35%) and critical (10%) vegetation. Scientifically, water deficit drastically reduced reflectance values in the near-infrared (NIR) band. The results were evident in the detection of moderate stress by 6% in the region (Table 3). However, data extraction from Khulna revealed a far more provocative anomaly. Soil moisture was not the sole driver of vitality. Although this coastal area recorded adequate physical water availability (55–65%), its crop stress levels actually exceeded 7%. Salinity intrusion was the culprit. Salt accumulation impaired the osmotic capacity of roots, triggering severe physiological stress amidst abundant water supplies.

The early diagnosis of this biophysical anomaly underpinned the automated formulation of spatial zoning (Table 4). The system successfully established a threshold of NDVI values below 0.4 as a high-precision alarm for detecting crop stress. Rather than maintaining orchards with a blanket assumption, this mapping forced land managers to implement a rigid differential strategy. The outdated approach of uniform rate application was officially abandoned. Healthy zones were allowed to thrive with routine maintenance. Instead, 35% of the medium-sized fields in Rajshahi were immediately targeted with input modifications such as extra water injection and site-specific fertilizers (site-specific crop management). Unhealthy zones? They were immediately quarantined for comprehensive amelioration interventions such as salt leaching. The integration of the operational guidelines in Table 5 theoretically and practically minimizes resource waste to the lowest point.

The long-standing debate regarding the techno-economic feasibility of this system has finally been resolved. The adoption of UAV-GIS demonstrates exponential advantages that outperform terrestrial methods in efficiency (Table 6). On-foot observations take 10 hours per hectare. It's incredibly slow. Amidst the threat of an agricultural labor crisis, aerial photogrammetry maneuvers reduce that to just two hours. This temporal efficiency directly impacts mid-term operational costs, dropping from $25 to $15 per hectare. This fact strongly confirms that the high capital expenditure for drone hardware is ultimately fully offset by operational savings in the field.

The significance of this aerial instrument becomes even more absolute when compared to diagnostic precision metrics. The human eye carries inherent biological defects. This limited visual acuity limits manual observation accuracy to 70% (Table 7), which often creates bias when identifying minor fluctuations in leaf cellular structure in the early stages of stress. UAV-GIS breaks through these limitations with a surge in accuracy exceeding 92%. Electromagnetic waves outside the visible spectrum are captured without mercy. Farmers now have the luxury of time thanks to this early warning system to mitigate crop failure before symptoms of chlorophyll necrosis appear.

Beyond spectral issues, spatial friction is no longer a barrier. Bangladesh's agricultural landscape, characterized by mudflats, dense canopies, and salt-covered soils, often presents blind spots. Ground observations are forced to settle for a coverage ratio of 75% (Table 8). Leaving even a quarter of the field unattended is a fatal oversight that would distort the entire ecological model calculation. Unmanned aerial vehicles eliminate these limitations. Their vertical and horizontal mobility allows for absolute spatial coverage penetration of up to 100%, resulting in a comprehensive database free from interpolation errors and information gaps.

5. Conclusion

UAV-GIS architectures do not merely improve conventional land monitoring in Bangladesh, they render it fundamentally obsolete. Diagnostic accuracy now scales to 92%. The system extracts high-fidelity NDVI/NDRE indices and soil moisture profiles with surgical precision. It even penetrates the hostile, saline tracts of Khulna. Historically, monitoring these fragmented zones manually was a logistical nightmare. No longer. The operational metrics are equally disruptive. Acquisition time is crushed from a grueling 10 hours down to a mere two hours per hectare. Corresponding expenditures plummet by 40%. Crucially, the resulting zoning maps transcend passive visualization. They are tactical blueprints. Agronomists can instantly translate these spatial grids into precise, variable-rate irrigation and fertilization commands. Yes, the initial hardware capital is steep. Yet, this upfront friction is rapidly absorbed by sustained operational savings and the aggressive mitigation of catastrophic crop failure. The techno-economic viability of this system is no longer speculation. It is a proven reality.

The analytical boundaries of this framework must be pushed further. Consider the fusion of aerial datasets with terrestrial IoT sensor networks. This synergy would enable autonomous, real-time microclimate surveillance. The computational engine must also evolve. Unleashing deep learning algorithms onto raw multispectral imagery holds immense potential for the preemptive detection of specific pathogens and pest infestations. Beyond immediate biophysical diagnostics, we must capitalize on historical vegetation indices. Developing robust crop yield prediction models is absolutely critical to fortify national food security planning. Finally, the socio-economic barrier must be dismantled. The luxury of spatial intelligence cannot remain monopolized by heavily capitalized investors. Investigating accessible operational frameworks, specifically the "Drone-as-a-Service" (DaaS) model, is imperative. True agricultural resilience demands data democratization, ensuring that even the most remote smallholder farmers in Bangladesh are equipped to survive an unpredictable climate.

Author's Declaration

The authors hereby declare significant contributions to the research process, manuscript preparation, and publication stages.

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