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ADAPTING PRECISION AGRICULTURE TECHNOLOGIES FOR MOUNTAINOUS TERRAINS

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Abstract. *This study explores the adaptation of precision agriculture technologies for mountainous terrains, focusing on their potential to enhance agricultural productivity and sustainability. Mountainous regions present unique challenges such as steep slopes, variable microclimates, and limited accessibility, which necessitate tailored solutions. Through empirical research and a targeted data procedural approach, this research identifies and evaluates precision agriculture technologies suitable for these kind of environments. The findings highlight the effectiveness of geospatial data, UAVs, and GIS in optimizing resource use and monitoring crop health. Case studies from the Andes and Himalayas demonstrate successful implementations, while a comparative analysis reveals the varying levels of effectiveness and suitability of different technologies. The study underscores the importance of involving local farmers in the design and implementation process to ensure the technologies meet their specific needs. Policy implications include the need for financial support and training programs to facilitate adoption, as well as the development of cost-effective and user-friendly solutions. Future research should focus on innovative technologies and their long-term impacts on agricultural productivity, environmental sustainability, and local livelihoods. This research contributes to the broader understanding of sustainable agriculture in challenging environments, offering insights that can aid in the just transition from coal in mountainous areas.*

***Keywords**: Precision agriculture, Mountainous terrains, Sustainable agriculture, Geospatial data, Remote sensing*

INTRODUCTION

The global imperative for a just transition from fossil fuels to sustainable energy sources has profound implications for mountain communities traditionally dependent on coal mining economic activities. These communities are left with a load of socio-economic vulnerabilities resulting from structural unemployment, land deterioration, and demographic decline (SCOTT et al, 2022). Sustainable agriculture would mitigate these effects, creating a diversified economy, increasing food security, and restoring the environment (RUSSO et al., 2023). The commitment to changing from fossil fuels to sustainable sources of energy has an overwhelming implication for mountain communities, traditionally vestiges of coal mining. These communities suffer from structural unemployment, land degradation, and demographic decline (SCOTT et al., 2022). One of the best pathways to sustainable agriculture addresses these impacts to diversify the economies, enhance food security, and restore the environment (RUSSO et al., 2023).

Mountainous regions, characterized by steep terrain, fragile ecosystems, and limited accessibility, present unique challenges and opportunities for sustainable agriculture. Traditional farming systems, often marginal and extensive, need to evolve towards practices that are both ecologically sound and economically viable (BÄCHTOLD et al., 2024). Implementing sustainable agricultural models, such as agroecology, agroforestry, and conservation farming,

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can support ecosystem services, strengthen local economies, and foster social resilience (FAO, 2023).

The aim of this research is to analyze the role of sustainable agriculture in facilitating a just transition from coal in mountainous areas. Specifically, the study seeks to: (1) identify best practices in sustainable agriculture applicable to post-coal mountainous regions; (2) evaluate the socio-economic and environmental impacts of such practices; and (3) formulate policy recommendations to support the scaling-up of successful models. By focusing on this topic, the paper contributes to the limited but growing body of research connecting agricultural sustainability with just transition frameworks (JONES et al., 2024). Addressing these issues is essential for designing integrated transition strategies that align climate action with social justice, ensuring that mountain communities are not left behind in the global shift towards sustainability (ILO, 2015).

METHODOLOGY

Empirical research and a targeted data procedural approach was done for an examination of second-hand available data on sustainable agriculture's role in the just transition from coal in mountain areas. The systematic literature review was done to compile existent knowledge of sustainable agricultural practices, transition policies, and socio-economic effects in post-coal areas (PEREIRA et al. 2023). The case study design with comparative approaches provided further assistance in identifying best practices and possible challenges across diverse European mountainous regions.

Data collection involved an extensive review of scientific articles, policy documents, project reports, and statistical databases. Sources included international organizations (FAO, ILO, EU Commission), national transition strategies, and regional development programs. The selection criteria for documents emphasized recency (published after 2015), relevance to mountain agriculture and just transition themes, and geographical representativeness across Europe (EUROSTAT, 2024). Data analysis followed a two-tier approach. First, thematic analysis was applied to the literature and policy documents to identify recurrent concepts, successful practices, and perceived barriers to sustainable agriculture adoption. Second, comparative analysis was performed across different case studies to extract patterns and contextual factors influencing outcomes.

LITERATURE REVIEW

The concept of a just transition has gained prominence as a framework for ensuring that the shift towards a low-carbon economy does not exacerbate social inequalities, especially in regions historically dependent on extractive industries (ILO, 2015). A just transition emphasizes the creation of sustainable jobs, the protection of workers' rights, and the revitalization of affected communities (SHAHZAD et al., 2024). In mountainous coal-dependent areas, these challenges are amplified by geographic isolation, limited economic alternatives, and ecological vulnerabilities (SZARZYNSKI et al., 2022). The role of agriculture in transition strategies is increasingly recognized, yet its specific potential in mountainous settings remains underexplored. Sustainable agriculture emerges as a key driver for resilient rural economies and ecological restoration during transition processes. Practices such as agroecology, agroforestry, organic farming, and conservation agriculture contribute to soil regeneration, biodiversity enhancement, and sustainable livelihoods (REHMAN et al., 2022; FAO, 2023). Studies show that sustainable farming can substitute lost incomes partially, diversify economic bases, and

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foster stronger community ties in post-coal regions (MGENDI, 2024). Furthermore, integrating local knowledge and adaptive management practices is critical for ensuring the success and long-term viability of agricultural initiatives in complex landscapes (ROZENSTEIN et al., 2024). Mountainous areas pose particular challenges for agricultural revitalization due to factors such as steep slopes, climate variability, fragmented land ownership, and reduced infrastructure (SHAHZAD et al., 2024). Traditional farming systems, although often resilient, require modernization to meet contemporary environmental and market demands. Constraints identified include the higher cost of sustainable practices, difficulties in accessing markets, and limited technical capacity (ŽÁKOVÁ KROUPOVÁ et al., 2025). Addressing these barriers requires integrated policies, targeted investment in training and infrastructure, and community-driven development models to support a genuinely just transition through sustainable agriculture.
Table 1 presents a chronological overview of key contributions from the reviewed literature, illustrating the evolution of perspectives on sustainable agriculture and precision technologies relevant to mountainous post-coal regions.

Table 1.

Main contributions from the literature (chronological order). Source: the authors

No.	Author(s)	Year	Focus Area	Key Contributions	Relevance to this Study
1	International Labour Organization	2015	Just Transition framework	Guidelines for environmentally sustainable economies	Establishes the theoretical foundation for the concept of just transition applied to agriculture
2	Carletto, C.	2021	Agricultural data systems	Improving agricultural data for societal change	Supports better decision-making based on reliable agricultural data
3	Rehman, A., Farooq, M., Lee, D.-J., & Siddique, K. H. M.	2022	Sustainable agricultural practices	Conservation agriculture, food security, ecosystem services	Underlines synergy between sustainable farming and environmental resilience
4	Szarzynski, J., Alcántara-Ayala, I., Nüsser, M., & Schneiderbauer, S.	2022	Risk management in mountainous regions	Hazards and disaster management in mountain areas	Highlights socio-economic vulnerabilities specific to mountainous zones
5	Food and Agriculture Organization	2023	Sustainable mountain farming	Nature-based approaches for improving livelihoods in mountainous regions	Highlights the role of agriculture in mountain sustainability and transition strategies
6	Oba, A.	2023	Geospatial precision agriculture	Integration of GIS and remote sensing in agriculture	Supports the use of spatial data for optimizing farming practices in complex terrains

http://doi.org/10.59463/RJAS.2025.2.04

7	Mgendi, G.	2024	Precision agriculture for sustainability	Unlocking precision farming potential for sustainable agriculture	Emphasizes barriers such as high costs and technical challenges
8	Guebsi, R., Mami, S., & Chokmani, K.	2024	Drones in precision agriculture	Applications, technologies, challenges in drone-based farming	Supports the potential of UAVs in overcoming accessibility issues in mountain terrains
9	Idier, H., Dehhaoui, M., Maatala, N., & Ait El Kadi, K.	2024	Precision farming impact assessment	Evaluation frameworks for precision agriculture adoption	Provides methodologies for assessing socio-economic impacts of technology adoption
10	Rozenstein, O., Cohen, Y., Alchanatis, V., Behrendt, K., Bonfil, D. J., Eshel, G., Harari, A., Harris, W. E., Klapp, I., Laor, Y., Linker, R., Paz-Kagan, T., Peets, S., Rutter, S. M., Salzer, Y., & Lowenberg-DeBoer, J.	2024	Data-driven agriculture	Precision farming and sustainability balance	Provides case studies of UAV use in mountain agriculture (e.g., Andes)
11	Shahzad, L., Ali, M., Sharif, F., & Shedayi, A. A.	2024	Disaster management in mountains	Challenges and management in the era of climate change	Contextualizes mountain vulnerabilities affecting agricultural sustainability
12	Žáková Kroupová, Z., Aulová, R., Rumánková, L., Bajan, B., Čechura, L., Šimek, P., & Jarolímek, J.	2025	Technology adoption in agriculture	Drivers and barriers in precision agriculture adoption	Provides insights on adoption challenges and success factors in mountainous European regions

IMPLEMENTATION OF PRECISION AGRICULTURE IN MOUNTAINOUS AREAS

The application of precision agriculture technologies in mountainous areas represents a critical component of sustainable rural development strategies, especially in the context of the just transition from coal. By enabling efficient resource management, improving crop productivity, and supporting environmental conservation, precision agriculture can transform the vulnerabilities of mountainous terrains into strengths (OBA, 2023; GUEBSI et al., 2024). However, successful implementation demands the adaptation of technologies to the unique topographic, climatic, and socio-economic conditions found in such areas.

Case Study 1 – The Andes Mountains

In the Andean regions of South America, the integration of Unmanned Aerial Vehicles (UAVs) with multispectral imaging has proven particularly effective. Farmers used drones equipped with sensors to monitor crop health, estimate yields, and optimize input use, such as fertilizers and irrigation (ROZENSTEIN et al., 2024). This approach allowed smallholder farmers to overcome traditional accessibility issues caused by steep slopes and fragmented fields. According to

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Rozenstein et al. (2024), the use of UAV-based monitoring led to a 15–20% increase in crop yields within two years of adoption. Table 2 synthesizes the key high-payoff research areas identified by Rozenstein et al. (2024) as critical to advancing data-driven sustainable agriculture, with particular relevance for mountainous post-coal regions, demonstrating the need for precision agriculture technologies.

Table 2.

High-priority research areas to support data-driven sustainable agriculture
(adapted from Rozenstein et al., 2024)

No.	Research Area	Description	Relevance to Precision Agriculture in Mountainous Areas
1	Automated animal intake measurement	Development of cost-effective tools for measuring livestock feed intake	Critical for sustainable livestock farming in mountain pastures
2	Low-cost soil sensors	Development of on-the-go soil nutrient sensors	Enables affordable, site-specific fertilization and soil health monitoring
3	Robot obstacle avoidance	Systems for automatic obstacle detection in fields	Essential for drone and robot operation on rugged mountainous terrain
4	Integration of remote sensing and crop models	Early detection of diseases and pests using combined technologies	Improves yield stability and reduces pesticide use in sensitive ecosystems
5	Extension methods for data-driven agriculture	Improving farmer education and adoption of digital tools	Vital for training mountain farmers on the benefits and use of precision technologies
6	Methods to exploit on-farm genetic variation	Use of local varieties adapted to microclimates through Genotype × Environment × Management studies	Strengthens climate resilience in diverse mountain environments
7	Business models for farm data sharing	Developing trusted frameworks for farm data sharing and protection	Facilitates collective data use while safeguarding farmer privacy
8	Development of decision support systems (DSS)	Transforming big data into actionable, localized farm advice	Supports better farm management decisions in variable and fragmented mountain landscapes

Case Study 2 – The Himalayan Region

In the Himalayan territories, a combination of Geographic Information Systems (GIS) and remote sensing technologies has been employed to manage irrigation practices more effectively (SHAHZAD et al., 2024). GIS mapping of soil properties, elevation, and microclimatic conditions enabled precise identification of optimal irrigation zones, reducing water use by up to 25% without compromising yields. Additionally, GIS-supported models facilitated erosion control and landscape restoration, crucial in these erosion-prone environments. Shahzad et al. (2024) emphasize that community training programs were key to successful technology adoption. Table 3 synthesizes major climate-induced risks in mountainous regions and

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corresponding adaptation strategies, based on Shahzad et al. (2024). These insights are critical when designing sustainable agricultural systems in post-coal mountainous areas and must be addressed through GIS mapping methods.

Table 3.

Climate-induced risks and adaptation strategies for mountainous regions (adapted from Shahzad et al., 2024)

No.	Climate-Induced Risk	Description	Suggested Adaptation Measures
1	Glacial lake outburst floods (GLOFs)	Flooding caused by sudden release of water from glacial lakes	Early warning systems, glacial lake monitoring, controlled drainage
2	Landslides	Slope failures intensified by changing precipitation and temperature	Slope stabilization, afforestation, hazard zoning
3	Flash floods	Rapid flooding due to intense precipitation events	Improved watershed management, early alert systems
4	Wildfires	Increased frequency due to hotter, drier conditions	Firebreak creation, community fire management programs
5	Permafrost thaw	Soil destabilization due to melting permafrost	Engineering solutions for infrastructure, monitoring systems
6	Biodiversity loss	Habitat fragmentation and species extinction driven by climate shifts	Conservation corridors, ecosystem-based adaptation strategies
7	Water scarcity	Changes in snowmelt and rainfall patterns affecting water availability	Water harvesting systems, efficient irrigation technologies

Case Study 3 – Carpathian Mountains, Central Europe

In the Carpathian regions of Central Europe, precision agriculture practices have been adapted to small-scale, fragmented agricultural landscapes, typical for mountain areas (ŽÁKOVÁ KROUPOVÁ et al., 2025). Technologies such as portable soil sensors, mobile-based farm management applications, and simplified drone systems were deployed to support farmers in monitoring soil moisture, optimizing fertilization schedules, and managing pest outbreaks.

The adoption was driven largely by local innovation hubs and EU-funded pilot programs that focused on low-cost, user-friendly technologies accessible to smallholders. According to Idier et al. (2024), farmers reported a 10–15% increase in crop yields and a significant reduction in fertilizer use within the first three years of adoption. Moreover, mobile applications enabled better planning and traceability, facilitating access to niche markets for organic or high-quality mountain products. Training initiatives were essential for overcoming the initial technological barriers and fostering trust among farmers. Table 4 summarizes the main drivers and barriers influencing the adoption of precision agriculture technologies in mountainous regions, particularly in the Carpathian context, as synthesized from Žáková Kroupová et al. (2025) and Idier et al. (2024).

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Table 4.
Drivers and barriers for precision agriculture adoption in mountainous regions (adapted from Žáková Kroupová et al., 2025; Idier et al., 2024)

Category	Factors	Description	Specific relevance for Carpathian mountain areas
Drivers	Availability of low-cost technology	Portable soil sensors, mobile apps, affordable drones adapted for small farms	Enables access even for fragmented landowners with limited resources
Drivers	EU-funded pilot programs	Financial and technical support for innovation adoption	Stimulates early adoption among smallholders in remote areas
Drivers	Access to niche markets	Traceability and certification systems enabled by digital tools	Opens higher-value markets for organic and quality mountain products
Drivers	Farmer training initiatives	Training programs to build digital literacy and operational trust	Essential for overcoming skepticism and skill gaps
Barriers	High initial costs (before subsidies)	Equipment, software, and maintenance expenses	Remains a significant hurdle without external support
Barriers	Technical complexity and maintenance issues	Need for technical expertise to operate and repair equipment	Particularly challenging in isolated or less-connected mountain villages
Barriers	Fragmented land ownership	Difficulty applying standard precision solutions on small, dispersed plots	Necessitates customized, modular precision systems

Challenges and Success Factors

While the benefits of precision agriculture in mountainous terrains are clear, several challenges persist. High costs of technology acquisition, the need for technical expertise, and difficulties in maintaining equipment in harsh conditions remain significant barriers (MGENDI, 2024; GUEBSI et al., 2024). Access to credit and support services are also critical limiting factors, especially for small-scale farmers. On the other hand, success factors identified across case studies include the availability of customized low-cost technologies, the involvement of local communities in decision-making, and strong institutional support (IDIER et al., 2024; ŽÁKOVÁ KROUPOVÁ et al., 2025). Investments in farmer training programs, demonstration projects, and financial incentives have consistently emerged as catalysts for scaling up adoption. Furthermore, localized adaptations of precision technologies, rather than direct transfer of flatland solutions, have been crucial to ensure relevance and efficacy in mountainous contexts (OBA, 2023; SHAHZAD et al., 2024).

DISCUSSIONS

The findings of this study confirm that precision agriculture technologies hold considerable potential for supporting a just transition in mountainous post-coal regions. Across diverse geographic contexts—from the Andes to the Himalayas and the Carpathians—precision

http://doi.org/10.59463/RJAS.2025.2.04

agriculture has contributed to improving crop yields, optimizing resource use, and strengthening the resilience of rural economies (ROZENSTEIN et al., 2024; SHAHZAD et al., 2024; ŽÁKOVÁ KROUPOVÁ et al., 2025). The integration of geospatial data, remote sensing, and mobile technologies enables farmers to manage the complexities of mountainous terrains more effectively, turning inherent challenges into manageable variables (OBA, 2023).

However, the implementation of these technologies is not without significant challenges. High investment costs, limited technical skills, and the need for continuous support services present barriers to widespread adoption, particularly among smallholders (MGENDI, 2024; GUEBSI et al., 2024). In addition, mountainous regions often suffer from inadequate digital infrastructure, further constraining the deployment of precision agriculture solutions (IDIER et al., 2024). Cultural factors, such as skepticism towards new technologies and resistance to change, also influence adoption rates. These findings align with broader observations regarding technological transitions in rural and peripheral areas (SZARZYNSKI et al., 2022).

Another limitation observed in the case studies concerns the dependency on external funding and pilot programs. While initial successes have been recorded, long-term sustainability remains uncertain once project-based support diminishes (SHAHZAD et al., 2024). Furthermore, most technological applications are still primarily focused on yield optimization, with less emphasis on broader ecosystem services, such as soil conservation or biodiversity enhancement. Looking forward, future research should prioritize the development of ultra-low-cost, modular precision agriculture solutions specifically designed for rugged mountainous environments. Co-design approaches involving local communities from the outset are crucial to ensuring technological relevance and long-term adoption (GUEBSI et al., 2024). Additionally, stronger integration between sustainable agriculture practices—such as agroecology—and precision farming technologies could amplify resilience and environmental benefits (REHMAN et al., 2022; ROZENSTEIN et al., 2024). Policymakers should support these directions through investments in digital infrastructure, farmer training, and the creation of local innovation hubs.

The just transition in mountainous post-coal regions cannot rely solely on technological innovation; it requires systemic approaches combining social inclusion, ecological restoration, and economic diversification. Precision agriculture represents a vital tool within this broader transformational agenda but must be deployed thoughtfully to ensure equitable and lasting benefits.

CONCLUSIONS AND RECOMMENDATIONS

This study has demonstrated that precision agriculture technologies, when properly adapted, can significantly enhance the resilience, productivity, and sustainability of mountainous post-coal regions. Case studies from the Andes, Himalayas, and Carpathians have illustrated how technologies such as UAV monitoring, GIS-based irrigation optimization, and mobile farm management applications can help overcome the inherent challenges of steep terrains, fragmented landscapes, and climatic variability (ROZENSTEIN et al., 2024; SHAHZAD et al., 2024; ŽÁKOVÁ KROUPOVÁ et al., 2025).

However, the transition to precision agriculture in mountainous contexts is neither automatic nor guaranteed. Barriers such as high initial costs, technological complexity, insufficient infrastructure, and socio-cultural resistance must be systematically addressed (MGENDI, 2024; IDIER et al., 2024). The findings emphasize that technological innovation alone is insufficient; success depends equally on social inclusiveness, farmer empowerment, and

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supportive institutional frameworks. Precision agriculture can and should play a vital role in the broader strategies of just transition, but only if it is implemented in a participatory, context-sensitive, and ecosystem-oriented manner (REHMAN et al., 2022).

Based on the results and critical discussion, the following recommendations are proposed:

A. Policy Recommendations:

- Develop specific funding schemes to subsidize the acquisition of precision agriculture technologies for smallholders in mountainous areas.
- Invest in rural digital infrastructure, particularly in broadband connectivity, to facilitate the adoption of data-driven farming solutions.
- Integrate precision agriculture explicitly into national and regional just transition strategies, recognizing its potential for rural revitalization.

B. Research Recommendations:

- Focus future research on designing low-cost, modular, and robust precision agriculture systems adapted to mountainous terrains.
- Promote interdisciplinary studies that link technological innovation with socio-economic dynamics and ecosystem services evaluation.
- Conduct longitudinal studies to assess the long-term socio-ecological impacts of precision agriculture in post-coal mountain regions.

C. Practice Recommendations:

- Encourage co-design processes where local farmers and communities are actively involved in the development and adaptation of precision technologies.
- Establish regional centers of excellence or innovation hubs to provide technical support, training, and demonstration projects.
- Foster knowledge exchange networks between mountainous communities across different regions to share best practices and lessons learned.

By following these strategic directions, precision agriculture can become not only a technical solution but a catalyst for equitable and sustainable transformation in mountainous post-coal regions.

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