Journal of Management Science Research Review
https://jmsrr.com/index.php/Journal/about

Volume 5 Issue No 2 (2026)

Online ISSN: 3006-2047
Print ISSN: 3006-2039

Innovative Aquaculture for Entrepreneurship Growth: Insights from RAS Adoption in Pakistan

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Abstract
Recirculating Aquaculture Systems (RAS) have emerged as a transformative technology in aquaculture, offering sustainable production through water recycling, biofiltration, and controlled environmental management. This study investigates the impact of RAS adoption on entrepreneurship development in Pakistan, focusing on provincial case studies, SME growth, value chain enhancement, employment generation, and innovation promotion. Using a qualitative exploratory design with secondary data sources, including peer-reviewed articles and government reports, thematic analysis was conducted to assess entrepreneurial outcomes. The findings indicate that RAS facilitates technology-driven startups, urban and peri-urban aquaculture enterprises, and high-value niche markets, while strengthening linkages across the aquaculture value chain. However, adoption is constrained by technical and energy-related challenges. The study applies Rogers' Diffusion of Innovations Theory to explain the adoption patterns of RAS among early and late entrepreneurial adopters, and Barney's Resource-Based View (RBV) to highlight how technological and knowledge resources provide a competitive advantage to entrepreneurs. The integration of these theories demonstrates that strategic resource deployment and innovation diffusion are critical for scaling RAS-based entrepreneurship in Pakistan. Policy

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Online ISSN: 3006-2047
Print ISSN: 3006-2039

support, training, and renewable energy integration are recommended to overcome adoption barriers, ensuring sustainable economic growth, enhanced food security, and the development of a technology-driven aquaculture entrepreneurial ecosystem.

Keywords: Recirculating Aquaculture Systems, Entrepreneurship, Pakistan, Diffusion of Innovations, Resource-Based View, Sustainable Aquaculture, SMEs, Innovation.

1 Introduction

Aquaculture has become one of the most rapidly expanding sectors of global food production, accounting for more than half of the world's seafood supply and playing a critical role in ensuring food security and nutritional sustainability (Food and Agriculture Organization [FAO], 2023). In developing countries such as Pakistan, aquaculture holds significant potential due to the availability of diverse water resources, including rivers, lakes, reservoirs, and an extensive coastline along the Arabian Sea. With a coastline stretching over 1,000 kilometers and increasing urbanization, Pakistan is well positioned to expand its aquaculture industry to meet the growing demand for affordable, protein-rich food. However, despite this potential, the sector remains underdeveloped and faces multiple structural and environmental challenges.

Traditional aquaculture practices in Pakistan are largely based on extensive and semi-intensive pond systems, which are often characterized by inefficient water use, low productivity, and vulnerability to environmental fluctuations. Issues such as water scarcity, climate change, and disease outbreaks have further constrained the sector's growth, limiting its contribution to economic development and employment generation (Rashid, 2022; Ende et al., 2025). These challenges highlight the urgent need for innovative, sustainable aquaculture solutions that enhance productivity while minimizing environmental impact.

Recirculating Aquaculture Systems (RAS) have emerged as a transformative technology that addresses many of these limitations. RAS operates by continuously filtering and reusing water within a closed-loop system, thereby significantly reducing water consumption and enabling high-density fish production in controlled environments. This technology not only improves resource efficiency but also enhances biosecurity, reduces disease risks, and allows year-round production regardless of climatic conditions (Badiola et al., 2012; Ahmed &Turchini, 2021). Furthermore, the integration of advanced technologies such as Internet of Things (IoT) sensors, automated feeding systems, and artificial intelligence-based monitoring has further increased the efficiency and scalability of RAS, making it a viable option for modern aquaculture development.

Beyond its technical advantages, RAS has considerable potential to foster entrepreneurship and economic growth. The adoption of RAS creates new opportunities for startups, small and medium enterprises (SMEs), and technology-driven agribusiness ventures, particularly in urban and peri-urban areas where traditional aquaculture is not feasible. The Pakistan Council of Scientific and Industrial Research (PCSIR) plays a pivotal role in promoting technological innovation 'in Pakistan's aquaculture sector by actively engaging in the development of Recirculating Aquaculture Systems (RAS).

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This initiative reflects a broader national effort to modernize fish farming practices by introducing resource-efficient, environmentally sustainable, and technology-driven production systems. In a context where traditional aquaculture is constrained by water scarcity, climate variability, and low productivity, PCSIR's intervention represents a significant shift toward innovation-based aquaculture development (PCSIR, 2023).

This process can be understood through the lens of the Diffusion of Innovations Theory, which explains how new technologies are adopted and spread within a population, especially through early adopters and demonstration projects (Rogers, 2003). At the same time, the Resource-Based View (RBV) emphasizes that access to technological capabilities, knowledge, and infrastructure can provide entrepreneurs with a sustainable competitive advantage, enabling the development of efficient and profitable business models (Barney, 1991).

In this context, the present study aims to examine the impact of RAS on entrepreneurial development in Pakistan by integrating technological, economic, and theoretical perspectives. Guided by a structured analytical framework, the study explores how RAS contributes to startup development, SME growth, value chain enhancement, employment generation, and innovation promotion. By linking the research problem, literature review, data analysis, and case study insights within a coherent framework, this study provides a comprehensive understanding of how innovation in aquaculture can drive entrepreneurship and support sustainable economic development in Pakistan.

Problem Statement

Despite the significant potential of aquaculture in Pakistan, the sector remains underdeveloped and contributes below its capacity to national food security, employment generation, and economic growth. Traditional fish farming practices, which dominate the industry, rely heavily on extensive pond systems that suffer from low productivity, inefficient water use, and high vulnerability to environmental fluctuations. Increasing water scarcity, climate change, and the prevalence of fish diseases have further exacerbated these challenges, limiting the scalability and sustainability of conventional aquaculture systems (Rashid, 2022; Food and Agriculture Organization [FAO], 2023).

In recent years, Recirculating Aquaculture Systems (RAS) have emerged globally as a technologically advanced and sustainable alternative, offering efficient water use, enhanced biosecurity, and controlled production environments. These systems enable high-density fish production and are particularly suitable for urban and resource-constrained settings (Badiola et al., 2012; Ahmed &Turchini, 2021). However, in Pakistan, the adoption of RAS remains limited due to several barriers, including high initial investment costs, lack of technical expertise, inadequate policy support, and limited awareness among potential entrepreneurs.

Furthermore, while existing studies have explored the technical and environmental benefits of RAS, there is a noticeable gap in the literature regarding its role in fostering entrepreneurship and developing an innovation-driven aquaculture ecosystem in Pakistan. The relationship between RAS adoption and entrepreneurial outcomes—such as startup development, SME growth, value chain expansion, and employment

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generation—remains insufficiently examined. This gap is particularly important in developing economies, where technological innovation can transform traditional sectors into dynamic drivers of economic growth.

From a theoretical perspective, the limited adoption of RAS can be explained through the Diffusion of Innovations Theory, which suggests that new technologies often face resistance due to uncertainty, lack of awareness, and perceived risks (Rogers, 2003). At the same time, the Resource-Based View (RBV) highlights that entrepreneurs require access to critical resources, including technology, knowledge, and infrastructure, to adopt and utilize innovations for competitive advantage effectively (Barney, 1991). In the absence of these enabling factors, the transition toward advanced aquaculture systems remains slow.

Therefore, this study addresses the critical gap by examining how RAS can contribute to entrepreneurial development in Pakistan. It seeks to explore the extent to which RAS adoption can enhance business opportunities, support SME growth, and generate employment, while also identifying the key challenges and enabling factors influencing its adoption. By doing so, the study provides valuable insights for policymakers, researchers, and practitioners aiming to promote sustainable aquaculture and innovation-driven economic development in Pakistan.

Significance of the Study

This study holds substantial significance in advancing both academic knowledge and practical understanding of innovation-driven aquaculture and entrepreneurship in Pakistan. As global demand for sustainable food production continues to rise, aquaculture has emerged as a critical sector for ensuring food security and economic development, particularly in developing economies (Food and Agriculture Organization [FAO], 2023). In this context, exploring Recirculating Aquaculture Systems (RAS) provides valuable insights into how modern technologies can transform traditional aquaculture practices into efficient, sustainable, and economically viable systems.

From a theoretical perspective, this study contributes to the existing body of knowledge by integrating the Diffusion of Innovations Theory and the Resource-Based View (RBV) within the context of aquaculture entrepreneurship. While these theories have been widely applied in technology adoption and strategic management research, their application to aquaculture—particularly in developing countries like Pakistan—remains limited. By linking RAS adoption with entrepreneurial development, this study extends the theoretical understanding of how technological innovations diffuse within emerging sectors and how access to strategic resources can enable competitive advantage and business growth (Rogers, 2003; Barney, 1991).

In practice, the study has important implications for entrepreneurs, investors, and small and medium enterprises (SMEs) by highlighting the potential of RAS as a viable business opportunity. The adoption of RAS can facilitate the establishment of technology-driven aquaculture enterprises, particularly in urban and peri-urban areas where conventional fish farming is not feasible. By demonstrating the economic and operational benefits of RAS, the study encourages the development of startups,

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Online ISSN: 3006-2047
Print ISSN: 3006-2039

innovation in aquaculture practices, and the expansion of value-added services within the sector (Ahmed &Turchini, 2021; Badiola et al., 2012).

In addition, the study is highly relevant for policymakers and government institutions seeking to promote sustainable economic development. The findings provide evidence-based insights into how RAS can contribute to employment generation, income diversification, and import substitution in Pakistan. This is particularly important given the country's increasing reliance on food imports and the need to strengthen domestic production systems. By identifying the challenges and enabling factors associated with RAS adoption, the study supports the formulation of targeted policies, including financial incentives, training programs, and infrastructure development (FAO, 2023; Rashid, 2022).

Furthermore, the study contributes to the broader discourse on sustainability and the achievement of the Sustainable Development Goals (SDGs). RAS aligns with global sustainability objectives by promoting efficient resource utilization, reducing environmental impact, and supporting responsible production practices. By linking sustainable aquaculture with entrepreneurship, the study highlights the role of innovation in achieving long-term environmental and economic sustainability (Ahmed &Turchini, 2021).

Finally, this research provides a foundation for future empirical studies by offering a conceptual framework and analytical approach that can be tested and refined in different contexts. It opens avenues for further investigation into technology adoption, innovation ecosystems, and entrepreneurship in the aquaculture sector, both within Pakistan and in other developing economies.

2. Literature Review

Concept and Features of RAS

RAS involves continuous water filtration, biofiltration, and reuse, significantly reducing water consumption and environmental discharge (Amponsah&Guilherme, 2021; Martins et al., 2010). Key features include high-density production, biosecurity, disease control, and environmental sustainability. The infrastructure, including tanks, pumps, and automated feeding systems, constitutes strategic resources under the Resource-Based View (Barney, 1991), enabling entrepreneurs to achieve competitive advantage through knowledge-intensive operations.

Technological Advancements in RAS

Recent innovations in RAS include AI-based monitoring, IoT sensors, and automated feeding systems (Ende et al., 2025). These technologies facilitate real-time water quality monitoring, predictive analytics for feed and growth optimization, and smart aquaculture systems that minimize labor and operational costs (Ahmed &Turchini, 2021). According to Diffusion of Innovations Theory (Rogers, 2003), the perceived benefits, trialability, and observability of these technologies accelerate adoption among early entrepreneurial adopters.

Entrepreneurial Potential of RAS

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RAS promotes technology-driven entrepreneurship by enabling urban and peri-urban startups, SMEs, and consultancy services. Entrepreneurs leverage RAS for high-density production, hatchery management, feed production, and water treatment solutions. Integration with value chains strengthens market access and supports the commercialization of research, reflecting RBV principles (Barney, 1991). Adoption patterns in Punjab and Sindh illustrate diffusion stages where early adopters influence broader SME uptake (Rogers, 2003; Rashid, 2022).

Challenges and Opportunities

Key barriers include high capital costs, technical skill gaps, energy dependency, and weak institutional support (Martins et al., 2010; Ahmed &Turchini, 2021). Opportunities arise through policy interventions, renewable energy integration, training programs, and public-private partnerships. Effective deployment of RAS resources and overcoming adoption barriers strengthens entrepreneurial ecosystems, aligning with RBV and Diffusion of Innovations Theory (Barney, 1991; Rogers, 2003).

RAS and Sustainable Entrepreneurship

RAS supports green entrepreneurship, technology startups, and circular economy practices. Nutrient recycling and biofloc production enhance resource efficiency, contributing to the Sustainable Development Goals (SDGs) 2, 8, and 12 (FAO, 2023). By leveraging technological and knowledge resources, entrepreneurs can achieve a competitive advantage while promoting sustainable production (Barney, 1991).

Challenges in RAS Adoption

Constraints include high initial investment requirements, alack of technical expertise, energy dependency, and weak institutional support (Badiola et al., 2012; Ende et al., 2025). These factors hinder adoption according to Rogers'(2003) diffusion framework, and limit strategic resource deployment under the RBV lens (Barney, 1991). Addressing these challenges requires subsidies, training, renewable energy solutions, and policy support.

Theoretical Framework: Diffusion of Innovations and Resource-Based View

The adoption of new technologies such as RAS can be better understood through established theoretical lenses. Two primary theories are relevant: the Diffusion of Innovations (DOI) and theResource-Based View (RBV).

Diffusion of Innovations Theory (Rogers, 2003) explains how, why, and at what rate new technologies spread within a social system. In Pakistan, early adopters—typically urban or peri-urban entrepreneurs—demonstrate higher productivity and innovation through pilot RAS projects. The theory suggests that the perceived relative advantage, compatibility with existing practices, complexity, trialability, and observability of RAS significantly influence adoption rates. Provincial case studies, including biofloc-RAS integration in Punjab and urban aquaponics in Karachi, reflect these diffusion patterns (Rashid, 2022; Ende et al., 2025).

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Resource-Based View (Barney, 1991) emphasizes the strategic role of firm-specific resources—tangible and intangible—in achieving sustained competitive advantage. In aquaculture entrepreneurship, RAS-related technological infrastructure, operational expertise, digital monitoring systems, and management knowledge constitute valuable, rare, inimitable, and non-substitutable (VRIN) resources. Entrepreneurs leveraging these resources can establish SMEs, technology startups, and niche market operations that outperform competitors. Examples include IoT-enabled trout farming in KP and integrated RAS systems in coastal Sindh (Ahmed &Turchini, 2021; Rashid, 2022).
Integrating DOI and RBV allows a comprehensive understanding of the interplay between technology, entrepreneurship, and value chain development in Pakistan's aquaculture sector.

3. Research Methodology

Research Design

This study adopts a qualitative exploratory research design to examine the impact of Recirculating Aquaculture Systems (RAS) on entrepreneurial development in Pakistan. A qualitative approach is appropriate given the study's focus on understanding patterns, relationships, and contextual dynamics associated with technology adoption and entrepreneurship. The research relies on secondary data sources, including peer-reviewed journal articles, government publications, and institutional reports such as those from PCSIR and the Food and Agriculture Organization (FAO). A thematic analysis approach was applied to evaluate the impact of RAS on entrepreneurial development in Pakistan, focusing on provincial variations, SME growth, and innovation pathways. The research framework incorporates Diffusion of Innovations Theory to examine adoption patterns and RBV to analyze strategic resource utilization in entrepreneurial ventures.

Data Collection

Data were collected through a systematic review of relevant literature on aquaculture innovation, RAS technology, and entrepreneurship. Sources were selected based on relevance, credibility, and recency, ensuring inclusion of studies that address technological advancements, economic impacts, and entrepreneurial outcomes. Key databases and reports provided insights into both global practices and Pakistan-specific developments.

Data Analysis: Thematic Analysis Approach

The collected data were analyzed using thematic analysis, a widely used qualitative method for identifying, analyzing, and interpreting patterns within textual data. The analysis followed a structured process adapted from established qualitative research procedures.
Initially, data familiarization was conducted through repeated reading of the selected literature to gain a comprehensive understanding of the subject. This stage enabled the identification of recurring ideas related to aquaculture innovation and entrepreneurial activities.

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Subsequently, initial coding was performed by systematically extracting meaningful units of information from the data. Codes were assigned to key concepts such as technology adoption, resource efficiency, startup development, employment generation, and value chain integration. The coding process was guided by the theoretical frameworks of Diffusion of Innovations and the Resource-Based View, which provided a conceptual basis for interpreting patterns related to technology adoption and resource utilization (Rogers, 2003; Barney, 1991).

Following coding, related codes were grouped into broader thematic categories. For instance, codes associated with business creation, SMEs, and consultancy services were consolidated under the theme of entrepreneurial development, while those related to water recycling, biosecurity, and controlled environments were categorized under technological innovation in RAS. Similarly, financial and technical constraints were grouped under adoption challenges.

The identified themes were then reviewed and refined to ensure coherence, consistency, and alignment with the research objectives. This process involved cross-checking themes against the data and integrating insights from Pakistan-specific case studies, including regional developments in Punjab, Sindh, and Khyber Pakhtunkhwa, as well as institutional initiatives such as those by PCSIR.

Finally, the themes were interpreted within a theoretical context, linking empirical observations with established theories. The Diffusion of Innovations Theory was used to explain patterns of RAS adoption among entrepreneurs, particularly the roles of early adopters and demonstration projects in facilitating technology adoption. The Resource-Based View was applied to understand how access to technological infrastructure, knowledge, and institutional support contributes to the development of competitive and sustainable aquaculture enterprises.

Validity and Reliability

To ensure the credibility of the findings, data were sourced from reputable, peer-reviewed publications and recognized institutional reports. Triangulation was achieved by comparing multiple sources to validate recurring themes and patterns. The use of established theoretical frameworks further enhances the study's reliability and analytical rigor.

Conceptual Framework: Insights from RAS adoption for Entrepreneurial Development in Pakistan

Visual Framework (Text Diagram)

Recirculating Aquaculture Systems (RAS)

Technological Features
(Water Efficiency, Biosecurity, Controlled Environment, Automation)

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Theoretical Foundations
- Diffusion of Innovations (DOI)
- Resource-Based View (RBV)

Entrepreneurial Drivers
(Technology Adoption, Knowledge, Infrastructure, Skills)

Entrepreneurial Outcomes
- Startup Development
- SME Growth
- Innovation (IoT, Smart Aquaculture)
- Value Chain Development

Economic Impact
- Employment Generation
- Income Growth
- Food Security
- Blue Economy Development

4. Case Studies

Punjab: Biofloc and RAS Integration

In Punjab, integrated Biofloc-RAS aquaculture projects have demonstrated significant commercial potential, with yields of 0.4–0.5 tons per tank per cycle. These initiatives have spurred the emergence of small-scale fish-farming startups, youth engagement in agribusiness, and the development of local feed and equipment markets. The integration of biofloc technology enhances water quality and reduces feed costs, supporting profitable and sustainable aquaculture operations (Ahmed &Turchini, 2021; FAO, 2023).

Sindh: Coastal and Urban Aquaculture

Sindh, particularly Karachi and coastal regions, presents strong opportunities for RAS adoption due to water scarcity and urban demand. Entrepreneurs are implementing indoor fish farming, container-based systems, and hybrid aquaponics models. These ventures reduce reliance on marine fishing, support urban food supply chains, and promote technology-driven entrepreneurship, particularly in densely populated areas (Ende et al., 2025; Rashid, 2022).

Khyber Pakhtunkhwa (KP): Trout Farming Innovations

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Northern regions of KP have modernized trout farming through RAS integrated with IoT-based monitoring systems. These technologies improve productivity, fish health, and resource efficiency, while promoting technology adoption in rural areas. Smallholder farmers report increased income, and niche export markets for trout have begun to develop, illustrating the economic and entrepreneurial potential of RAS (Martins et al., 2010; Badiola et al., 2012).

PCSIR's Contribution to Innovation-Led Aquaculture Entrepreneurship in Pakistan

The Pakistan Council of Scientific and Industrial Research (PCSIR) plays a pivotal role in promoting technological innovation within Pakistan's aquaculture sector through its active engagement in the development of Recirculating Aquaculture Systems (RAS). The initiative reflects a broader national effort to modernize fish farming practices by introducing resource-efficient, environmentally sustainable, and technology-driven production systems. In a context where traditional aquaculture is constrained by water scarcity, climate variability, and low productivity, PCSIR's intervention represents a significant shift toward innovation-based aquaculture development (PCSIR, 2023).

In early 2023, PCSIR initiated a dedicated RAS project to demonstrate the feasibility of controlled, land-based aquaculture systems that recycle water and optimize resource use. The project, primarily implemented at the PCSIR Laboratories Complex in Lahore, focuses on establishing a model facility capable of supporting high-density fish production with minimal environmental impact. Through this initiative, PCSIR is not only testing advanced aquaculture technologies but also creating a platform for knowledge transfer and capacity building within the sector (PCSIR, 2023).

The project has been closely supervised by senior leadership, ensuring both technical rigor and strategic alignment with national development goals. Periodic monitoring and evaluation visits by top officials, along with technical briefings from project engineers and specialists, highlight the institutional commitment to fostering innovation in aquaculture. Such initiatives serve as demonstration models that can influence wider adoption among stakeholders, including entrepreneurs, investors, and policymakers.

From an entrepreneurial standpoint, the PCSIR RAS project provides a foundation for the emergence of innovation-driven aquaculture enterprises. By demonstrating the economic and technical viability of RAS, the project encourages new businesses to enter, particularly in urban and peri-urban areas where conventional aquaculture is not feasible. This process aligns with the Diffusion of Innovations Theory, which suggests that pilot projects and demonstration units play a critical role in reducing uncertainty and accelerating the adoption of new technologies among potential users (Rogers, 2003).

Furthermore, the initiative contributes to the development of key strategic resources necessary for competitive entrepreneurship. The availability of technical expertise, modern infrastructure, and operational knowledge enables entrepreneurs to build sustainable and efficient aquaculture businesses. This reflects the principles of the Resource-Based View (RBV), which emphasizes that access to valuable and

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specialized resources is essential for achieving long-term competitive advantage (Barney, 1991).

The benefits of RAS technology, as demonstrated by the PCSIR project, further strengthen its relevance for entrepreneurial development. These systems significantly reduce water consumption through continuous recycling processes, making them suitable for regions facing water constraints. In addition, the controlled production environment enables consistent, year-round fish farming, thereby improving productivity and profitability. Enhanced biosecurity within closed systems also minimizes disease risks, reduces reliance on chemical treatments, and improves product quality. Collectively, these advantages lower operational uncertainties and increase the attractiveness of aquaculture as a viable business opportunity (Ahmed &Turchini, 2021).

The RAS initiative is embedded within PCSIR's broader research and development framework, which aims to promote technological advancement, reduce reliance on imports, and stimulate economic growth. By supporting the adoption of modern aquaculture systems, PCSIR is contributing to the creation of a technology-oriented entrepreneurial ecosystem in Pakistan. This ecosystem fosters innovation, supports small and medium enterprises (SMEs), and enhances value chain development within the aquaculture sector.

Private Sector and Startups

Emerging startups in Pakistan are exploring smart aquaculture solutions, water filtration technologies, and innovations in fish feed. RAS enables a shift toward tech-driven agribusiness, creating opportunities for system design, consulting, and digital monitoring enterprises. This contributes to a vibrant private sector ecosystem capable of scaling modern aquaculture operations (Ahmed &Turchini, 2021; Ende et al., 2025).

5. Entrepreneurial Outcomes.

The thematic analysis of Recirculating Aquaculture Systems (RAS) adoption in Pakistan reveals a set of interrelated entrepreneurial outcomes that collectively contribute to the development of a technology-driven aquaculture ecosystem. These outcomes are categorized into four major themes: startup development, SME growth, innovation, and value chain development. Each theme reflects patterns identified through the systematic coding and interpretation of secondary data, consistent with the thematic analysis approach outlined by Virginia Braun and Victoria Clarke.RAS supports a technology-driven entrepreneurial ecosystem by promoting innovative startups, consultancy services, market linkages, and youth engagement. University-industry collaborations enable technology transfer and commercialization of research. Startups adopting RAS contribute to skill development, employment generation, and the creation of high-value agri-tech products (Ahmed &Turchini, 2021; Rashid, 2022).

Startup Development

One of the most prominent themes emerging from the analysis is the growth of aquaculture-based startups. RAS technology lowers entry barriers for urban and peri-

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urban entrepreneurs by enabling fish production in controlled and space-efficient environments. Startups are increasingly focusing on indoor aquaculture systems, consultancy services, and system design solutions. This trend aligns with the Diffusion of Innovations framework, where early adopters leverage technological advantages to create new business models and influence wider market adoption (Rogers, 2003). Moreover, access to technological knowledge and infrastructure provides a competitive edge, consistent with the Resource-Based View (Barney, 1991; Ahmed &Turchini, 2021).

RAS fosters the development of agri-tech startups, IoT-based monitoring systems, and aquaculture consulting firms. By enabling precision aquaculture, data-driven decision-making, and controlled production environments, RAS encourages innovation, knowledge-based entrepreneurship, and diversification of business models (Rashid, 2022; Ende et al., 2025).

SME Growth

The analysis further highlights the expansion of small and medium enterprises (SMEs) as a critical outcome of RAS adoption. Modular and scalable RAS units enable entrepreneurs to initiate operations with limited resources and gradually expand production capacity. SMEs benefit from improved productivity, reduced water dependency, and year-round production cycles, which enhance financial stability and market competitiveness. This supports the argument that resource efficiency and technological capability are key drivers of firm performance and growth (Barney, 1991; Badiola et al., 2012).

Innovation (IoT and Smart Aquaculture)

Innovation emerges as a central theme, particularly in the integration of Internet of Things (IoT), artificial intelligence, and automated monitoring systems within RAS operations. These technologies enable real-time water quality monitoring, predictive analytics, and efficient feed management, reducing operational risks and labor costs. The adoption of smart aquaculture solutions reflects the increasing shift toward knowledge-based entrepreneurship and digital transformation in agriculture. According to innovation diffusion theory, the observability and relative advantage of such technologies accelerate their uptake among entrepreneurs (Rogers, 2003; Ende et al., 2025).

Value Chain Development

Another significant theme is the strengthening of the aquaculture value chain. RAS contributes to the development of upstream and downstream industries, including hatcheries, feed production, equipment manufacturing, processing, and distribution networks. By ensuring consistent and high-quality fish production, RAS enhances market reliability and opens opportunities for export-oriented businesses. This integrated value chain development supports economic diversification and aligns with sustainable production systems (FAO, 2023; Martins et al., 2010).

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6. Economic Impact

The thematic analysis of Recirculating Aquaculture Systems (RAS) adoption in Pakistan reveals a set of critical economic outcomes that extend beyond productivity gains to broader socio-economic development. Through systematic coding and theme development, four dominant economic impact themes emerge: employment generation, income growth, food security, and blue economy development. These themes are derived following the analytical framework of Braun, V., & Clarke, V. (2006), ensuring a rigorous interpretation of qualitative data patterns.

Employment Generation

One of the most significant economic impacts identified is the creation of diverse employment opportunities across the aquaculture sector. RAS operations require skilled and semi-skilled labor for system management, water quality monitoring, feeding operations, and maintenance of filtration systems. In addition, indirect employment is generated through supporting industries such as equipment manufacturing, feed production, logistics, and distribution networks. This expansion of employment aligns with the labor-intensive nature of technologically advanced aquaculture systems and contributes to both rural and urban job creation (Badiola et al., 2012; FAO, 2023). From a theoretical perspective, the Resource-Based View suggests that human capital and technical expertise are critical resources that enhance organizational performance and sustainability (Barney, 1991).

Income Growth

RAS adoption significantly enhances income for entrepreneurs and small-scale producers. The controlled environment of RAS enables higher stocking densities, improved feed conversion ratios, and reduced mortality rates, thereby increasing productivity and profitability. Entrepreneurs benefit from consistent year-round production, which supports stable revenue streams and reduces exposure to seasonal risks. Thematic patterns indicate that income diversification is particularly evident among SMEs and startup ventures adopting RAS technologies. This reflects the strategic utilization of technological and knowledge resources to achieve competitive advantage, as emphasized in the Resource-Based View (Barney, 1991; Martins et al., 2010).

Food Security

Food security emerges as a key theme in the analysis, highlighting the role of RAS in ensuring a reliable and sustainable supply of fish protein. By enabling continuous production independent of environmental fluctuations, RAS systems reduce the uncertainty associated with traditional aquaculture and capture fisheries. This is particularly important in Pakistan, where rapid population growth and urbanization are driving demand for affordable, nutritious food. RAS contributes to local food systems by supporting urban and peri-urban aquaculture, reducing reliance on imports, and

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enhancing domestic production capacity (Food and Agriculture Organization, 2023; Ahmed &Turchini, 2021).

Blue Economy Development

The development of the blue economy is another critical economic outcome associated with RAS adoption. By promoting sustainable aquaculture practices, RAS supports the efficient use of aquatic resources while minimizing environmental impact. The integration of technology-driven aquaculture into the broader economic framework contributes to value addition, export potential, and sectoral diversification. In Pakistan, RAS has the potential to strengthen the blue economy by reducing pressure on marine fisheries, encouraging inland aquaculture, and fostering innovation-led growth. This aligns with global sustainability goals and highlights the role of aquaculture in supporting long-term economic resilience (FAO, 2023; Badiola et al., 2012).

7. Discussion

The findings of this study indicate that the integration of Recirculating Aquaculture Systems (RAS) into aquaculture sector represents a significant shift from conventional, resource-intensive fish farming practices toward a more technology-driven, efficiency-oriented production model. RAS facilitates controlled environmental conditions, improved resource utilization, and higher production efficiency, thereby enhancing the overall performance of aquaculture enterprises. This transformation not only improves productivity but also stimulates entrepreneurial activity, including the establishment of startups, the expansion of small and medium enterprises (SMEs), and the creation of employment opportunities across the aquaculture value chain.

From a theoretical perspective, these outcomes align with the principles of the Diffusion of Innovations Theory, which explains how technological advancements such as RAS are gradually adopted by entrepreneurs, particularly through early adopters and demonstration-based learning (Rogers, 2003). At the same time, the Resource-Based View (RBV) underscores the importance of access to technological infrastructure, technical expertise, and institutional support as critical resources that enable firms to achieve sustained competitive advantage (Barney, 1991). The interplay of these theoretical frameworks highlights that both innovation adoption and strategic resource utilization are essential for the successful development of RAS-based enterprises.

Despite these positive developments, the widespread adoption of RAS in Pakistan remains constrained by several structural challenges. High initial capital investment requirements pose a significant barrier, particularly for small-scale entrepreneurs with limited access to financing. In addition, the lack of technical knowledge and skilled human resources restricts the effective operation and management of RAS facilities. Energy dependency is another critical issue, as the continuous operation of pumps, filtration systems, and monitoring technologies results in high operational costs, especially in regions with unreliable energy supplies. These constraints are consistent with existing literature, which identifies financial, technical, and operational challenges as key limitations in the scalability of RAS (Badiola et al., 2012; Ende et al., 2025).

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Addressing these challenges requires a comprehensive, coordinated approach that includes policy interventions, institutional support, and capacity-building initiatives. Financial incentives, including subsidies and soft loans, can reduce entry barriers and encourage investment in RAS technology. Similarly, targeted training programs and knowledge-transfer initiatives are essential for developing the technical skills needed for system management and innovation. The integration of renewable energy solutions can further enhance the economic feasibility of RAS by reducing operational costs and improving sustainability.

In conclusion, while RAS offers substantial opportunities to advance entrepreneurship and modernize aquaculture in Pakistan, its long-term success depends on effectively addressing existing constraints. A supportive ecosystem that combines innovation diffusion, resource accessibility, and policy facilitation is crucial for scaling RAS adoption and achieving sustainable sectoral growth.

8. Policy Recommendations

To effectively scale the adoption of Recirculating Aquaculture Systems (RAS) and strengthen entrepreneurship development in Pakistan, a comprehensive and coordinated policy framework is essential. First, the government should introduce targeted financial support mechanisms, such as subsidies, soft loans, and grant schemes, to reduce the high initial capital requirements faced by startups and small-scale entrepreneurs. Access to affordable financing will encourage investment in RAS infrastructure and enable wider participation in technology-driven aquaculture ventures.

Second, establishing specialized provincial-level aquaculture training centers is critical for building technical capacity. These centers should focus on hands-on training in RAS operation, water quality management, digital monitoring systems, and business development skills, thereby equipping entrepreneurs with the expertise required to manage modern aquaculture enterprises efficiently.

Third, given the high energy requirements of RAS, integrating renewable energy solutions such as solar and wind power should be prioritized. Government incentives for renewable energy adoption can significantly reduce operational costs, enhance sustainability, and improve the economic viability of RAS-based businesses, particularly in energy-constrained regions.

Furthermore, fostering strong public–private partnerships (PPPs) is essential to promote innovation, investment, and technology transfer. Collaboration among government agencies, private-sector investors, research institutions, and universities can facilitate the development of infrastructure, the dissemination of best practices, and the commercialization of aquaculture technologies.

Finally, a comprehensive national aquaculture policy is needed to provide a clear regulatory framework for RAS development. Such a policy should address quality standards, environmental sustainability, certification processes, and market access, while aligning with international best practices. A well-structured policy environment will not only enhance investor confidence but also support the long-term growth of a competitive and sustainable aquaculture sector in Pakistan (Food and Agriculture Organization [FAO], 2023; Ahmed &Turchini, 2021).

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9. Conclusion

This study provides a comprehensive examination of the role of Recirculating Aquaculture Systems (RAS) in advancing entrepreneurship development in Pakistan, highlighting their potential to transform a traditionally resource-intensive sector into a technology-driven, innovation-oriented industry. The findings demonstrate that RAS offers significant advantages in water efficiency, biosecurity, and controlled production, thereby enhancing productivity and reducing environmental risks. More importantly, the adoption of RAS extends beyond technical improvements by creating new avenues for entrepreneurial activity, particularly in the form of agri-tech startups, small and medium enterprises (SMEs), and urban aquaculture ventures.

The integration of provincial case insights reveals that RAS adoption is gradually gaining momentum across Pakistan, with diverse applications ranging from biofloc-integrated systems in Punjab to urban aquaponics in Sindh and technologically enhanced trout farming in Khyber Pakhtunkhwa. These developments illustrate RAS's adaptability across diverse socio-economic and environmental contexts, reinforcing its relevance as a scalable solution for sustainable aquaculture. Institutional initiatives, particularly those led by research organizations, further underscore the importance of demonstration projects and knowledge dissemination in accelerating technology uptake.

From a theoretical standpoint, the study confirms the relevance of the Diffusion of Innovations Theory in explaining the gradual adoption of RAS among entrepreneurs, where early adopters and pilot projects play a critical role in reducing uncertainty and influencing wider acceptance. Simultaneously, the Resource-Based View highlights that access to technological infrastructure, technical expertise, and institutional support constitutes a key determinant of competitive advantage in RAS-based enterprises. The combined application of these frameworks provides a robust analytical lens for understanding the interplay between innovation, resource utilization, and entrepreneurial performance.

Despite these promising outcomes, the study identifies several constraints that limit the widespread adoption of RAS in Pakistan. High initial investment costs, limited technical capacity, and energy-related challenges remain significant barriers, particularly for small-scale entrepreneurs. These findings emphasize the need for targeted policy interventions, including financial incentives, capacity-building programs, and the integration of renewable energy solutions to enhance feasibility and scalability.

In conclusion, RAS represents a strategic pathway for fostering sustainable aquaculture and entrepreneurship in Pakistan. Its ability to support efficient resource use, promote innovation, and generate employment aligns closely with broader economic and environmental objectives, including food security and the development of the blue economy. For RAS to realize its full potential, a coordinated effort involving policymakers, research institutions, and the private sector is essential. Future research should focus on empirical validation through quantitative models and field-based studies to further strengthen the evidence base and support informed decision-making.

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Print ISSN: 3006-2039

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