التحالف السعودي لتقنيات الزراعة والغذاء
Saudi AgriFood Tech Alliance

نبراس
NPRAS
المنصة الوطنية لاستشراف البحث والابتكار للاستدامة
National Platform of R&I Analytics for Sustainability

وزارة البيئة والمياه والزراعة
Ministry of Environment Water & Agriculture

Agriculture Innovation Trends

Foreword

Eng. Abdulrahman Abdulmohsen AlFadley

His Excellency Minister of Environment, Water, and Agriculture

The Kingdom's leadership believes in the importance of research and innovation to build a knowledge economy and achieve true diversification of the state's resources, especially in the vital, priority sectors of environment, water, and agriculture. The Ministry of Environment, Water, and Agriculture aims to enable partners across the innovation ecosystem to stimulate and localize technologies to provide effective sustainability solutions within the Ministry's sectors.

Eng. Mansour bin Hilal Al Mushaiti

His Excellency Vice Minister of Environment, Water, and Agriculture

The innovation ecosystem enjoys unlimited support and keen interest from our wise leadership; may God support them. The Ministry of Environment, Water, and Agriculture has taken several steps to enable innovation, including establishing a deputyship for research and innovation to help find innovative solutions for issues related to sustainability of natural resources, environmental protection, meeting basic water and food needs, and achieving economic and developmental outcomes.

Dr. Suliman bin Ali Al-Khateeb

Deputy Minister for Agriculture

Innovation in the agriculture and food security sectors has become an existential necessity, forming the foundation for stability and the horizon of sustainability in a world increasingly able to harness the analytical capabilities and advanced digital systems offered by agricultural technologies. In the Kingdom of Saudi Arabia, we believe that achieving global food security no longer depends on the abundance of natural resources as much as it depends on the efficiency with which they are managed. Building a prosperous future will only be possible through agricultural and food systems grounded in sustainable innovations and technologies that align with global challenges. Accordingly, we move forward with confidence toward a future led by innovation as a cornerstone of development and comprehensive agricultural transformation.

Foreword

Dr. Abdulaziz bin Malik Al-Malik

Deputy Minister for Research and Innovation

Saudi Arabia has devoted increasing attention to developing its technological and innovation capabilities, recognizing the pivotal role that emerging technologies play in advancing sustainability, ensuring resource availability, and achieving both food and water security. This focus aligns with the goals of the wise leadership—may Allah protect them—which outlined the priorities and ambitions of the research, development, and innovation sector for the coming two decades. This was followed by the launch of the national missions under the priority of environmental sustainability and basic needs, including food security and achieving more than 50% self-sufficiency by 2040, as well as water security through reducing dependence on non-renewable water sources by 90% and lowering water production costs by 50% by 2035

Innovation in the agricultural sector has witnessed remarkable progress, driven by a clear vision to enhance local production and create new economic opportunities through research, innovation, and the adoption and localization of emerging technologies. Currently, the need to strengthen efforts to adopt agricultural innovation is growing, as it serves as a fundamental pillar in building a sector capable of increasing food production, reducing reliance on limited resources, expanding and preserving green spaces, and supporting sustainability objectives.

In line with these priorities, the Ministry launched the Executive Plan for Research and Innovation to adopt and disseminate agricultural technologies, through analyzing challenges and opportunities and drawing inspiration from best implementation practices. This plan identified four initiatives: directing resources toward the adoption of priority technologies, stimulating demand for innovative solutions, strengthening partnerships and knowledge dissemination, and building research and development capabilities. This approach further supported the development of monitoring and foresight tools based on artificial intelligence technologies and systematic analysis of technological indicators.

Within this framework, and as part of its commitment to enhancing sustainability and advancing the environment, water, and agriculture sectors, the Ministry launched the National Platform of R&I Analytics for Sustainability, “NPRAS”. NPRAS serves as a pioneering national platform for monitoring and anticipating major trends in innovation-support policies and investments in emerging and promising technologies.

The publication of the “Agriculture Innovation Trends” report represents an outcome of the Executive Plan and is part of a series of sectoral reports that NPRAS issues regularly. The report provides an in-depth analytical view of technological development pathways and identifies technology priority groups in the agricultural sector. These groups form an integrated system that contributes to increasing productivity, improving crop quality, reducing waste, and maximizing economic value.

At the Ministry of Environment, Water and Agriculture, we reaffirm our commitment to continuing to support the agricultural innovation ecosystem, enhancing national readiness to adopt innovative solutions, and enabling all relevant stakeholders to keep pace with developments and leverage them in alignment with the national priorities for research, development, and innovation. We believe that the integration of efforts among government entities, the private sector, and academic institutions is a decisive factor in achieving the desired agricultural transformation—leading to a sustainable food and agriculture system and a globally competitive sector that aligns with the Kingdom of Saudi Arabia’s Vision 2030 aspirations for a prosperous future.

National Platform of R&I Analytics for Sustainability “NPRAS”

نبراس
NPRAS
المنصة الوطنية لاستشراف البحث والابتكار للاستدامة
National Platform of R&I Analytics for Sustainability

The Ministry of Environment, Water and Agriculture has placed research and innovation at the forefront of its priorities to advance its sectors and ensure their long-term sustainability. Through its Executive Plan for Research and Innovation, the Ministry aims to effectively direct research and innovation efforts toward national priorities and strengthen sustainability in support of the Kingdom’s Vision 2030 objectives. In line with this commitment, the Ministry recently launched the National Platform of R&I Analytics for Sustainability, “NPRAS”, which aggregates accurate and up-to-date data related to the environment, water, and agriculture sectors. The platform analyzes this data using advanced analytical tools such as big data analytics, artificial intelligence, generative AI, agentic AI, and scenario analysis tools. NPRAS relies on more than **10,000** local and international sources, including databases of scientific publications, patents, sectoral reports, and news, and it monitors over **100** million data points updated daily. This enables the platform to deliver precise insights that support evidence-based research and innovation decision-making within the environment, water, and agriculture sectors.

NPRAS serves as an effective model for transforming data into insights with tangible national impact. It supports leaders, decision-makers, and policymakers by providing data-driven guidance and strategic insights that enhance innovation adoption policies and identify promising technologies to address national challenges. The platform also equips investors with information that helps mitigate investment risks and uncover opportunities aligned with national priorities. Moreover, it opens the door for innovators and entrepreneurs to better understand sectoral needs and funding opportunities. For researchers and scientists, NPRAS provides access to a network of scientists and researchers, highlighting innovation and research gaps, and priority areas—thereby enhancing scientific collaboration and facilitating the practical application of research outcomes.

Policymakers and Decision-Makers

- Data-driven and analytical decision-making
- Strategic insights to improve policies
- Identifying promising technologies for national challenges

Investors

- Data that reduces investment risks
- Investment opportunities aligned with national priorities
- Access to data on high-impact projects

Innovators and Entrepreneurs

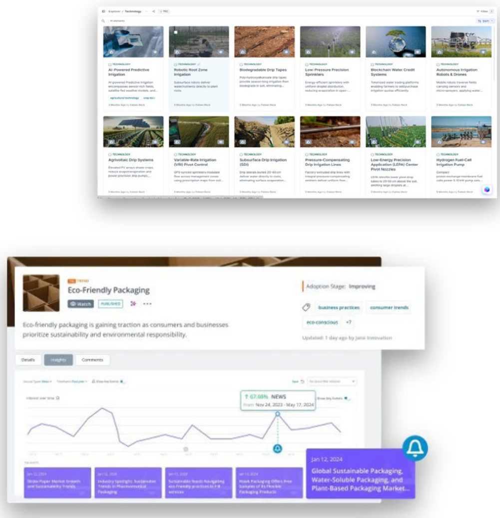
- Access to the needs of national sectors
- Data on partnership opportunities and financing for promising technologies
- Highlighting innovative solutions

Researchers and Scientists

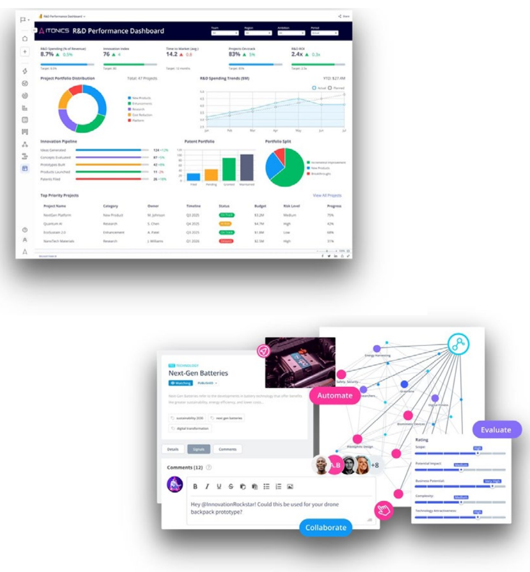
- Data on leading scientists and researchers
- Identifying research gaps and priorities
- Data that strengthens collaboration to apply research outcomes

National Platform of R&I Analytics for Sustainability “NPRAS”

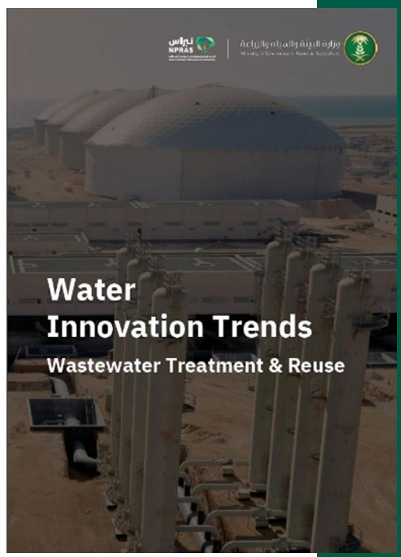
NPRAS offers a comprehensive suite of solutions that include platform access as well as specialized value-added services. The platform continuously monitors and anticipates technological trends by tracking the latest global innovations and developments and aligning them with the needs of the Kingdom’s sectors. It also supports decision-making by providing dashboards and analytical methodologies that enable relevant entities to assess technological solutions and select the most suitable ones.



NPRAS specialized services also include the development of technology adoption roadmaps in collaboration with various entities, helping them adopt effective technological solutions at lower costs. In addition, the platform publishes periodic sectoral reports highlighting key technologies, trends, and future opportunities, as well as a monthly innovation brief that tracks the most important global and local technological developments in a simplified and practical manner. NPRAS additionally provides knowledge-based and training workshops that support knowledge transfer, clarify practical technology applications, and strengthen technical and innovation-related collaboration.



Furthermore, the platform promotes knowledge dissemination, generating analytical reports, and knowledge briefs that help raise awareness of emerging technologies, their impact, and opportunities for adoption. It also enhances scientific collaboration by offering a space for interaction among experts, researchers, and relevant stakeholders to foster joint efforts and knowledge exchange.



In September, the platform published its first report, titled “Water Innovation Trends: Wastewater Treatment & Reuse” The report examined the most prominent technological innovation trends, innovation-support policies, and investment opportunities in emerging technologies, serving as a strategic reference for policymakers, sector leaders, investors, and entrepreneurs. It included insights from several leaders in the private sector, reflecting the pivotal role of national companies and adding a practical, market-oriented dimension to the report. Additionally, the report provided data-driven insights supported by interviews with innovation leaders, offering a practical framework that supports ongoing efforts to advance innovation in the water sector in alignment with the objectives of Saudi Vision 2030.

Thus, NPRAS Platform serves as the Ministry’s foresight arm, transforming data into insights that support research and innovation decision-making. It aims to support advancing the development of the environment, water, and agriculture sectors, and to strengthen water and food security as well as environmental sustainability—all in alignment with the national priorities for research, development, and innovation.

About the report

The strategic direction of the sectoral innovation system necessitates continuous and comprehensive monitoring of key technology and innovation trends. This is essential to enable stakeholders across various sectors to refine their policies and strategic plans in response to an increasingly complex and competitive global landscape, both technologically and economically. To support this effort, the Ministry of Environment, Water, and Agriculture established the NPRAS Platform, a dedicated platform designed to utilize advanced monitoring tools and analytical methodologies. Its objective is to guide the innovation ecosystem within the environment, water, and agriculture sectors by identifying and prioritizing technologies and innovations with the highest potential impact at the sectoral level.

This report is one in a series of regular sector-specific publications issued by the NPRAS Platform, which is committed to tracking and analyzing innovation trends within the environment, water, and agriculture sectors. This edition focuses on the agriculture sector, offering a detailed examination of five technology priority groups that demonstrate strong potential across the sector's value chain. It provides insights into the latest trends, emerging developments, and key opportunities to shape the future of agriculture.

This series aims to achieve several aspects:

1. **Raising stakeholder awareness** of emerging technologies, market dynamics, best practices, and global policies related to innovation in the environment, water, and agriculture sectors.

2. **Accelerating efforts to localize and deploy agriculture technologies** by highlighting the most ready technologies that can enhance the efficiency and sustainability of the agriculture sector.

3. **Enable strategic decision-making** by providing policymakers, industry leaders, and investors with data-driven insights to guide innovation initiatives.

Table of Contents

Executive Summary

This report examines the future of agricultural innovation in Saudi Arabia by analyzing five technology priority groups and their alignment with national strategies. It provides stakeholders with actionable insights into challenges, opportunities, and technology pathways that can enhance productivity, resilience, and sustainability across the agricultural value chain. Importantly, the five technology priority groups are deeply interconnected, creating synergies that multiply their overall impact: precision irrigation supports controlled environment agriculture, aquaculture and food preservation reduce environmental pressures, and UAVs integrate across all production systems. Together, these technologies form a cohesive innovation ecosystem aligned with Vision 2030, positioning Saudi Arabia to not only address pressing agricultural challenges but also emerge as a global leader in sustainable, technology-driven agriculture.

Building on this foundation, the report follows a rigorous, three-stage methodology aligned with global best practices—specifically the **OECD Framework for Anticipatory Governance** — ensuring that its insights are not only robust and in-depth but also actionable for driving innovation and policy development. The first stage in the OECD framework is systematic monitoring, where the NPRAS Platform tracks +10,000 sources (scientific publications, patents, industry reports, and news) with 100M+ data points, updated twice daily to identify signals of high-interest technologies. The second stage is technology trend analysis, where technologies are evaluated for momentum, innovation maturity, and relevance to national agriculture challenges. Moreover, redundancy is removed by clustering similar innovations. The final stage is technology assessment. Where rapidly evolving, high-impact technologies are selected and then examined in greater depth to assess their strategic significance and inform relevant policy decisions. Additionally, Agricultural experts were consulted to validate the identified technologies, provide practical insights on adoption and relevance, and ensure the report reflects both data-driven evidence and sector expertise.

The agriculture innovation trends report builds upon the Innovation in the Agriculture Sector in Saudi Arabia – Technology Adoption Roadmap report, which will highlight the key technology segments within each technology priority group (TPG) (refer to Table [1]), stating relevant technologies under each technology segment from each TPG. A chart will assist in selecting the top technologies, with each one assessed based on Innovation and Interest scores (refer to Figure [4]). The following five key selected technologies represent the top choices within each TPG:

- **AI-Powered predictive Irrigation** from the Irrigation and Water Management TPG
- **Genomic & CRISPR-Enabled Breeding** from the Integrated Aquaculture Farm Management TPG
- **AI Vision for Early Pest / Disease Alerts** from the Protected Agriculture and Controlled Environments TPG
- **Edible Bio-Coatings** from the Food Preservation and Valorization of Waste TPG
- **Edge-AI Drones** from the Unmanned Aerial Vehicles (UAVs) and Satellite Imagery TPG

In the following Technology Spotlight section, the report delves into detailed insights for each selected technology, highlighting key players, Capability Readiness Level (CRL), Technology Readiness Level (TRL), technology advantages & disadvantages, key signals & facts, current state, localization, future trajectory, key uncertainties, and case studies.

The selection criteria used for scoring the five technologies are based on the technology table described in the Appendix.
The two criteria are:

- Technology Readiness level (TRL)
- Spotlight Score*

*a composite score of current research volume (no. of patents & scientific publications in 2024) and growth rate (2019-2024 CAGR of patents and scientific publications) in relation to the leading technology in the priority field. A score of 100 indicates that the technology ranks first among the 15 selected technologies in both research volume and growth rate, whereas a score of 0 indicates that it ranks last in both areas

In conclusion, the report incorporates insights gathered from interviews with innovation leaders, providing an overview of key priorities. These insights collectively serve as a guiding framework for policymakers, industry leaders, and investors to foster innovation and advance the sustainable agriculture sector in alignment with Vision 2030.

Introduction

Agriculture today stands at the intersection of urgent global challenges and unprecedented technological opportunities. Across the world, the sector faces mounting pressures from climate variability, limited natural resources, and rising production costs. In Saudi Arabia, these challenges are intensified by acute water scarcity, limited arable land, and high energy inputs, making agricultural resilience and innovation a national priority. According to the Food and Agriculture Organization (FAO), nearly %70 of global freshwater withdrawals are consumed by agriculture, with efficiency losses that jeopardize food security and sustainability. Locally, Saudi Arabia's agriculture sector has already grown to contribute SAR 114 billion to GDP in 2024, underscoring both its economic importance and its vulnerability to global shifts.

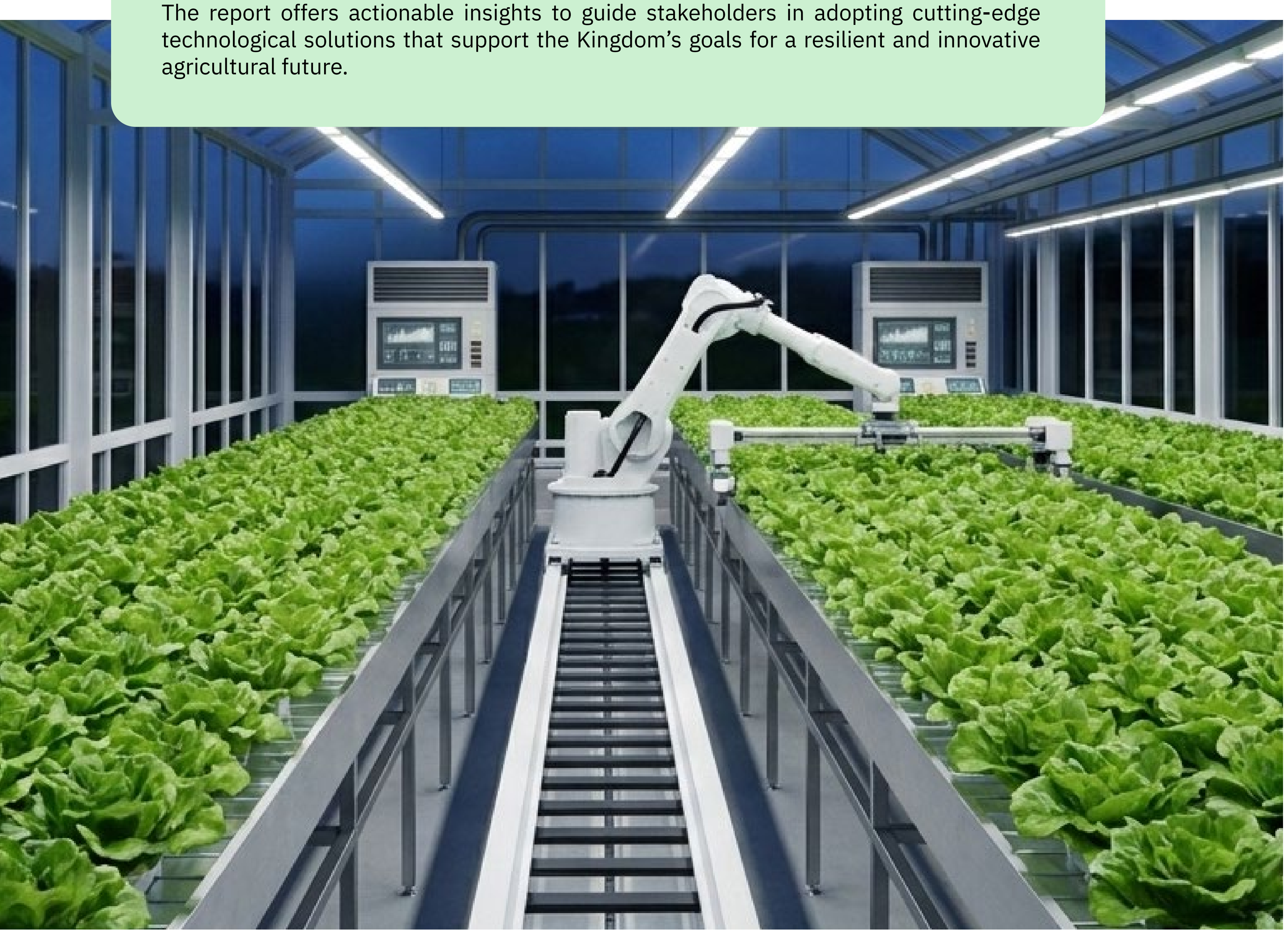
Nevertheless, within these constraints lie vast opportunities. Emerging technologies are enabling data-driven, resource-efficient, and environmentally sustainable farming systems. From predictive irrigation that reduces water use by up to %30 while maintaining yields, to aquaculture innovations that integrate genomic breeding and biosecurity production, science and innovation are reshaping how agricultural value chains operate. Global initiatives, such as the World Economic Forum's work on integrated aquaculture systems, demonstrate how advanced breeding, biosecurity, and nutrient cycling can transform protein supply chains. Similarly, the Kingdom's Vision 2030 places agricultural innovation at the center of food security, sustainability, and economic diversification goals.

By exploring agricultural TPGs, the report highlights current trends, technology readiness, local capability maturity, and pathways for localization. The agriculture sector is undergoing a radical transformation driven by technological innovation, particularly in the areas of irrigation and water management, aquaculture, protected agriculture, food preservation, and the use of drones and satellites. Saudi Arabia has significant potential to adopt and benefit from these technologies to achieve food security and sustainability, thanks to its investments in research, development, and infrastructure. However, realizing the full potential of these technologies requires addressing challenges related to costs, regulatory frameworks, local capacity development, and consumer acceptance. By focusing on innovation and strategic partnerships, the Kingdom can become a global leader in sustainable and smart agriculture.

Scope of the Report [1/6]

This report centers on the advancement of Saudi Arabia's agriculture sector by examining five technology priority groups: **"Irrigation and Water Management", "Integrated Aquaculture Farm Management", "Protected Agriculture and Controlled Environment", "Food Preservation and Valorization of Waste",** and **"Unmanned Aerial Vehicles (Drones) and Satellite Imagery"**. It explores key players, Capability Readiness Level (CRL), Technology Readiness Level (TRL), technology advantages & disadvantages, key signals & facts, current state, localization, future trajectory, key uncertainties, and case studies.

The report offers actionable insights to guide stakeholders in adopting cutting-edge technological solutions that support the Kingdom's goals for a resilient and innovative agricultural future.



Target Audience:

This report is developed for the key stakeholders driving the transformation and sustainability of Saudi Arabia's agriculture sector.

Leaders and Decision Makers
Senior officials and executives within Saudi ministries, authorities, and government-affiliated organizations who shape national strategies and lead sustainability initiatives across the Environment, Water, and Agriculture (EWA) sectors.

Policymakers
Government officials and advisors responsible for formulating agriculture-related policies and regulations in line with Saudi Arabia's Vision 2030, national priorities, and regional development plans.

Investors
Public and private sector stakeholders, including sovereign funds, local investment firms, and strategic partners committed to financing innovative, high-impact agriculture technologies and infrastructure projects within the Kingdom.

Researchers and Scientists
Experts from Saudi universities, research centers (such as KAUST and KACST), and specialized institutes driving R&D to advance sustainable agriculture solutions tailored to the Kingdom's unique agricultural context.

Innovators and Entrepreneurs
Saudi-based startups, incubators, and technology developers creating localized, scalable innovations to address challenges in agricultural productivity, resource efficiency, and sustainability, aligned with national goals for food security and sectoral transformation.

The report outlines key advancements across the five technology priority groups and presents data on their potential economic and environmental impact, highlighting the need for targeted investments and supportive policies. These insights align with Saudi Arabia's Vision 2030 objectives, reinforcing the importance of adopting innovative solutions and strategic planning to enhance agricultural productivity, sustainability, and food security.

Scope of the Report [2/6]

Saudi Arabia's agriculture sector faces a range of interconnected challenges across its value chain, from crops production and livestock management to aquaculture and food processing. High production costs, scarce water resources, and climate variability underscore the urgent need for innovative solutions to optimize inputs, enhance productivity, and ensure long-term sustainability. Key challenges include high resource consumption, low efficiency in traditional farming practices, and significant post-harvest losses. Addressing these issues through targeted technological interventions is essential to achieving the agricultural transformation and food security goals set forth in Vision 2030.

This report provides a detailed analysis of each technology priority group. It offers in-depth insights into **Irrigation and Water Management**, and **Protected Agriculture and Controlled Environments**, both are critical to enhancing **crops** production efficiency. Furthermore, to support data-driven **crops** management, the report explores the application of **Unmanned Aerial Vehicles (drones) and Satellite Imagery.** Additionally, the report examines **Integrated Aquaculture Farm Management**, focusing on innovations in **aquaculture.** Moreover, the report explores advancements in **Food Preservation and Valorization of Waste** within the **food** element of the agriculture value chain.

1

Irrigation and Water Management

Addressing the challenge of inefficient water use by improving irrigation efficiency and optimizing water application based on plant and soil needs.

2

Integrated Aquaculture Farm Management

Improving sustainability in fish and seafood farming by addressing resource inefficiency and environmental impact through optimized water use, nutrient recycling, and systems like cages, flow-through setups, and aquaponics.

3

Protected Agriculture and Controlled Environments

Overcoming challenges of harsh climates and water scarcity by enabling crop production in controlled settings that optimize growth conditions and conserve resources.

4

Food Preservation and Valorization of Waste

Resolving the challenges of food loss and spoilage by extending shelf life, reducing contamination, and converting waste into valuable resources—thereby cutting greenhouse gas emissions, especially methane.

5

Unmanned Aerial Vehicles (drones) and Satellite Imagery

Enhances crop management by enabling precise irrigation, monitoring soil and crop health, improving input accuracy, and providing advanced remote sensing and communication capabilities for smarter agricultural practices

Scope of the Report [3/6]

Strategic Benefits and Alignment with National Goals

To drive sustainable growth and food security in Saudi Arabia's agriculture sector, the integration of advanced technologies is critical. The upcoming technology priority groups sections that are explored in this report offer transformative potential across the agricultural value chain. Each group addresses pressing sectoral challenges such as water scarcity, low productivity, and increased emission levels, while remaining closely aligned with the Kingdom's Vision 2030 objectives. The following are strategic benefits and alignment with national goals for each technology priority group:

Irrigation and Water Management
(Crops)

This technology priority group plays a vital role in enhancing water use efficiency and minimizing agricultural water waste by enabling optimized irrigation tailored to specific crop and soil needs. It directly supports Saudi Arabia's commitment to conserving water resources and improving agricultural productivity, in alignment with Vision 2030 goals for sustainable resource management and reduced reliance on non-renewable water sources.

Integrated Aquaculture Farm Management
(Livestock and fish)

By improving sustainable practices in fish and seafood production, this group advances efficient water reuse, nutrient cycling, and environmental protection. It contributes to national food security by diversifying protein sources and fostering the responsible use of marine and inland water systems, reinforcing the environmental sustainability objectives set forth in Vision 2030.

Protected Agriculture and Controlled Environments
(Crops)

These technologies enable consistent, year-round crop production in controlled settings that mitigate the impacts of Saudi Arabia's harsh climate. By increasing agricultural productivity while conserving critical resources such as water and arable land, they support national efforts to boost local food production and reduce dependence on imports, in line with Vision 2030's agricultural transformation goals.

Food Preservation and Valorization of Waste
(Food)

Focused on extending food shelf life, this group facilitates the conversion of agricultural waste into valuable resources. These innovations contribute to lowering greenhouse gas emissions, particularly methane, and support the Kingdom's transition to a circular economy, further advancing Vision 2030's food security and environmental sustainability targets.

Unmanned Aerial Vehicles (Drones) and Satellite Imagery
(Crops)

Empowers precision agriculture through real-time monitoring of crop and soil conditions, improving resource application and decision-making processes. It aligns with the Kingdom's push toward digital transformation in agriculture and supports Vision 2030's objectives for a data-driven economy and the development of advanced smart farming systems.

Scope of the Report [4/6]

To ensure long-term sustainability and food security, Saudi Arabia is prioritizing the adoption of advanced technologies across its agriculture sector. In alignment with Vision 2030, a focused set of five technology priority groups has been identified for their potential to address pressing sectoral challenges and drive innovation throughout the agricultural value chain. These technologies not only offer targeted solutions to current inefficiencies but also work collectively to create a more integrated, resilient, and high-performing agricultural system. The following sections highlight how these technologies address key challenges and how their synergies amplify their overall impact.

Addressing Key Challenges Across the Agriculture Value Chain

Saudi Arabia's agriculture value chain can achieve greater sustainability and global competitiveness by focusing efforts on critical missions, including efficient water management, adapting to diverse climatic conditions, enhancing input efficiency, reducing food loss, and expanding data-driven decision-making. The five technology priority groups, ranging from precision irrigation and sustainable aquaculture to climate-controlled farming, food waste valorization, and remote sensing tools, collectively address these issues by enhancing resource use, increasing productivity, reducing environmental impact, and supporting year-round, sustainable food production across crops, livestock, and aquaculture.

Interconnection & Synergy Between the Groups

The five technology priority groups are inherently interconnected, with strong synergies that enhance their collective impact across the agriculture value chain. For instance, precision irrigation enabled by UAVs and satellite imagery complements protected agriculture systems by optimizing water usage within controlled environments. Similarly, insights gained from remote sensing technologies can inform both crop and aquaculture management practices, promoting resource efficiency and environmental stewardship. Food preservation and waste valorization technologies further close the loop by transforming residual outputs from crop, livestock, and aquaculture operations into valuable products. Together, these technologies form an integrated innovation ecosystem that supports data-driven, sustainable, and resilient agricultural development in alignment with national priorities.

Table No. [1] below demonstrates that for each technology priority group examined in this report, specific technology segments have been identified to enable a deeper and more focused analysis within each group.

Table 1: Overview of the technology segments across the technology priority groups

Technology Priority Group	Technology Segments			
Irrigation & Water Management	Water supply and allocation	On-farm Delivery and Water Retention	Automation control and Optimization	Sensing and Intelligence
Integrated Aquaculture Farm Management	Production Systems and Water Infrastructure	Precision Operations and Automation	Health, Genetics and Feeds	Circularity and Value chain
Protected Agriculture & Controlled Environment	Climate & Energy Optimization	Water and Nutrient Circularity	Sensing, Automation, and Control	Crop Performance & Assurance
Food Preservation and Waste Volarization	Cold chain & Atmosphere control	Non-thermal Preservation & Decontamination	Smart Packaging and Product life Intelligence	Waste to value & Chain of custody
Unmanned Aerial Vehicles & Satellite Imagery	Satellite constellation & on-orbit Analytics	UAV Sensing Payload & Modalities	UAV Platforms & Infrastructure	Field Operations & Actuation

Scope of the Report [5/6]

Agriculture Sector Challenges and Opportunities

Saudi Arabia's agriculture sector is increasingly turning to innovation and advanced technologies to tackle critical challenges such as water scarcity, limited arable land, high production costs, and climate variability. Through the adoption of precision irrigation, controlled environment agriculture, aquaculture systems, remote sensing technologies, and food preservation innovations, the sector is enhancing productivity, resource efficiency, and environmental sustainability. These efforts are driven by national strategies led by the Ministry of Environment, Water, and Agriculture (MEWA) and align with the broader objectives of Vision 2030, which aims to improve food security, reduce reliance on imports, and localize agricultural technologies. By integrating research, development, and innovation across the value chain, Saudi Arabia is not only addressing existing constraints but also creating new opportunities for sustainable growth in the agriculture sector. In 2024, Saudi Arabia's food and agriculture sector marked significant progress toward achieving Vision 2030 goals. The sector's contribution to GDP reached an unprecedented SAR 114 billion, underscoring its increasing economic importance within the Kingdom.

Figure No. [2] outlines the current challenges and opportunities of the agricultural sector, categorized into three main areas in the agriculture value chain: **crops, livestock and fish, and food.**

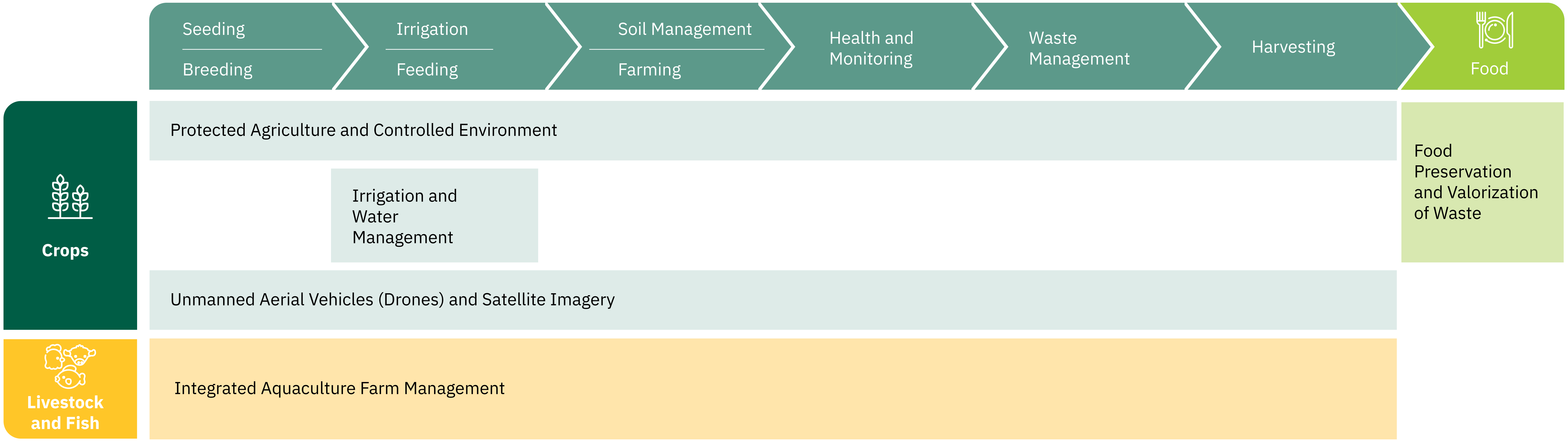
<table>
<tr><th>Crops</th><th>Livestock and Fish</th><th>Food</th></tr>
<tr><td colspan="3">Support local production of agricultural and food products in order to replace high level of imported food</td></tr>
<tr><td colspan="3">Implement efficient technologies and best practices to increase productivity and combat rising production costs (energy, labor and inputs)</td></tr>
<tr><td colspan="3">Reduce emission levels (incl. CO2, CH4, PM)</td></tr>
<tr><td colspan="2">Minimize the negative impact plant pests and animal diseases on the agricultural output</td><td></td></tr>
<tr><td>Increase use of water from renewable sources</td><td rowspan="2">Increase the usage of different grades of feeds by livestock farms</td><td rowspan="2">Ensure food production growth to address changing demographics and consumption patterns</td></tr>
<tr><td>Stimulate development of crops adapted to KSA challenging climate conditions</td></tr>
<tr><td>Improve soil health and fertilizer quality</td><td></td><td></td></tr>
<tr><td>Secure agricultural production growth without influencing protected areas</td><td></td><td></td></tr>
</table>

*"Innovation in the Agriculture Sector in Saudi Arabia - Technology Adoption Roadmap" 2024

Scope of the Report [6/6]

Figure No. [3] below shows the technological framework and it is organized into the focused five technology priority groups. The diagram is classified vertically by elements of the agricultural value chain, and horizontally by the main areas, which are crops, livestock and fish. It also highlights the fifth technology priority group within the food area. Food in the diagram is both within the three areas as well as part of the elements of the value chain.

Figure 3: Technological framework for the agriculture sector



*"Innovation in the Agriculture Sector in Saudi Arabia - Technology Adoption Roadmap" 2024

Methodology

Specifically, the content of this report is based on a four-stage process for analyzing technology signals.

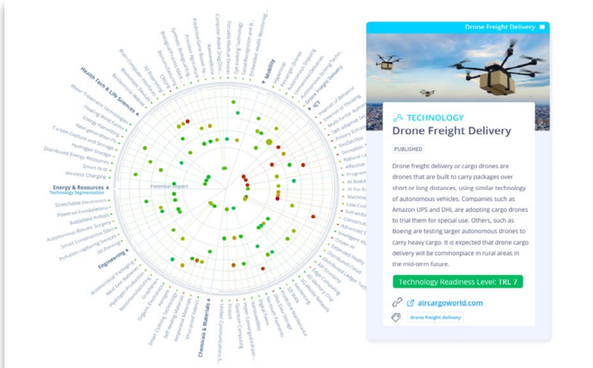
1. Signal Collection & Technology Identification
Considering established practices, such as the Framework for Anticipatory Governance of Emerging Technologies (OECD 2024), the first analysis step involved the systematic collection and evaluation of signals to identify relevant technologies. To achieve this, the team employed a scanning method that combines the advantages of human expertise and machine intelligence, utilizing a signals database that contains over 100 million data points (e.g., patents, industry reports, scientific publications, etc.). Over the past five years, about 68,000 signals related to MEWAs' strategic priorities in the agriculture sector were sourced. Using Retrieval-Augmented Generation (RAG) AI and human expert validation, a longlist of 200 distinct technologies mentioned in patents, scientific publications, and news articles was compiled for in-depth analysis – comprising each of the five technology priority groups. as outlined in the MEWA Agriculture Technology Adoption Roadmap.

2. Technology Assessment & Landscape Creation
In the second step, a comprehensive technology landscape was created from the long list of technologies mentioned in the signals. In the first step, conceptual overlap among the technologies was minimized by subsuming similar or idiosyncratic technologies (e.g., "AI-powered Predictive Irrigation", "AI-Integrated Hydroponics", and "Smart Mobile Irrigation Apps"). After that, for each of the five technology priority groups, the 15 technologies receiving the most mentions in signals in 2024 were selected for the technology landscapes. Those 15 technologies were clustered into technology segments based on the purpose of use and functional characteristics. Finally, all technologies included in the landscape were evaluated on technology and national capability maturity (TRL & CRL), impact potential, and ease of implementation following the criteria outlined in the MEWA Agriculture Technology Adoption Roadmap.

3. Detail Analysis & Spotlight Selection
In the final step, the signals for each technology were examined in detail. Based on this, technology descriptions covering information such as global key players, current state of adoption, development outlook, and relevant case studies were created. In this report, one technology in each of the identified segments was selected to be presented as a spotlight in this report. The selection was done by a quantitative assessment of the current innovation activity level and the growth trajectory of innovation activity. To this end, a composite score of current research volume (no. of patents & scientific publications in 2024) and growth rate (2024-2019 CAGR of patents and scientific publications) in relation to the leading technology in the priority field. A score of 100 indicates that the technology ranks first among the 15 selected technologies in both research volume and growth rate, whereas a score of 0 indicates that it ranks last in both areas (see the Selection Criteria section in the Appendix for a full overview of the technologies and the scoring).

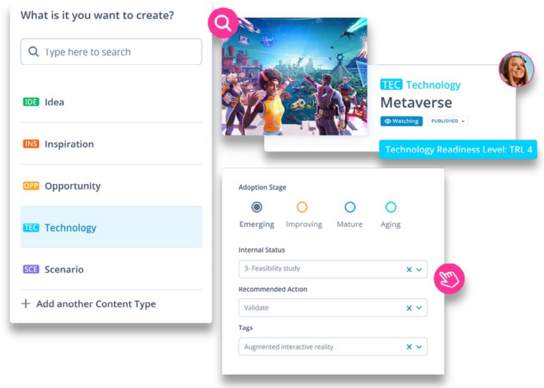
4. Expert Insights & Validation
To complement the quantitative and signal-based analysis, the methodology incorporated insights from agricultural experts with extensive experience in technology adoption and sectoral innovation. A group of selected experts was consulted through structured interviews to validate the identified technologies, assess practical relevance, and provide contextual perspectives on adoption barriers, policy considerations, and regional applicability. Expert input was used to refine technology descriptions, verify the accuracy of key players and adoption trends, and identify emerging use cases that may not be fully captured by signals alone. This step ensured that the report reflects both data-driven evidence and practical expertise, enhancing the robustness, relevance, and actionable value of the technology landscape and spotlight selection.

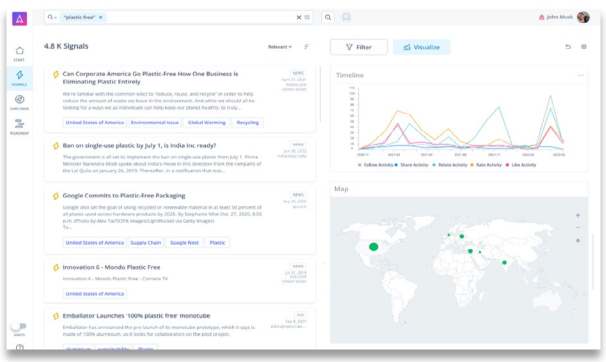
The analyses leading to this report were conducted during the first iteration of MEWA's NPRAS Platform— an AI-enhanced Innovation Operating System that enables the systematic scouting of technology signals, the continuous tracking of emerging technologies and innovation



Technology Radar
In an interactive, visual radar view, emerging technologies can be analyzed and their relevance, maturity level (TRL), and application potential assessed. The Technology Radar helps identify new developments early, strategically prioritize innovation fields, and continuously monitor technology trends.

Collaborative Evaluation
The platform enables a structured, collaborative evaluation of emerging technologies. The involvement of various experts minimizes subjective assessments and facilitates the efficient identification of innovation opportunities and risk evaluation.





Automated Monitoring
The platform's scouting function utilizes AI-powered analytics to continuously capture technological developments from various sources such as scientific publications, patents, industry reports, and news. Through intelligent filters and algorithms, relevant signals are identified, categorized, and updated in real time.

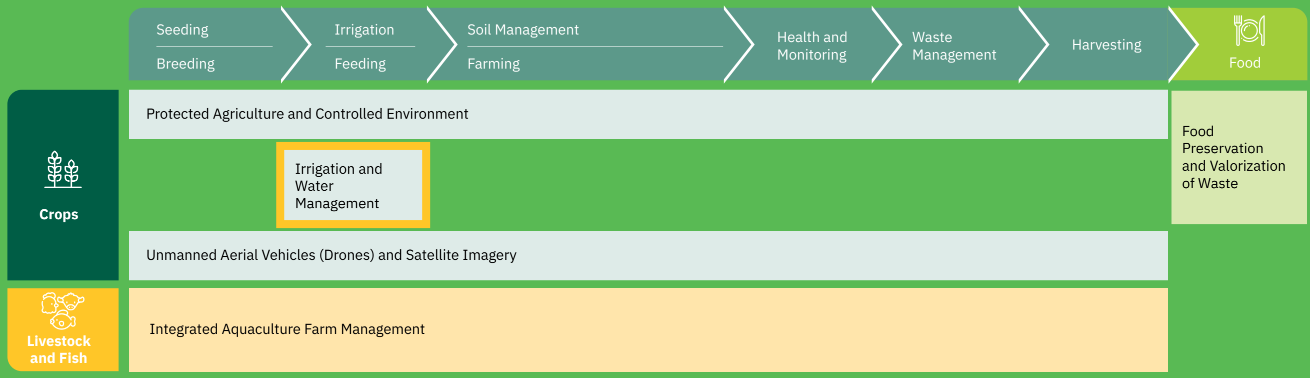
03

TECHNOLOGY PRIORITY GROUPS

TECHNOLOGY PRIORITY GROUP FOCUS

3.1 IRRIGATION & WATER MANAGEMENT

Irrigation and water management technologies comprise a range of technologies aimed at improving water use efficiency, increasing irrigation efficiency, and effectively managing water resources. They target reducing wasteful water use in irrigation and identifying optimal technologies for each plant and soil type.



Frontier Technologies in Irrigation & Water Management

WATER SUPPLY & ALLOCATION	ON-FARM DELIVERY & WATER RETENTION	AUTOMATION, CONTROL, & OPTIMIZATION	SENSING & INTELLIGENCE
Treated Sewage Effluent (TSE) Reuse Networks (TRL 9)	Super Absorbent Hydrogel Soil Amendments (TRL 7)	Autonomous Irrigation Robots & Drones (TRL 7)	Soil-Moisture Sensing (TRL 9)
Offgrid & Portable Desalination Units (TRL 7)	LPWAN (LoRaWAN) Smart Valve & Flow Meter Controllers (TRL 7)	AI-Powered Predictive Irrigation (TRL 8)	Inline Real Time Nitrate & Salinity Sensors (TRL 7)
Blockchain Enabled Water Rights Trading & Audit Platforms (TRL 7)	Agrivoltaic Drip Systems (TRL 8)	AI Enabled Leak Detection (TRL 8)	GIS-Based Irrigation Mapping (TRL 9)
	Subsurface Drip Irrigation (SDI) (TRL 9)	Digital Twin Irrigation Management Platforms (TRL 7)	Satellite Imagery for Irrigation Monitoring (TRL 7)

The definitions of the listed technologies are in the glossary

Innovation, Interest, and Investment by Technology (2024)

To assess the development of each emerging technology, our team collected data on four tangible measures of activity: **news publications, patents, research publications,** and **investment.**

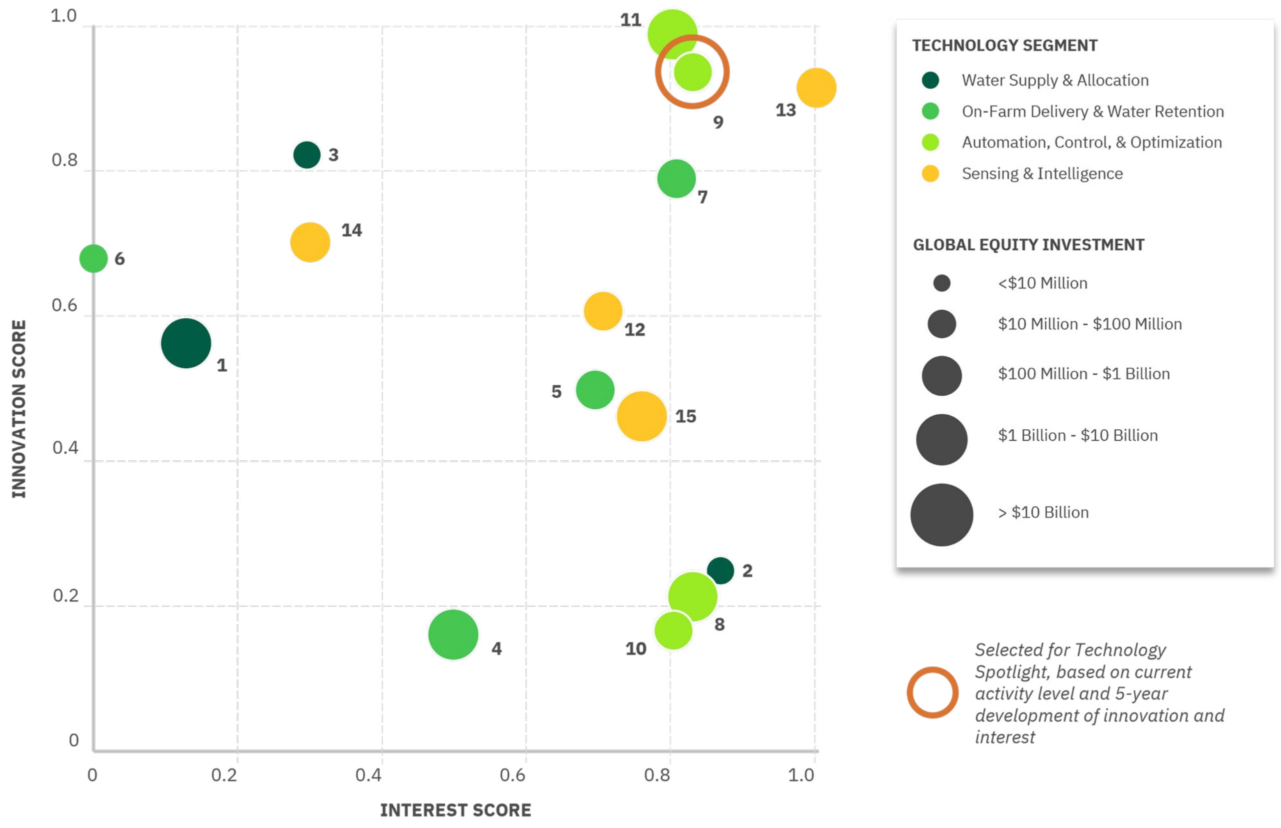
For each measure and in Figure No. [4], we used a defined set of data sources to find occurrences of keywords associated with each of the 15 technologies, screened those occurrences for valid mentions of activity, and indexed the resulting numbers of mentions on a 0–1 scoring scale that is relative to the technologies studied:

The **innovation score** combines the patents and research scores. The patents score is based on a measure of patent filings, and the research score is based on a measure of research publications.

The **interest score** reflects the number of global news publications, relative to the technologies studied (While we recognize that an interest score can be inflated by deliberate efforts to stimulate news coverage, we believe that each score fairly reflects the extent of discussion and debate about a given technology).

Investment depicts the flows of funding into companies linked with the technology, including private-market and public-market capital raises (venture capital and corporate and strategic M&A, including joint ventures), private equity (including buyouts and private investment in public equity), and public investments (including IPOs).

Figure 4: Chart representing Innovation Score vs Interest Score across all 15 technologies



1 – Treated Sewage Effluent (TSE) Reuse Networks
2 – Blockchain-Enabled Water-Rights Trading & Audit Platforms
3 – Offgrid & Portable Desalination Units
4 – Subsurface Drip Irrigation (SDI)
5 – Agrivoltaic Drip Systems
6 – LoRaWAN Smart Valve & Flow-Meter Controllers
7 – Super-Absorbent Hydrogel Soil Amendments
8 – AI-Enabled Leak Detection Analytics
9 – AI-Powered Predictive Irrigation
10 – Digital-Twin Irrigation Management Platforms
11 – Autonomous Irrigation Robots & Drones
12 – GIS-Based Irrigation Mapping
13 – Soil-Moisture Sensing
14 – Inline Real-Time Nitrate & Salinity Sensors
15 – Satellite Imagery for Irrigation Monitoring

Based on the scoring methodology of the McKinsey Tech Report

Note: Innovation and interest scores for the 15 trends are relative to one another. All 15 trends exhibit high levels of innovation and interest compared with other topics. While some technologies may have applications outside of agriculture, this analysis considered only patents, publications, news, and investments in the agriculture context.

Technologies Trending in Innovation Output and Public Interest

Static innovation and interest scores snapshot technological vitality, but momentum reveals trajectory. Tracking growth or decline exposes breakouts before rivals, flags waning hypes, guides timing of subsidies, calibrates capacity-building, and aligns infrastructure budgets with future demand. Dynamics safeguard against sunk costs and amplify the impact of the resources in the EWA ecosystem.

Figure No. [5] investigates the global growth rates in patents, publications, and news published on the technologies studied over the past 5 years, particularly the growing momentum in the segment **Automation, Control, & Optimization,** is evident. In particular, the following technologies display high growth rates across all three measures examined:

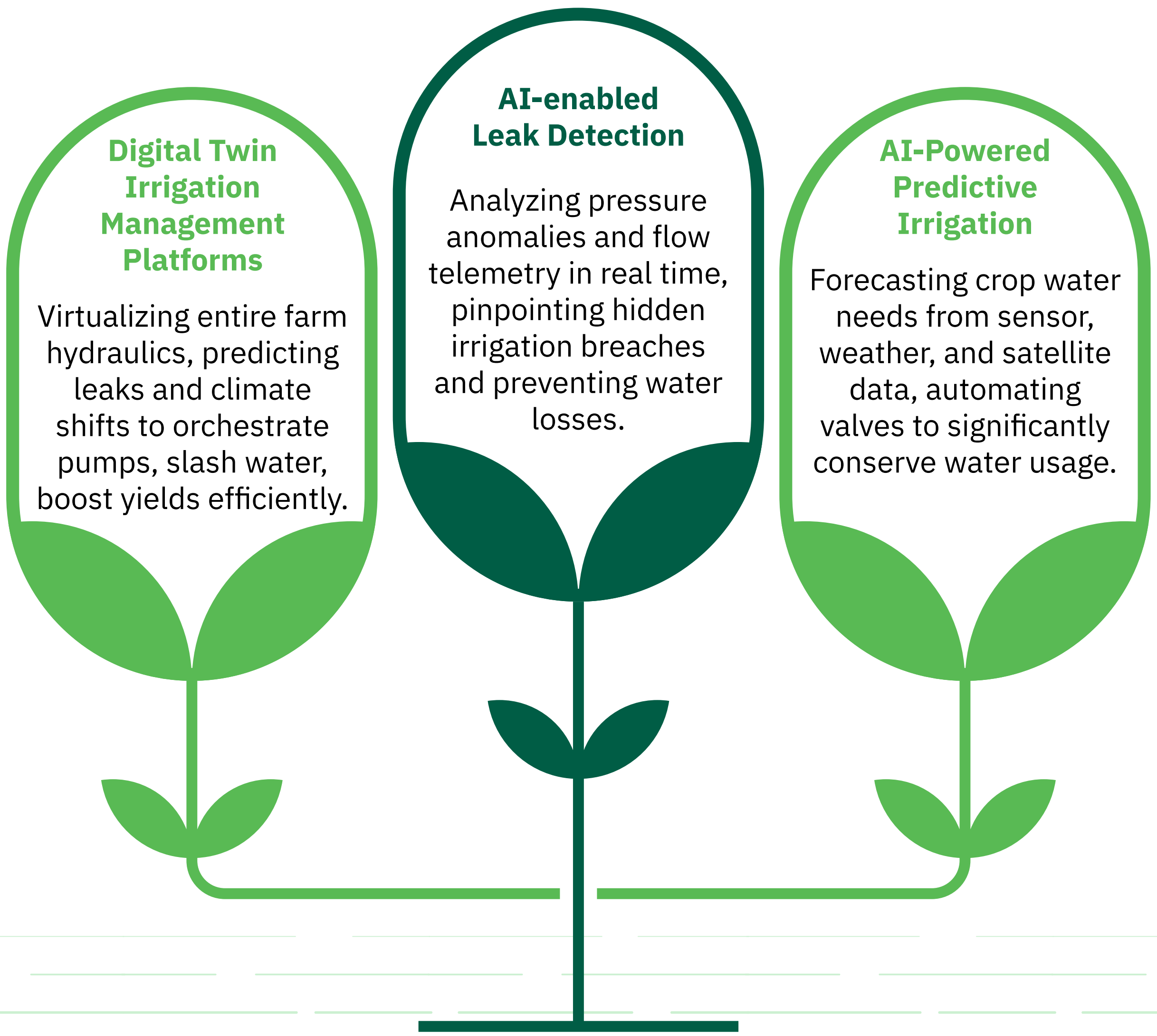
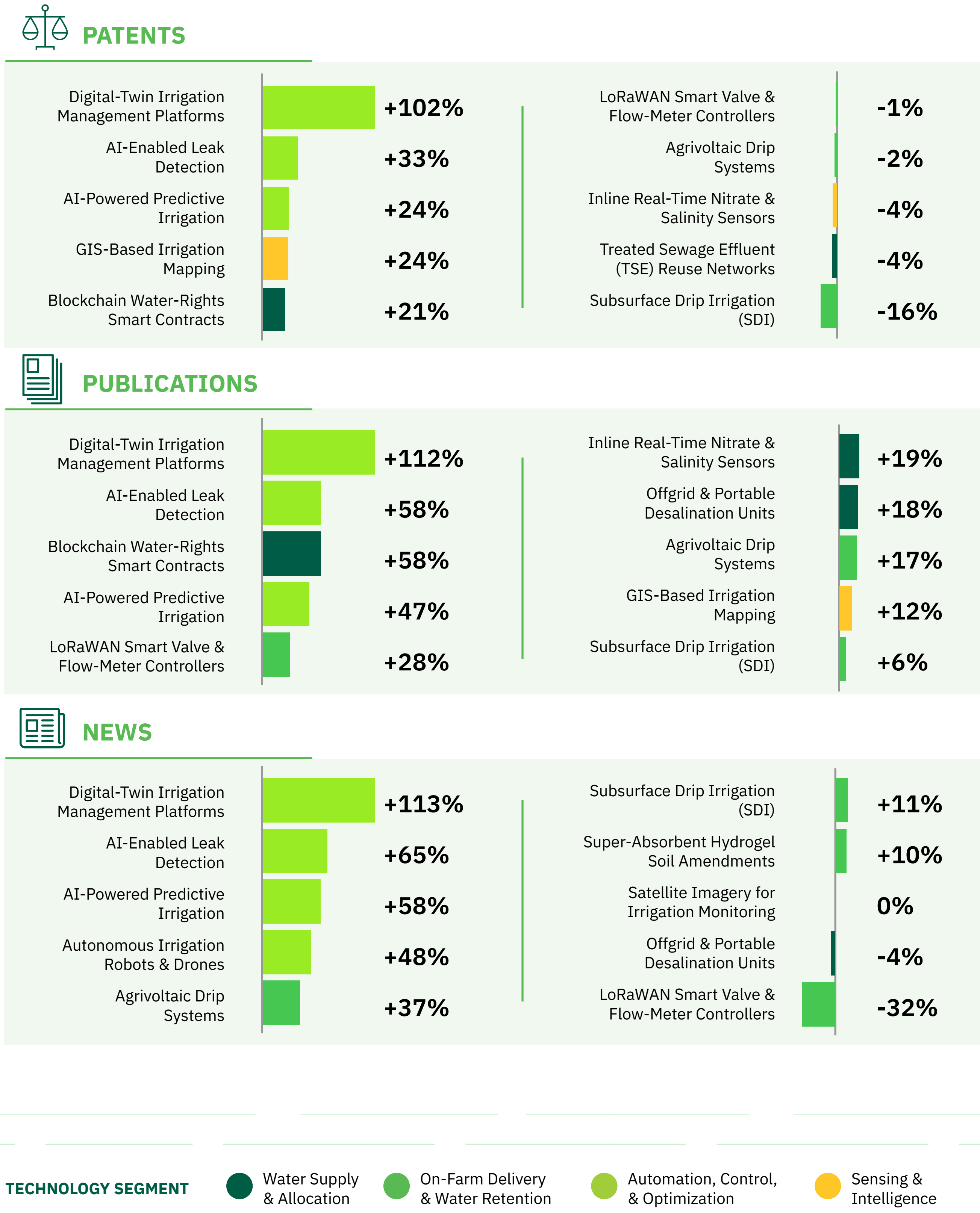


Figure 5: Continuous Annual Growth Rate of Patents, Publications, and News (2019-2024), Top 5 and Bottom 5 Technologies



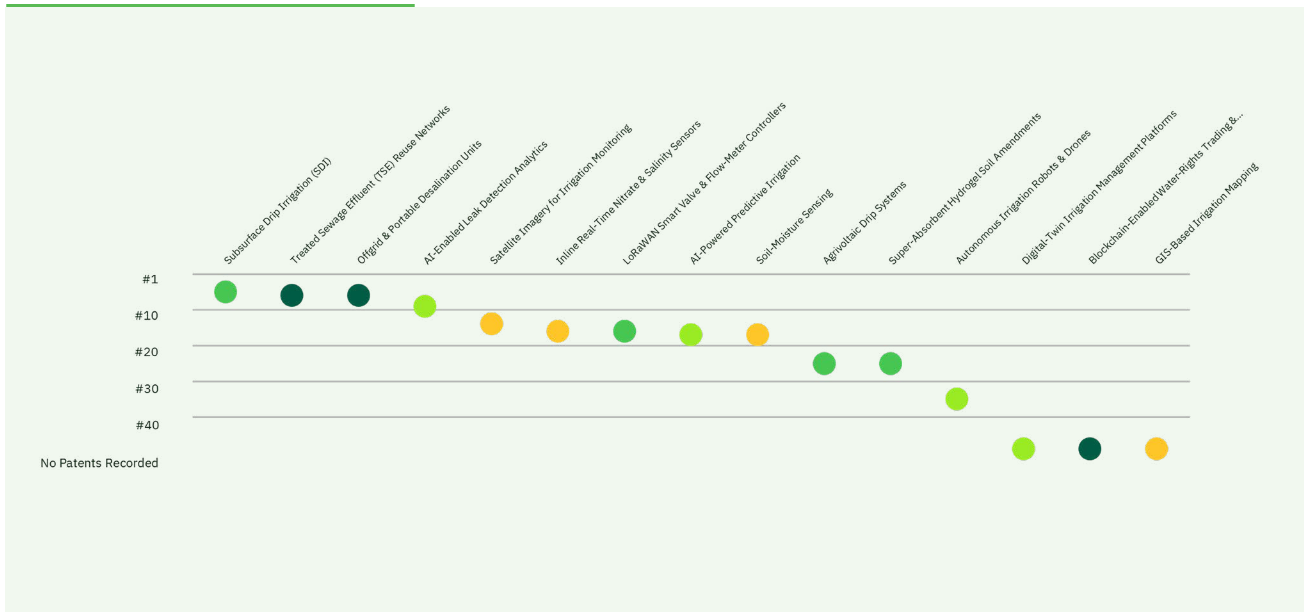
Overview of National RDI Output

Overall, Saudi Arabia is well-positioned in the technologies investigated. Regarding **Patents**, compared to the overall Global Patent Rank (27th), our nation ranks in the global Top-20 for more than half of the irrigation technologies surveyed, and Top-10 in ~25% of key emerging technologies in the field. Saudi Arabia takes a leadership position, especially in the segment **Water Supply & Allocation.**

Regarding **Publications** and in Figure No. [6] below, the positioning is even more promising with a Top-10 ranking in more than 40% of the technologies observed and a Top-20 ranking in all but one technology. Most notably, recent investments into digital technologies have placed Saudi Arabia in the global leadership group for scientific publications in the segments **Automation, Control, & Optimization** and **Sensing & Intelligence**. As scientific publication activity is a major early indicator for innovation potential in the future, the outlook toward 2030 and beyond is promising, especially considering the large potential for efficiency gains and sustainable water usage that digital tools, AI, and advanced analytics offer.

Figure 6: Saudi Arabia's Positioning across Emerging Technologies, Global Rank in No. of Patents & Publications (2019-2024)

PATENTS



PUBLICATIONS

TECHNOLOGY SEGMENT: Water Supply & Allocation; On-Farm Delivery & Water Retention; Automation, Control, & Optimization; Sensing & Intelligence

TECHNOLOGY SPOTLIGHT

3.1.1 AI-POWERED PREDICTIVE IRRIGATION

AI-powered Predictive Irrigation encompasses sensor-rich fields, satellite-fed weather models, and self-learning algorithms that anticipate each crop's thirst hours in advance. By orchestrating valves and pumps just-in-time, the system trims water use up to 30 percent, raises yields, and delivers real-time resilience dashboards to farmers' smartphones, while cutting labor and carbon footprints.

AI-Powered Predictive Irrigation

AI-Powered Predictive Irrigation uses machine-learning models to forecast crop water demand from soil-moisture sensors, weather forecasts, and satellite/imagery, then schedules precise irrigation volumes and timing, often executing them automatically via connected valves/pumps. Reviews show ML consistently outperforms rule-based schedules, improving water-use efficiency while maintaining yields (ScienceDirect, MDPI). Field deployments demonstrate substantial savings and more stable production under heat spikes by predicting evapotranspiration and soil water dynamics ahead of time (ScienceDirect). At scale, low-power IoT architectures (e.g., LoRaWAN) make continuous sensing/actuation feasible across large fields with low operating cost critical for arid, groundwater-dependent systems like Saudi Arabia's (ScienceDirect). Beyond water, optimized pump scheduling can also cut energy use, improving farm economics and resilience (MDPI).

Technology and National Capability Maturity

AI-Powered Predictive Irrigation has a high technology readiness (TRL 8) with the system complete and qualified, with commercial farm-scale deployments and peer-reviewed validation. CRL is rated at 6 as strong domestic RDI and institutional scaffolding — KAUST's irrigation/ET* research, the Food and Agriculture Organization and Saudi Irrigation Organization (FAO–SIO) capacity program and the Saudi Data and Artificial Intelligence Authority (SDAIA)-MEWA AI Center enable deployable pilots and early farm-scale rollouts (KAUST Discovery, FAOHome, iotsquared.com.sa). However, in-country productization/manufacturing of specialized sensing and actuation stacks remains nascent and adoption is concentrated among larger, tech-forward farms.

Capability Readiness Level (CRL)

6

Technology Readiness Level (TRL)

8

*ET (Evapotranspiration): The combination of two separate processes whereby water is lost on the one hand from the soil surface by evaporation and on the other hand from the crop by transpiration (FAO)
*Capability Readiness Level (CRL) and Technology Readiness Level (TRL) descriptions are in the Glossary

Global Key Players

01 Netafim
02 Lindsay
03 Valmont
04 Rivulis
05 CropX
06 SupPlant
07 Hydrosat
08 Tule Technologies
09 Arable
10 GroGuru

Technology Potential

AI models forecast crop water demand from sensors, weather, and imagery to optimize irrigation timing and volumes, raising water-use efficiency and resilience in arid farming.

Advantages

- **Proven water savings:** Field deployments pairing IoT sensing with ML cut applied water while maintaining performance (e.g., ~31% reduction in bananas), demonstrating tangible, at-scale gains beyond rule-based scheduling. ScienceDirect
- **Scalable with low OPEX:** LPWAN-based systems cover multi-hectare farms with long-range, low-power telemetry, enabling continuous sensing and control which is key for distributed Saudi fields. ScienceDirect
- **Forecast-driven decisions:** Real-time scheduling tools that fuse forecasts and field observations improve timing and amounts under variable weather, reducing risk of stress or waste. AGU Publications

Disadvantages

- **Cost and complexity barriers:** Precision/AI irrigation can demand new hardware, data pipelines, and analytics skills; high upfront costs and system complexity slow adoption especially for smaller farms. Government Accountability Office
- **Forecast uncertainty propagates:** Errors in weather forecasts translate into irrigation misestimation; studies show significant sensitivity of crop-stress predictions to forecast quality, necessitating safeguards and local calibration. ScienceDirect
- **Cyber and data-privacy risks:** Connected irrigation platforms expand the attack surface and can expose sensitive farm data; securing devices, networks, and cloud services is non-negotiable. ScienceDirect
- **Dependence on imported components:** High dependence on imported parts and components as local manufacturing of agricultural sensors and robotics is still growing *.

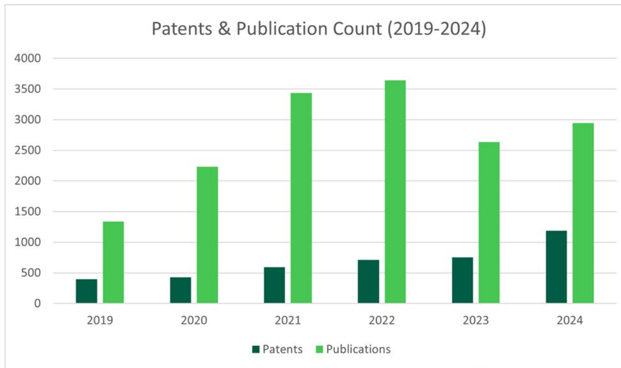
*Insights taken from experts in the agriculture sector

Latest Developments

A fast-maturing stack is converging new ET sensors, edge-AI controllers, and reinforcement-learning schedulers pushing predictive irrigation from pilots to production during 2024–2025.

Key Innovation Signals

- **Field-level ET sensors arrive:** Vendors now measure actual evapotranspiration (ETa) in real time to drive predictions, complementing soil probes and improving scheduling ROI e.g., CropX's Evato ET sensor rollout for row crops. cropx.com
- **Whole-farm AI advisory wins awards:** Lindsay's FieldNET Advisor—real-time modeling and recommendations across entire operations earned an American Society of Agricultural and Biological Engineers (ASABE) AE50 award, signaling mainstream acceptance of ML-based scheduling. Lindsay
- **Reinforcement learning gains momentum:** A 2025 systematic review finds RL increasingly viable for water-management decisions, underscoring rapid research growth toward adaptive irrigation policies. Frontiers
- **Edge-AI irrigation controllers mature:** New 2025 designs integrate sensors, forecasting, and automated actuation, showing practical pathways from lab models to on-farm predictive control. MDPI
- **Better plant-stress forecasting:** Deep multi-task learning methods improve prediction of stem water potential which is a key input for anticipatory irrigation under heat and drought extremes. ScienceDirect
- **Scaled sensor programs in Asia:** The International Rice Research Institute (IRRI) 2025 field work combines soil sensors, automated water-depth monitors, and drone mapping to generate location-specific, data-driven irrigation advisories for smallholders. timesofindia.indiatimes.com



The figure below is investment development of the technology against Innovation score vs Interest score

Insights and Statistics

Predictive irrigation is delivering measurable water and energy savings at field scale while building a credible evidence base and commercialization momentum.

Key Stats & Facts

- **30%+ water reduction demonstrated:** An Agricultural Water Management field study on bananas using IoT + ML reported 31.14% less irrigation water versus conventional practice, validating predictive control benefits at crop scale. ScienceDirect
- **Water and energy savings compound:** A predictive algorithm–based system reported up to 27% water and 57% energy savings (Monte Carlo evaluation), highlighting dual resource gains when AI optimizes irrigation and pump operations. iamm.ciheam.org
- **Scalable low-power comms proven:** A 22-hectare olive-grove deployment showed LPWAN (LoRaWAN) can support long-range, low-energy sensing and automated irrigation control which is critical for cost-effective rollout across large farms. ScienceDirect
- **Evidence base expanding fast:** A 2024 review synthesized 16 studies using ML for irrigation scheduling, documenting improved decision quality and water-use efficiency across settings. ScienceDirect
- **Macro need is overwhelming:** ~70% of global freshwater withdrawals and ~90% of consumptive use are for agriculture — underscoring the outsized impact of smarter irrigation on water security. FAOHome
- **Commercial momentum building:** The smart irrigation market is projected to grow from $1.59B (2025) to $2.65B (2030) (10.8% CAGR), driven by AI integration and conservation. marketsandmarkets.com

Technology Adoption

Adoption is accelerating via OEM platforms and satellite services; in Saudi Arabia, success hinges on tight alignment with water law, TSE safety rules, and NCM-grade weather inputs.

Current State

- **OEM platforms are mainstreaming AI scheduling:** Lindsay's FieldNET Advisor embeds machine learning with soil maps and hyper-local weather, delivering field-level "when/where/how much" recommendations and remote control — evidence that predictive scheduling is shipping at scale. Lindsay
- **Major public programs fund modernization:** Spain's Recovery Plan finances modernization of 550,000 ha of sustainable irrigation across 15 regions, targeting significant annual water savings — policy momentum that accelerates digital and data-driven irrigation upgrades. La Moncloa
- **Satellite-first advisory at scale:** Rivulis Manna delivers site-specific irrigation recommendations from frequently refreshed satellite imagery and weather, marketed as field-tested and globally deployed — expanding reach where dense in-field sensors aren't yet viable. Rivulis

Requirements for Localization

- **Bind optimization to Water Law duties:** Systems must ingest well-meter telemetry and enforce parcel water budgets, so recommendations respect Saudi Water Law provisions on conservation and regulated abstraction. Laws of Saudi Arabia
- **Instrument TSE reuse for safety:** Predictive schedules should integrate real-time TSE quality (e.g., turbidity, pathogens, EC) and constrain crop/application per the Executive Regulations of Treated Sewage Water. FAOLEX
- **Use authoritative local forecasts/alerts:** Models need National Center for Meteorology (NCM) weather and sand-/dust-storm early warnings to anticipate heat/dust impacts and adjust irrigation safely under extremes. beta.ncm.gov.sa

Outlook

Edge AI, richer ET sensing, and smarter algorithms will push predictive irrigation toward closed-loop autonomy, but data quality, cybersecurity, and integration hurdles will decide who scales — and who stalls.

Future Trajectory

- **ET sensing goes mainstream:** New field-level evapotranspiration sensors complement soil probes, enabling "measure-and-manage" irrigation that learns crop water use directly and improves ROI, accelerating adoption beyond pilots into broadacre row crops. cropx.com
- **RL powers closed-loop control:** Reinforcement learning is moving from papers to production-ready policies, optimizing sequential irrigation under uncertainty and variable weather signaling a shift from static rules to autonomous, continuously improving schedulers. Frontiers
- **Interoperability becomes the pathway:** Irrigation data/control standards progress (AgGateway's PAIL moving into ISO 7673 series) enable vendor-neutral, plug-and-play links between AI schedulers, controllers, and FMIS which are critical for cross-OEM scaling and national rollouts. aggateway.org

Key Uncertainties

- **Forecast error propagation:** Inaccurate weather forecasts can cascade through crop-stress models, mis-timing irrigation and eroding benefits, making local calibration, ensembles, and fail-safes essential. ScienceDirect
- **Cyber exposure of connected farms:** Expanding IoT footprints increase attack surfaces; weak security practices and patchy regulation create real operational risks for irrigation controllers and data clouds. ScienceDirect
- **Integration gaps slow impact:** Many tools still fail to fuse real-time crop measurements, forecasts, and field constraints into actionable schedules, limiting transferability across crops, soils, and climates. ScienceDirect

Source: AI-generated image created using Google Gemini, prompt-based synthesis.

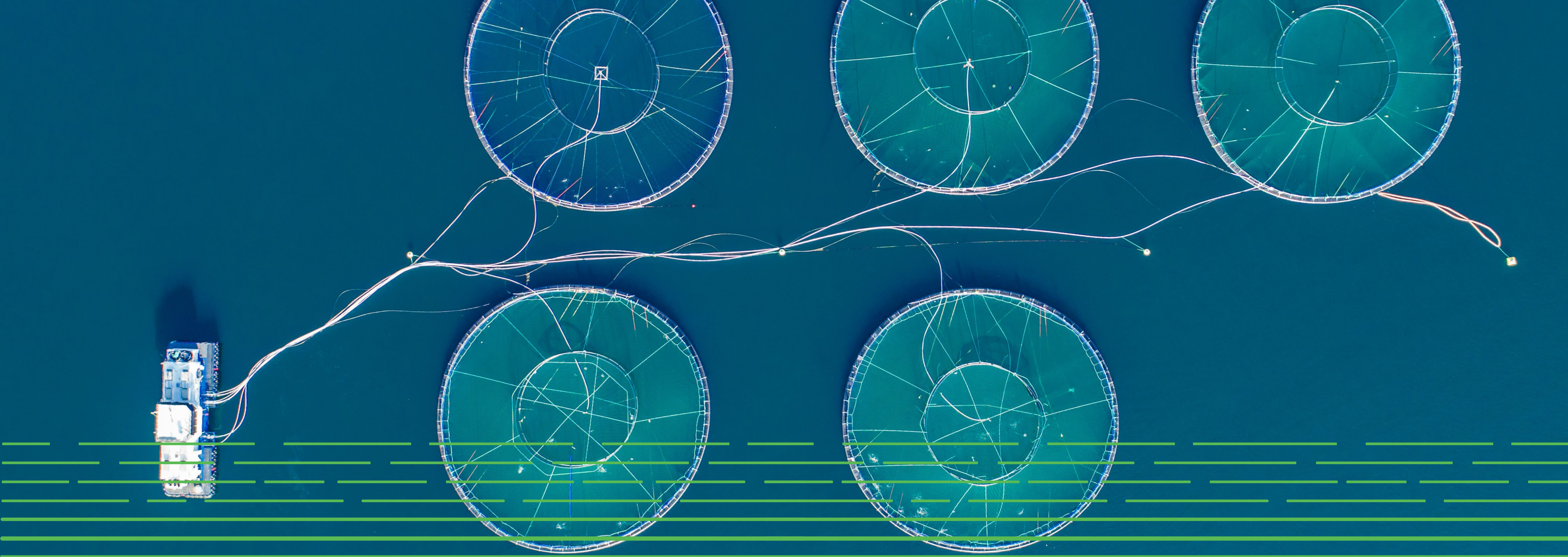
Local Case Study

Al-Ahsa Oasis

Al-Ahsa Oasis, Saudi Arabia's largest date-palm cluster, faces groundwater depletion, salinity creep, and extreme summer evapotranspiration. Many growers still rely on fixed-time surface/drip schedules that over-wet the surface, waste pumping energy, and miss tree-to-tree variability. There was still lack of proof that subsurface, data-driven control could save water without hurting yields, and that low-cost sensing would be accurate enough to trust in the field. Recent local research documents Al-Ahsa's irrigation-water quality constraints (mix of groundwater, drainage, and TSE), underscoring why precision control matters (MDPI, PubMed).

A 64-tree demo block installed IoT-enabled subsurface drip with predictive control. Calibrated soil-moisture sensors streamed to an on-farm controller that forecast soil-water deficit from microclimate and recent uptake, dosing only when thresholds were crossed. Solenoid valves executed setpoints; logs captured flow, runtime, and overrides. Fail-safes reverted to conservative timers on sensor faults. The design emphasized maintainability (modular nodes, filtration SOPs) and quick farmer onboarding. The architecture mirrors peer-reviewed Al-Ahsa work — cloud/edge control, calibrated sensing, automated scheduling, and practical bill-of-materials, showing a clear blueprint for replication (MDPI).

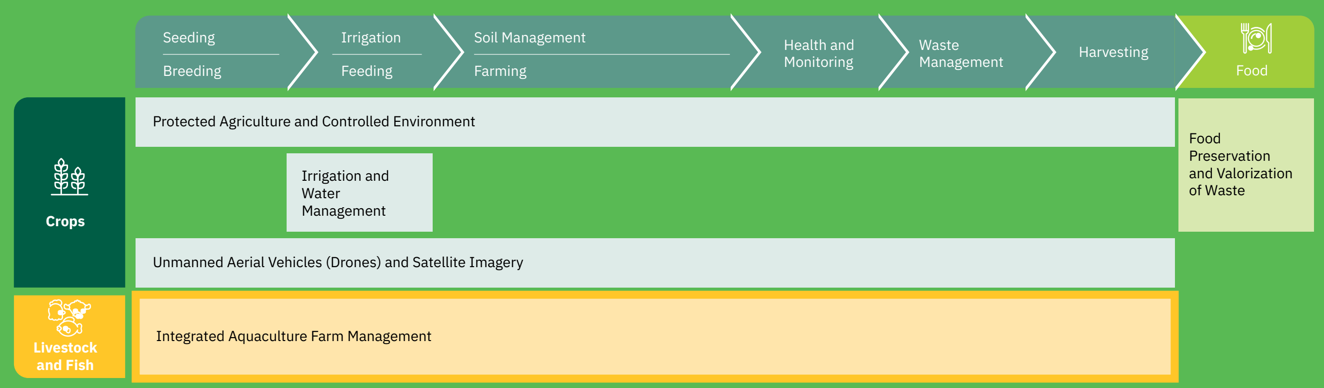
Across the season, the system delivered ~%25 less irrigation water vs. farmer practice while maintaining commercial yield/quality. Sensor calibration achieved R0.96 ≈ ^{2} against laboratory moisture, building confidence that algorithmic dosing reflected true root-zone status. Subsurface application reduced surface wetting and weeds, stabilized moisture, lowered pump hours, and simplified fertigation timing. Independent Al-Ahsa trials likewise show subsurface systems significantly lift water productivity versus traditional surface methods (MDPI, pmc.ncbi.nlm.nih.gov).



TECHNOLOGY PRIORITY GROUP FOCUS

3.2 INTEGRATED AQUACULTURE FARM MANAGEMENT

Integrated aquaculture farm management involves a set of technologies and practices for managing aquaculture operations that integrate components like site selection, species integration, nutrient cycling, water management, and biosecurity. It works to promote sustainable and efficient aquaculture production while minimizing environmental impacts.



Frontier Technologies in Integrated Aquaculture Farm Management

PRODUCTION SYSTEMS & WATER INFRASTRUCTURE	PRECISION OPERATIONS & AUTOMATION	HEALTH, GENETICS, & FEEDS	CIRCULARITY & VALUE CHAIN
Recirculating Aquaculture Systems (RAS) 2.0 (TRL 9)	AI driven Feeding & Biomass Monitoring (TRL 8)	Genomic & CRISPR Enabled Breeding (TRL 6)	Sludge Valorization (TRL 7)
Renewable Energy Powered RAS (TRL 8)	Aquaculture Digital Twins (TRL 7)	Functional Probiotic & Postbiotic Feeds (TRL 8)	Blockchain based Traceability Platforms (TRL 7)
Biofloc Technology (BFT) (TRL 8)	Autonomous Net Cleaning & Inspection Robots (ROV/AUV) (TRL 8)	AI based Health Diagnostics (TRL 7)	Integrated Multi Trophic Aquaculture (IMTA) (TRL 7)
Nanobubble Oxygenation Systems (TRL 7)	Satellite & UAV Algae and Water Quality Monitoring (TRL 7)		
	Water Quality Sensor Networks (TRL 8)		

The definitions of the listed technologies are in the glossary

Innovation, Interest, and Investment by Technology (2024)

To assess the development of each emerging technology, our team collected data on four tangible measures of activity: **news publications, patents, research publications,** and **investment.**

For each measure, we used a defined set of data sources to find occurrences of keywords associated with each of the 15 technologies, screened those occurrences for valid mentions of activity, and indexed the resulting numbers of mentions on a 0–1 scoring scale that is relative to the technologies studied:

- The **innovation score** combines the patents and research scores. The patents score is based on a measure of patent filings, and the research score is based on a measure of research publications.

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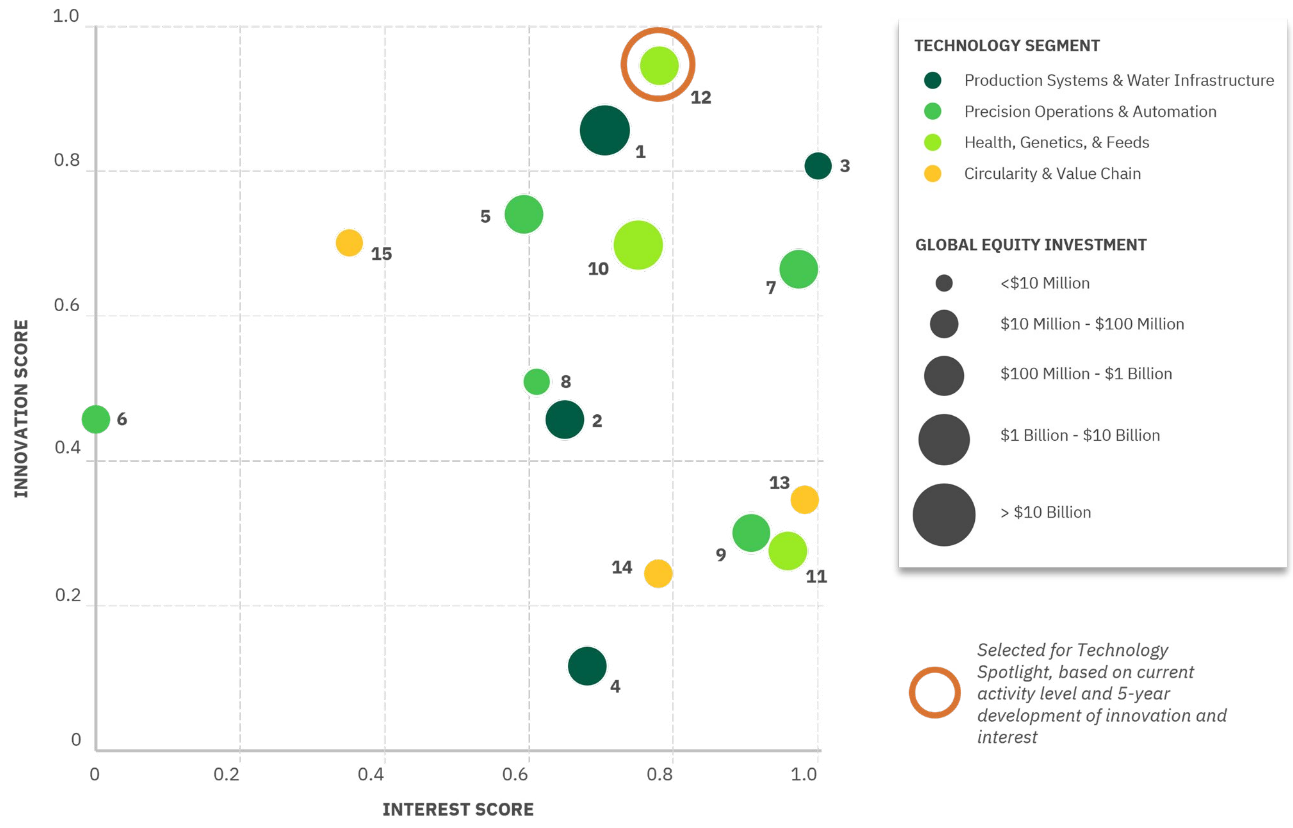
- **Investment** depicts the flows of funding into companies linked with the technology, including private-market and public-market capital raises (venture capital and corporate M&A, including joint ventures), private equity (including buyouts and private investment in public equity), and public investments (including IPOs).

Figure 7: Chart representing Innovation Score vs Interest Score across all 15 technologies



1 – Recirculating Aquaculture Systems (RAS) 2.0
2 – Biofloc Technology (BFT)
3 – Renewable-Energy-Powered RAS
4 – Nanobubble Oxygenation Systems
5 – AI-driven Feeding & Biomass Monitoring
6 – Autonomous Net-Cleaning & Inspection Robots (ROV/AUV)
7 – Water-Quality Sensor Networks
8 – Aquaculture Digital Twins
9 – Satellite & UAV Algae and Water-Quality Monitoring
10 – Functional Probiotic & Postbiotic Feeds
11 – AI-based Health Diagnostics
12 – Genomic & CRISPR-Enabled Breeding
13 – Blockchain-based Traceability Platforms
14 – Integrated Multi-Trophic Aquaculture (IMTA)
15 – Sludge Valorization

Based on the scoring methodology of the McKinsey Tech Report

Note: Innovation and interest scores for the 15 trends are relative to one another. All 15 trends exhibit high levels of innovation and interest compared with other topics. While some technologies may have applications outside of agriculture, this analysis took into account only patents, publications, news, and investments in the agriculture context.

Technologies Trending in Innovation Output and Public Interest

Static innovation and interest scores snapshot technological vitality, but momentum reveals trajectory. Tracking growth or decline exposes breakouts before rivals, flags waning hypes, guides timing of subsidies, calibrates capacity-building, and aligns infrastructure budgets with future demand. Dynamics safeguard against sunk costs and amplify the impact of the resources in the EWA ecosystem.

Looking into the global growth rates in patents, publications, and news published on the technologies studied over the past 5 years, less momentum compared to the other technology priorities covered in this report is evident, regarding patents and publications. Nonetheless, the following technologies display high growth rates across all three measures examined:

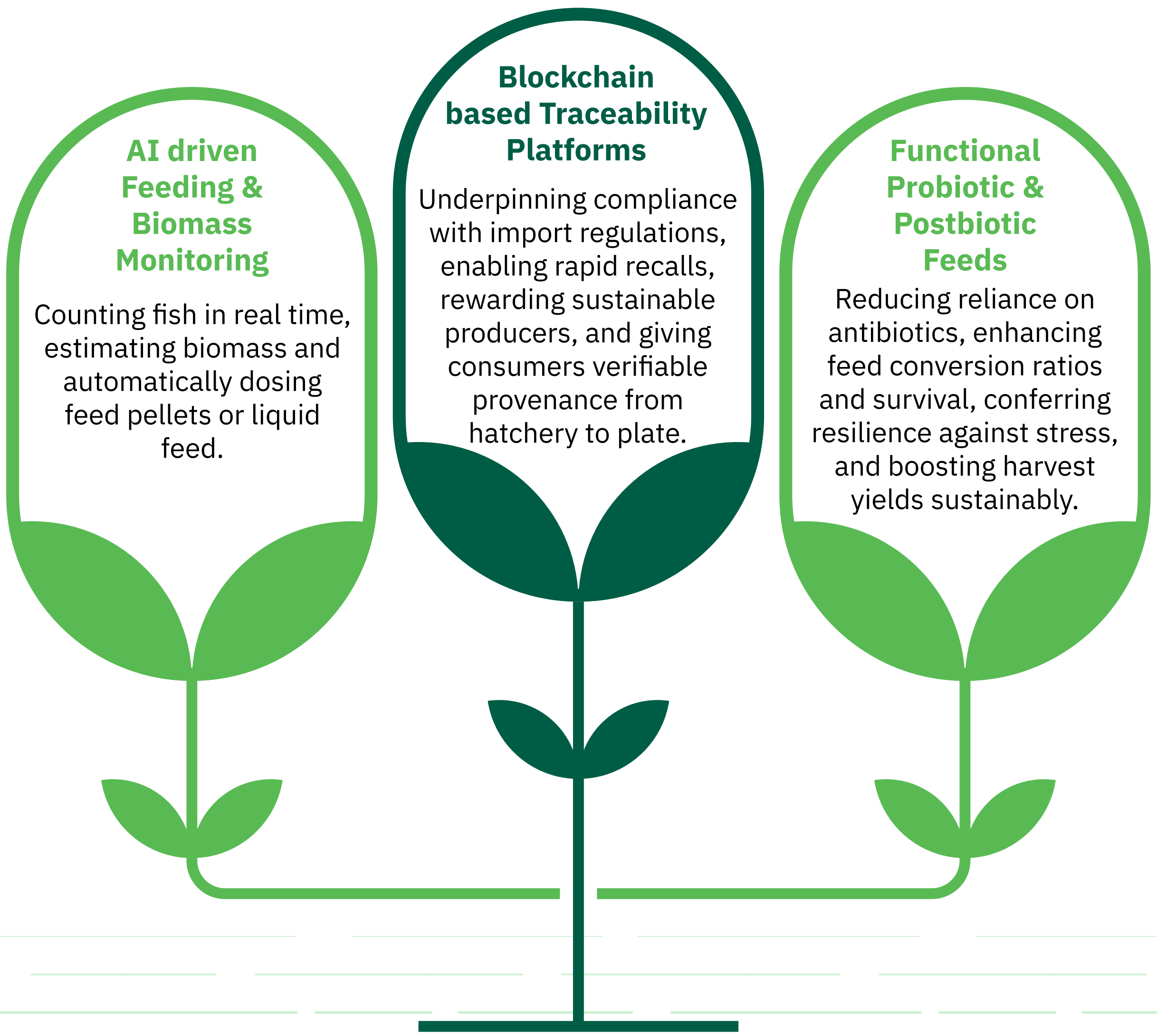
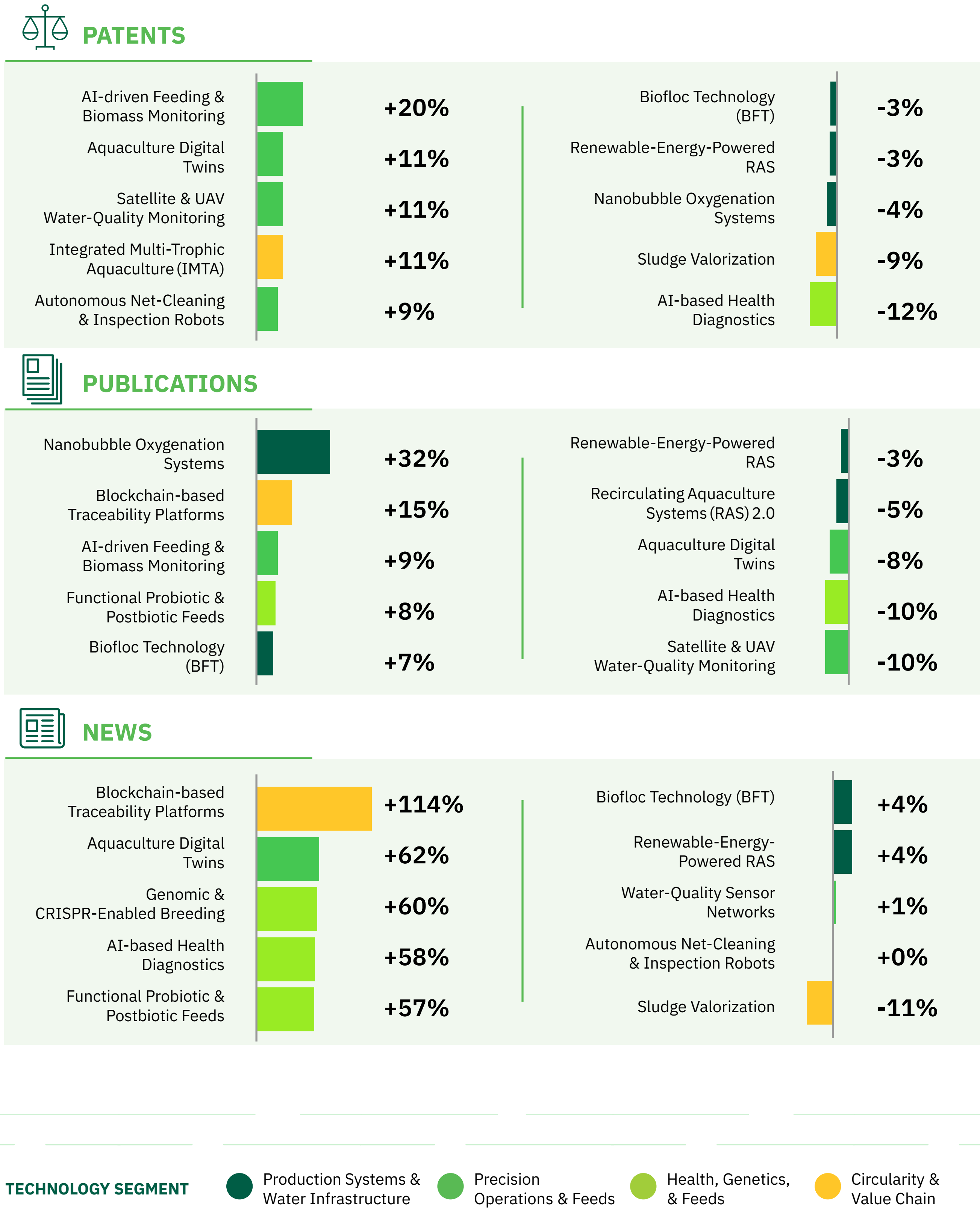


Figure 8: Continuous Annual Growth Rate of Patents, Publications, and News (2019-2024), Top 5 and Bottom 5 Technologies

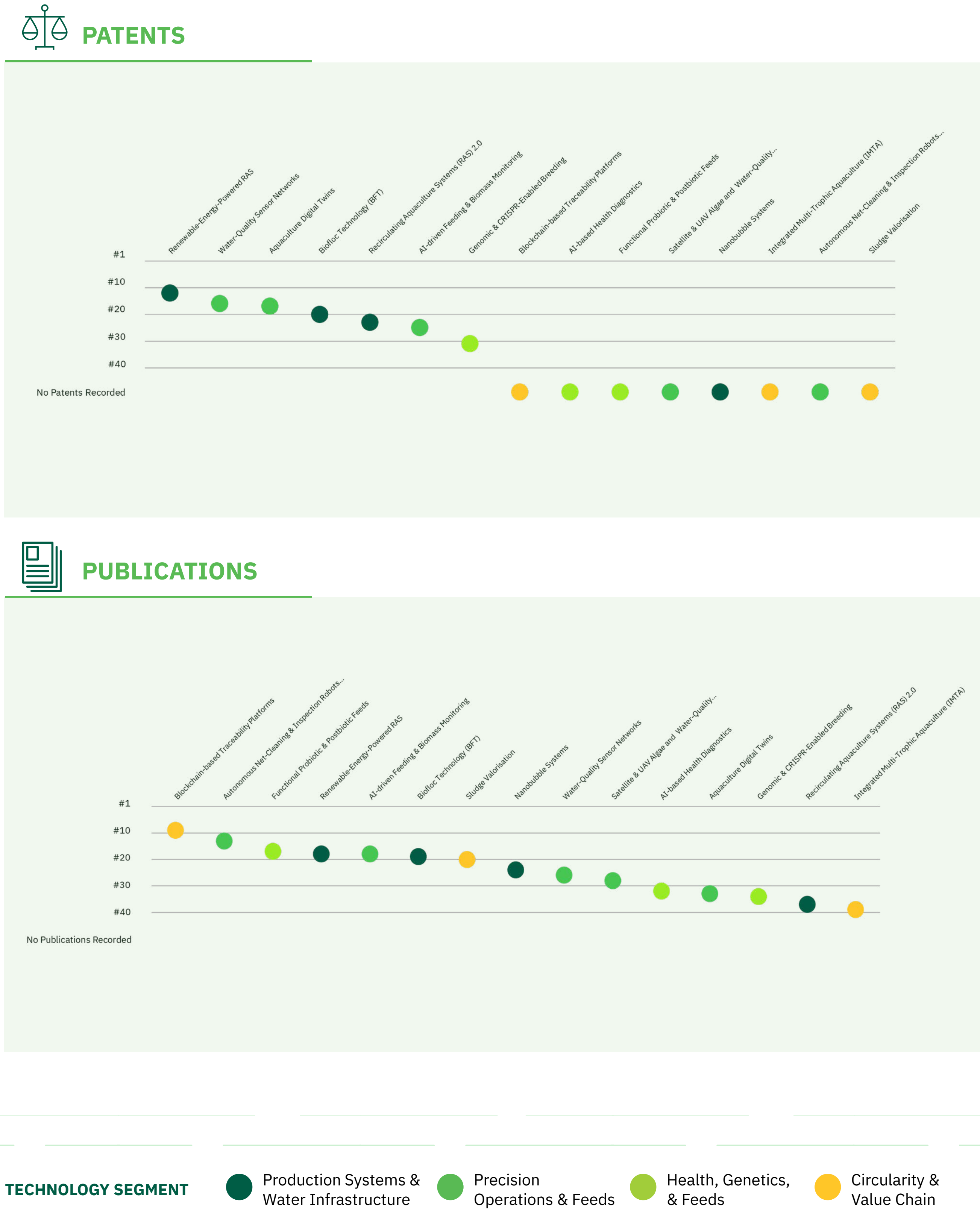


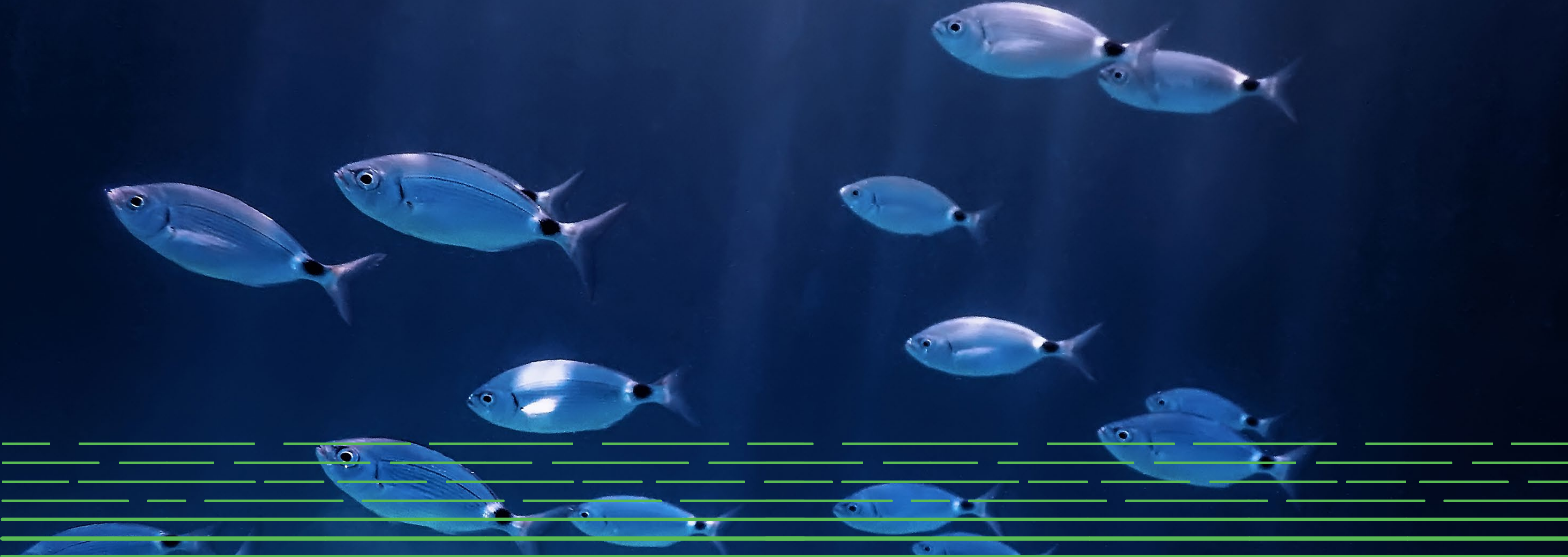
Overview of National RDI Output

Overall, Saudi Arabia is in a mediocre competitive position in the technologies investigated. Regarding **Patents**, compared to the overall Global Patent Rank (27th), our nation ranks in the global Top-20 for ~20% of the technologies surveyed, and Top-10 in none of the key emerging technologies in the field. The country appears most competitive in the segment **Production Systems & Water Infrastructure.**

Regarding **Publications**, the positioning is slightly more promising with a Top 10 ranking in one of the technologies observed and a Top 20 ranking in roughly half of the technologies. Most notably, Saudi Arabia is in a good position regarding the technologies **Blockchain Based Traceability Platforms, Autonomous Net Cleaning & Inspection Robots,** and **Functional Probiotic & Postbiotic Feeds**, with the first and the latter appearing as top-growing technology fields in terms of research output and public interest over the past five years. However, according to experts in the agriculture field, Saudi Arabia's position is weak in terms of patents compared to leading countries. Hence, an increase is needed to fund R&D activities to enhance local capabilities.

Figure 9: Saudi Arabia's Positioning across Emerging Technologies, Global Rank in No. of Patents & Publications (2019-2024)





TECHNOLOGY SPOTLIGHT

3.2.1 GENOMIC & CRISPR ENABLED BREEDING

Genome editing tools like CRISPR Cas9 introduce targeted mutations that confer resistance to sea lice or viral diseases, speed growth or improve fillet quality without transgenic DNA insertion. Precision broodstock programs shorten breeding cycles, reduce chemical treatments and feed usage, while rigorous containment and regulatory frameworks aim to address biosafety concerns and acceptance. While this analysis focuses on genomic and CRISPR applications within aquaculture, these technologies have equally transformative applications in crop breeding, enabling drought-resistant varieties and enhanced nutritional profiles critical for Saudi Arabia's agricultural sustainability. The cross-sector applicability underscores their strategic importance as foundational tools driving innovation across multiple agricultural domains.

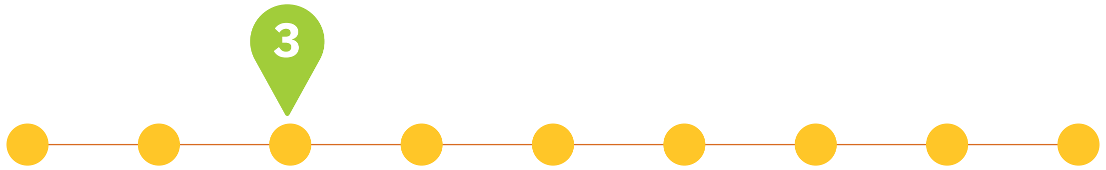
Genomic & CRISPR Enabled Breeding

Genomic & CRISPR-enabled breeding couples two tools. Genomic selection uses genome-wide DNA markers to predict the best broodstock for traits like growth, disease resistance and robustness, delivering faster genetic gain than traditional selection in many aquaculture species (Edinburgh Research, ScienceDirect). CRISPR/CAS enables precise, heritable edits that can introduce beneficial changes (e.g., faster growth, resistance to pathogens, tolerance to heat/salinity) or induce sterility to protect wild populations and improve welfare (PMC, vkm.no). Commercialization is already happening: Japan has approved CRISPR-edited red sea bream and tiger puffer with enhanced growth, demonstrating regulatory and market pathways for aquaculture gene-edited fish (Nature, SeafoodSource). Guidance for responsible use in aquaculture emphasizes trait choice, welfare, containment and risk assessment (Wiley).

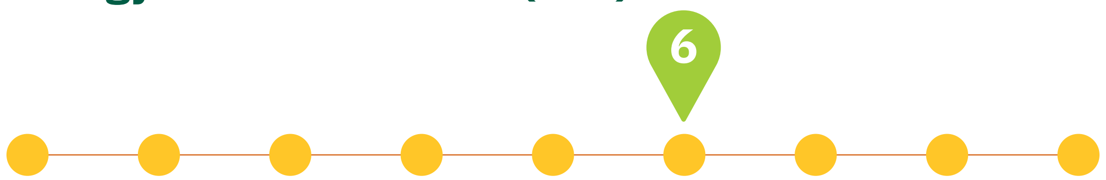
Technology and National Capability Maturity

Prototype gene-edited aquaculture lines have been demonstrated in relevant environments, where Japan approved and sold CRISPR-edited red sea bream and tiger puffer, matching TRL 6. Global roll-out is still constrained by uneven regulation and welfare/biosecurity protocols, so most programs remain pilot-scale (SeafoodSource, PMC). Saudi has credible RDI foundations in KAUST & MEWA aquaculture program, local fish/tilapia genomes, and large integrated hatcheries (e.g., NAQUA) that could operationalize advanced breeding once permitted, which will allow Saudi Arabia to capitalize on the technology's CRL. However, gene-editing policy remains undefined, so near-term market deployment is constrained despite research capacity (KAUST, MDPI, Naqua).

Capability Readiness Level (CRL)



Technology Readiness Level (TRL)



Capability Readiness Level (CRL) and Technology Readiness Level (TRL) descriptions are in the Glossary

Global Key Players

01 Regional Fish Co.
02 Kyoto University
03 Kindai University
04 The Roslin Institute, University of Edinburgh
05 Nofima
06 Benchmark Genetics
07 AquaGen
08 Xelect
09 Center for Aquaculture
10 GenoMar Genetics

Technology Potential

A powerful pairing of genomic selection and precise gene editing to accelerate genetic gain, harden stocks against disease and stress, and lift feed/water efficiency — provided governance, biosafety, and capability gaps are addressed.

Advantages

- **Accelerated genetic gain:** Genome-wide markers enable more accurate selection than pedigree schemes, speeding improvement in complex traits (growth, robustness, fecundity); this compounds across cycles and shortens time-to-impact in commercial hatcheries, especially for salmonids and tilapia. Frontiers
- **Built-in disease resistance, fewer drugs:** CRISPR and functional genomics target host-pathogen pathways to create lines with improved resistance, reducing antibiotic/chemical dependence and strengthening biosecurity in intensive systems. PMC
- **Market proof emerging:** Japan approved and sold CRISPR-edited red sea bream and tiger puffer, showing a feasible regulatory/consumer path for gene-edited fish and signaling investability beyond lab pilots. Nature

Disadvantages

- **Regulatory patchwork slows scale:** Governance is fragmented and evolving; responsible deployment demands case-by-case risk assessment, traceability, and welfare standards, raising time and compliance costs across jurisdictions. Wiley
- **Biosafety & welfare risks:** Potential gene flow to wild stocks, off-target edits, and welfare implications (e.g., sterility edits) require stringent containment, monitoring, and ethics review before large-scale release. Open Knowledge FAO
- **Capability & cost barriers:** Genotyping, data pipelines, and breeding program design demand expertise and capital; smaller producers face hurdles in establishing effective reference populations and analytics. Frontiers
- **Infrastructure Costs:** The need for costly infrastructure and specialized expertise.*

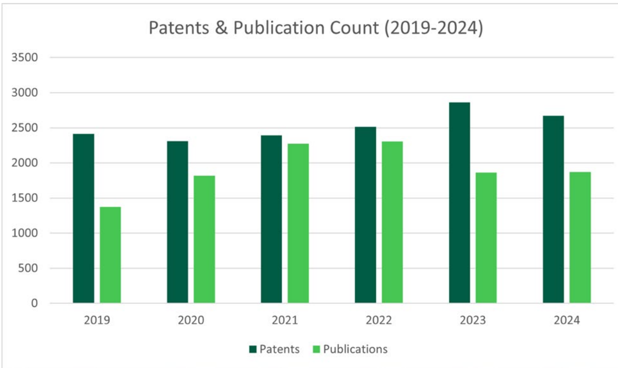
*Insights taken from experts in the agriculture sector

Latest Developments

Momentum accelerated across funding, functional edits, and lice-resistance research, with Japan's commercial pioneers scaling and multiple 2024–2025 studies sharpening the path from lab models to deployable traits.

Key Innovation Signals

- **Commercial scaling in Japan:** Regional Fish closed JPY 4.0B (≈USD 25M) Series C to expand genome-edited species and production — clear market confidence in CRISPR-enabled aquaculture beyond pilots. regional.fish
- **Immune-system edit in salmon:** Researchers created IgM+ B-cell-deficient Atlantic salmon via CRISPR/Cas9, a platform for dissecting disease immunity and informing resistance breeding strategies. Nature
- **Mechanism for lice resistance:** Nofima/Roslin identified skin-cell features linked to lice defense, informing candidate pathways /targets for selective breeding or edits in Atlantic salmon. Nofima
- **Pipeline toward lice-resistant edits:** CrispResist consortium reported progress comparing salmon species' immune responses; findings guide CRISPR gene-edit candidates to transfer resistance into Atlantic salmon. SeafoodSource
- **First gene-edited prawn reported:** Scientists bred a CRISPR-edited giant freshwater prawn, signaling expansion of gene editing beyond finfish toward high-value crustaceans. Undercurrent News
- **Capacity build-out in the US:** 2025 BioMed Central (BMC) Genomics roadmap details priorities for genome-enabled breeding (reference genomes, multi-omics, phenomics, AI) across U.S. aquaculture — indicative of broader infrastructure maturing for genomic selection and targeted edits. bmcgenomics.biomedcentral.com



The figure below is investment development of the technology against Innovation score vs Interest score

Insights and Statistics

Targeted genetics is already delivering measurable gains in yield, disease resistance, and program cost-efficiency, positioning the tech to scale as genotyping prices fall and regulatory pathways clarify.

Key Stats & Facts

- **Genomic selection lifts resistance gains:** In Tasmanian Atlantic salmon, switching to genomic selection raised annual genetic gain for amoebic gill disease from 3.7% → 5.7% (~54% relative), via within-family selection and ~29% higher prediction accuracy. PMC
- **CRISPR fish show real performance uplifts:** Japan's gene-edited red sea bream reports 20–60% more edible yield and ~14% better feed utilization, demonstrating tangible, consumer-facing benefits beyond lab pilots. SeafoodSource
- **Genotyping costs can drop ~80%:** A 2024 study cut per-sample genotyping from ~$50 to ~$10 using low-density panels plus imputation (1,000-fish scenario), materially improving SME access to genomic selection. SciELO
- **Low-density panels retain accuracy:** Across four species, 300–6,000 SNP low-density panels with imputation delivered genomic predictions comparable to high-density arrays; in trout, imputed LD equaled 28K SNP accuracy and beat pedigree by ~11%. BioMed Central
- **CRISPR sterility enables biosafety:** Knocking out the dnd gene yields germ-cell-free salmon expected to be 100% sterile, a powerful tool to curb gene flow while deploying performance traits. ScienceDirect
- **The addressable market is large and growing:** Aquaculture produced 94.4 million tons of aquatic animals in 2022, surpassing capture fisheries, magnifying the upside from genetic efficiency gains. fao.org

Technology Adoption

Adoption is led by Japan's commercial rollouts and major R&D programs in salmon, while the U.S. has clarified regulatory paths; Saudi Arabia can localize via policy updates, anchor hatcheries, and KAUST-led RDI.

Current State

- **Japan moves from pilots to scale:** Regional Fish closed a ¥4.07B (~$25M) Series C to expand genome-edited species and production — evidence of commercial traction beyond lab trials. thebridge.jp
- **U.S. clarifies gene-edited animal oversight:** Food and Drug Administration (FDA) issued updated guidance (GFI #187A/#187B) for heritable intentional genomic alterations in animals, increasing regulatory predictability for aquaculture developers. U.S. Food and Drug Administration
- **Europe advances lice-resistance pipeline:** Nofima's CrispResist consortium reported 2025 progress on mechanisms and windows to defeat sea lice—an R&D pathway toward selective breeding and potential edit targets in Atlantic salmon. Nofima

Requirements for Localization

- **Regulatory pathway definition:** Current Gulf Cooperation Council (GCC) rule Gulf Standards Organization 2141:2011 prohibits import of genetically modified animals, birds, and fish; Saudi would need to define a domestic risk-based framework for gene-edited aquaculture (research pilots, containment, labeling) to enable controlled deployment. USDA Apps
- **Anchor industrial adopters:** NAQUA's large, integrated Red Sea operations can be leveraged as early testbeds for genomic selection and (when permitted) edited broodstock, offering hatchery scale, biosecurity, and distribution. Naqua
- **RDI capacity building with KAUST:** The KAUST–MEWA aquaculture program could serve to stand up reference genomes, phenomics pipelines, and breeder training for priority species (tilapia, marine finfish, shrimp), linking to MEWA targets. kaust.edu.sa

Outlook

Advances in genomic tools, CRISPR precision editing, and AI-driven breeding analytics are redefining aquaculture's next growth frontier. Yet, the pace of progress will hinge on policy alignment, biosafety assurance, and scalable infrastructure — shaping who leads and who lags in adoption.

Future Trajectory

- **Demand pull from aquaculture growth:** As aquaculture becomes the main global source of aquatic animal protein, productivity-boosting genetics will be prioritized to meet rising demand with fewer inputs and lower risk. FAOHome
- **Prime editing becomes fish-ready:** New PE7 ribonucleoprotein workflows markedly improve prime-editing efficiency in fish models, opening a path to precise, minimal-change edits for traits like disease resilience and sterility. MDPI
- **AI-powered multi-omics pipelines:** Breeding will likely fuse SNPs, structural variants, phenomics and AI/ML to pinpoint causative alleles and speed genomic selection and edit target discovery across priority species. BioMed Central

Key Uncertainties

- **Policy patchwork & acceptance:** Governance remains uneven, requiring case-by-case risk assessment, traceability, and welfare standards; public acceptance varies, raising adoption risk across markets. Wiley
- **Biosafety and welfare management:** Potential gene flow to wild stocks, off-target edits, and welfare impacts necessitate robust containment, monitoring, and ethical review — preconditions for wider release. PMC
- **Infrastructure & cost gaps:** Scaling requires reference genomes, high-quality phenotyping, bioinformatics, and trained breeders; without this stack, many programs won't be economically viable. bmcgenomics.biomedcentral.com

Source: KAUST

Local Case Study

National Center for Fish Resources

Saudi aquaculture needs heat and salt tolerant finfish to expand Red Sea cage farming without competing for scarce freshwater. Legacy reliance on Nile tilapia and a handful of marine species leaves production vulnerable to temperature spikes, salinity, and biosecurity constraints. National ambitions to lift domestic output to ~530,000 t by 2030 heighten the pressure to localize broodstock and seed supply for open-water systems (Saudi Aquaculture Society, KAUST).

The National Fisheries Center in Jeddah, working with the Saudi Aquaculture Society and KAUST, domesticated a saline-tolerant Sabaki tilapia line and established hatchery protocols for broodstock, spawning, and larval rearing in full-strength seawater. Critically, in 2021 researchers published the first draft genome of the newly prescribed subspecies O*. spilurus Saudi, supplying markers for traits like osmoregulation, growth, and putative antimicrobial peptides. The Center's saline-tolerant work is explicitly documented by SAS, while cage-system know-how (e.g., HDPE floating cages) provides the operational template to push production offshore with higher biosecurity (Saudi Aquaculture Society, MDPI).

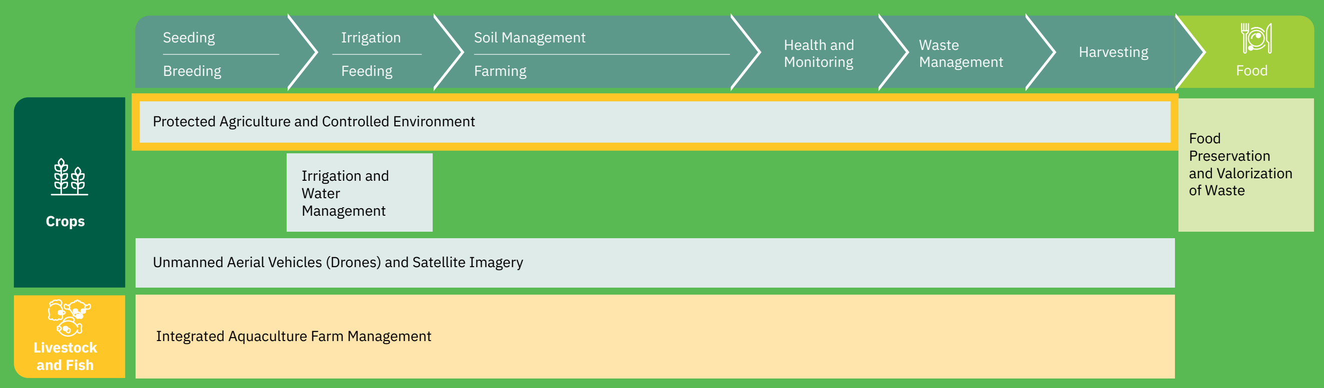
With domestication achieved and a reference genome in hand, the Center has scaled seed supply, reporting intensive larval/fry production runs (e.g., 150,000 larvae in a single month in 2020) and, according to local reporting, progressing toward million-plus fingerlings annually to service Red Sea growers. The program directly supports Vision 2030 aquaculture targets and import substitution, and it offers a tractable pathway to integrate advanced breeding (genomic selection; later, gene-edited sterility/resilience where permitted) into national hatcheries, improving yield, biosecurity, and farmer economics in coastal governorates. (KAUST)

*O is an abbreviation for the genus Oreochromis in the scientific name Oreochromis spilurus saudi.

TECHNOLOGY PRIORITY GROUP FOCUS

3.3 PROTECTED AGRICULTURE & CONTROLLED ENVIRONMENT (CEA)

Protected agriculture and controlled environment encompass technologies that enable growing plants in a defined space with control over conditions like temperature and humidity. This allows increased food production, water conservation, and adapting to unfavorable environmental conditions like the Kingdom's hot climate. This section provides an in-depth look at vertical farming, as well as hydroponic and aeroponic systems, highlighting the emerging technologies within them.



Frontier Technologies in Protected Agriculture & Controlled Environment (CEA)

CLIMATE & ENERGY OPTIMIZATION	WATER & NUTRIENT CIRCULARITY	SENSING, AUTOMATION, & CONTROL	CROP PERFORMANCE & ASSURANCE
Industrial Waste Heat Integration (TRL 6)	Low Energy Aeroponics (TRL 7)	AI Vision for Early Pest / Disease Alerts (TRL 7)	Antimicrobial & IR Reflective Films (TRL 7)
Energy Recovery HVAC (TRL 8)	AWG Greenhouse Systems (TRL 6)	Autonomous Greenhouse Robots (TRL 7)	Blockchain Traceability for CEA Produce (TRL 8)
PCM Thermal Batteries (TRL 7)	Closed Loop Fertigation (TRL 8)	AI-Based Climate Control (TRL 8)	On Site CO_2 Capture & Enrichment (TRL 7)
Agrivoltaics for Greenhouses (TRL 8)			Tunable Spectrum LED Lighting (TRL 9)
Electrochromic Smart Glass (TRL 7)			

The definitions of the listed technologies are in the glossary

Innovation, Interest, and Investment by Technology (2024)

To assess the development of each emerging technology, our team collected data on four tangible measures of activity: **news publications, patents, research publications,** and **investment.**

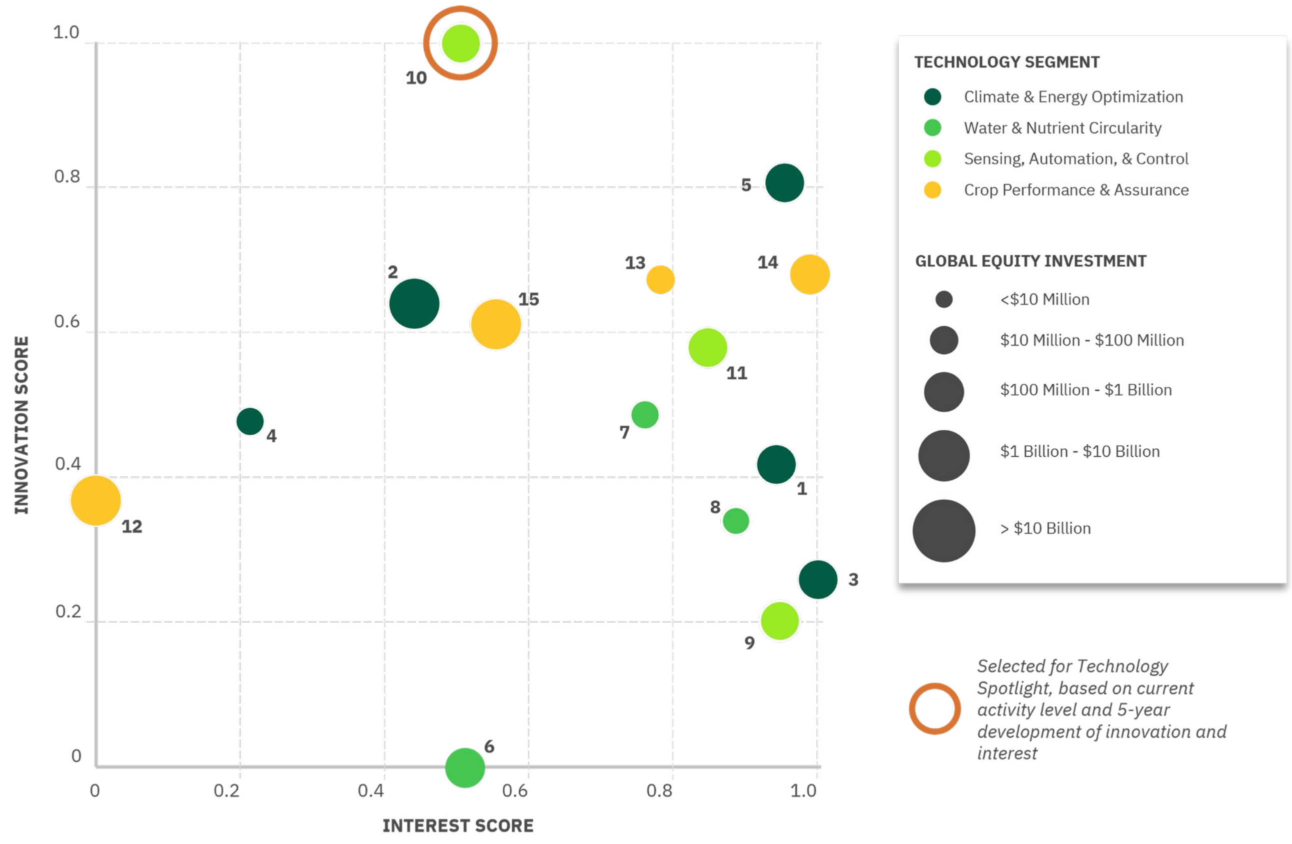
For each measure, we used a defined set of data sources to find occurrences of keywords associated with each of the 15 technologies, screened those occurrences for valid mentions of activity, and indexed the resulting numbers of mentions on a 0–1 scoring scale that is relative to the technologies studied:

The **innovation score** combines the patents and research scores. The patents score is based on a measure of patent filings, and the research score is based on a measure of research publications.

The **interest score** reflects the number of global news publications, relative to the technologies studied (While we recognize that an interest score can be inflated by deliberate efforts to stimulate news coverage, we believe that each score fairly reflects the extent of discussion and debate about a given technology).

Investment depicts the flows of funding into companies linked with the technology, including private-market and public-market capital raises (venture capital and corporate M&A, including joint ventures), private equity (including buyouts and private investment in public equity), and public investments (including IPOs).

Figure 10: Chart representing Innovation Score vs Interest Score across all 15 technologies



1 – Agrivoltaics for Greenhouses
2 – Energy-Recovery HVAC
3 – Electrochromic Smart Glass
4 – PCM Thermal Batteries
5 – Industrial Waste-Heat Integration
6 – Closed-Loop Fertigation
7 – Low-Energy Aeroponics
8 – AWG Greenhouse Systems
9 – AI-based Climate Control
10 – AI Vision for Early Pest / Disease Alerts
11 – Autonomous Greenhouse Robots
12 – Tunable-Spectrum LED Lighting
13 – Blockchain Traceability for CEA Produce
14 – Antimicrobial & IR-Reflective Films
15 – On-Site CO_2 Capture & Enrichment

Based on the scoring methodology of the McKinsey Tech Report

Note: Innovation and interest scores for the 15 trends are relative to one another. All 15 trends exhibit high levels of innovation and interest compared with other topics. While some technologies may have applications outside of agriculture, this analysis considered only patents, publications, news, and investments in the agriculture context.

Technologies Trending in Innovation Output and Public Interest

Static innovation and interest scores snapshot technological vitality, but momentum reveals trajectory. Tracking growth or decline exposes breakouts before rivals, flags waning hypes, guides timing of subsidies, calibrates capacity-building, and aligns infrastructure budgets with future demand. Dynamics safeguard against sunk costs and amplify the impact of the resources in the EWA ecosystem.

Looking into the global growth rates in patents, publications, and news published on the technologies studied over the past 5 years, particularly the growing momentum in the segment **Crop Performance & Assurance** is evident. In particular, the following technologies display high growth rates across all three measures examined:

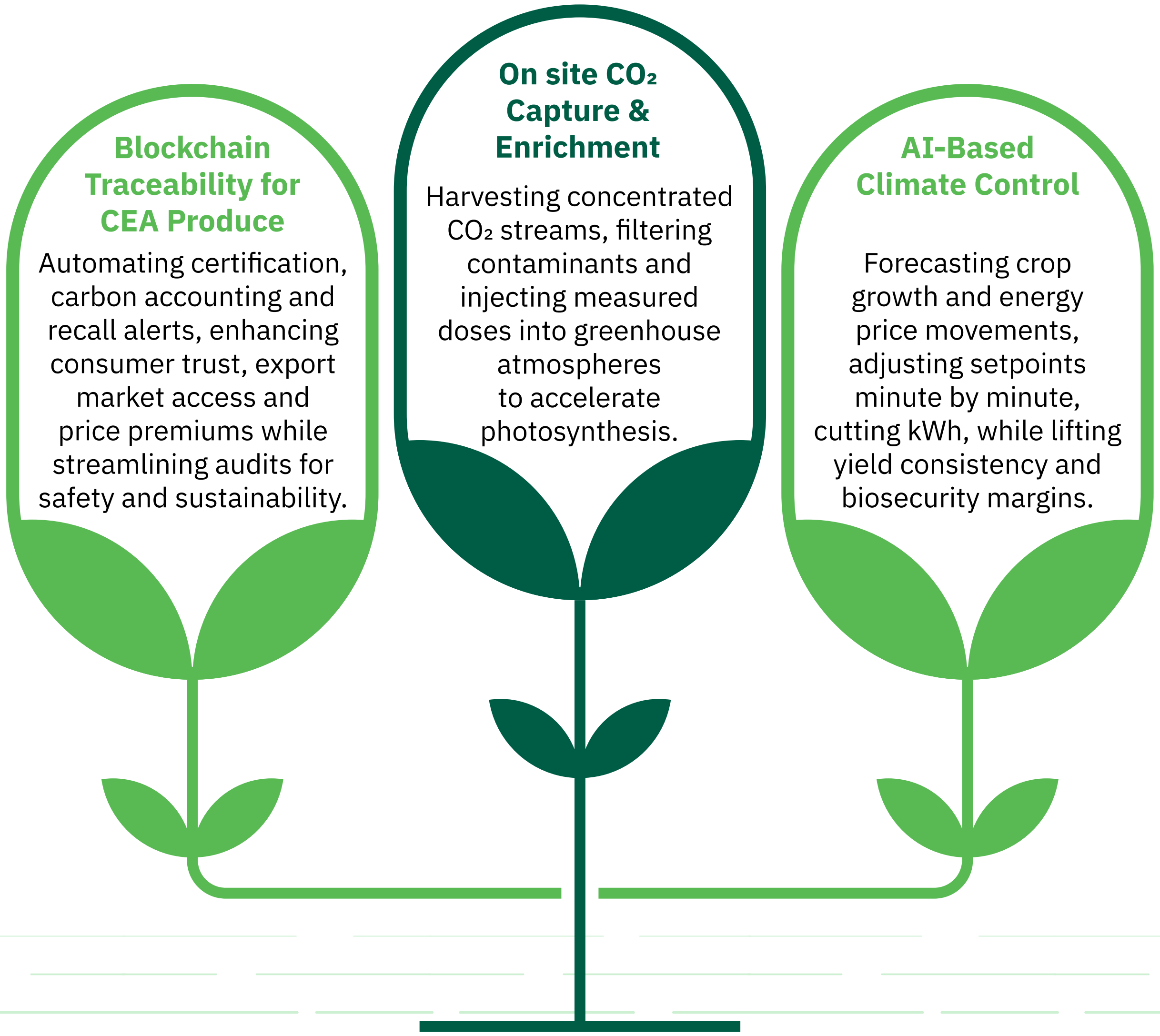
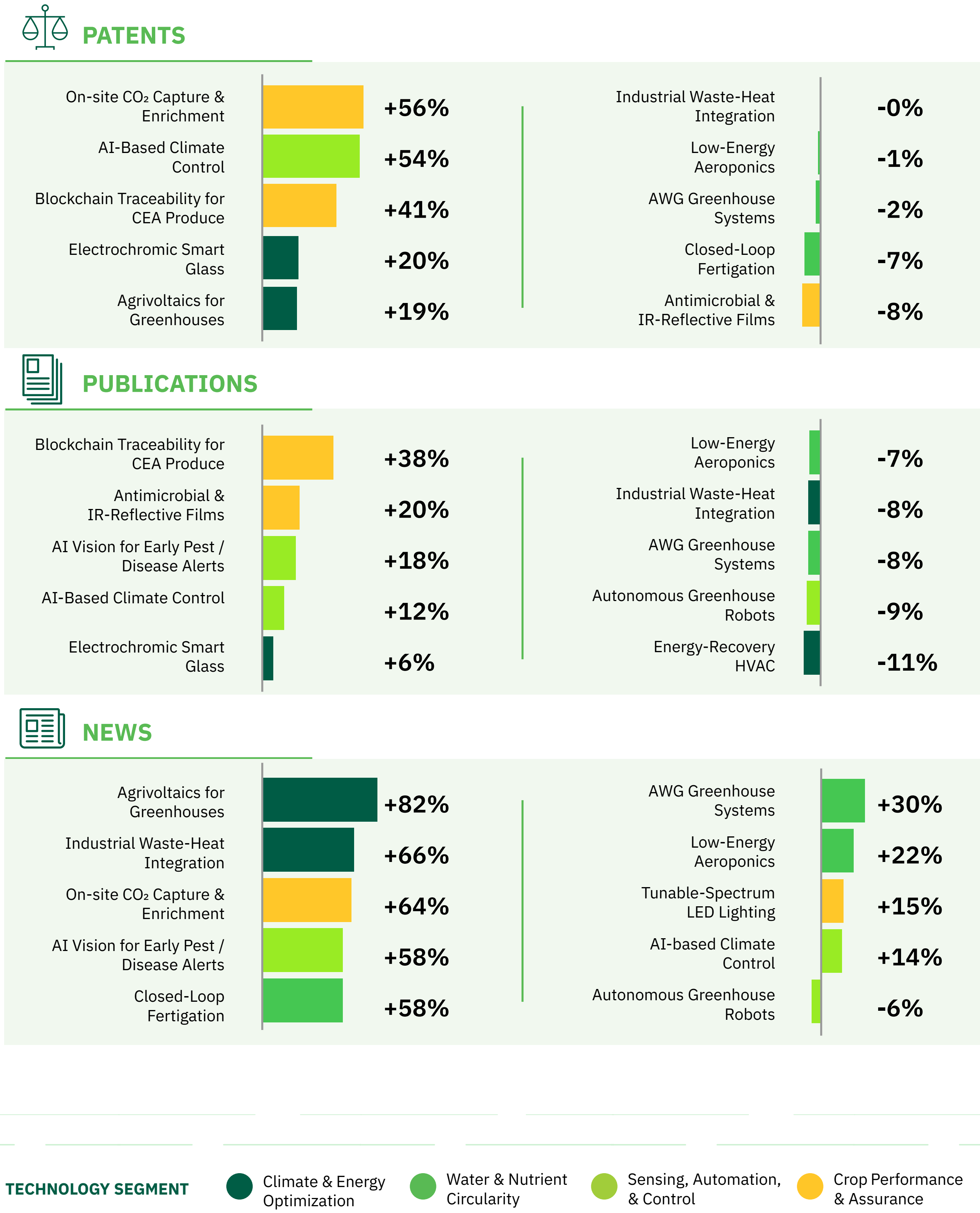


Figure 11: Continuous Annual Growth Rate of Patents, Publications, and News (2019-2024), Top 5 and Bottom 5 Technologies



Overview of National RDI Output

Overall, Saudi Arabia is well-positioned in the technologies investigated. Regarding **Patents**, compared to the overall Global Patent Rank (27th), our nation ranks in the global Top-20 for two-thirds of the technologies surveyed, and Top-10 in ~35% of key emerging technologies in the field. The country takes a leadership position especially in the segment **Climate & Energy Optimization.**

Regarding **Publications**, the positioning is less promising, with no Top-10 ranking in either of the technologies observed and a Top-20 ranking in ~50% of technologies. Most notably, Saudi Arabia is positioned best in technologies related to the **digitization of operations** and the utilization or modification of **solar energy** for the improvement of crop yields. The following points are in accordance to experts' insights where the technologies under this TPG offer tremendous potential to increase productivity, reduce water consumption, and improve crop quality, especially in resource-limited areas. For instance, **AI-Based Climate Control** and **Electrochromic Smart Glass** reduce energy consumption and increase production stability. However, experts have illustrated that greenhouse development in Saudi Arabia faces several challenges, including high construction and maintenance costs, the need for specialized technical skills for operations, limited applied research in Saudi Arabia compared to academic studies, and the necessity to develop solutions adapted to the desert environment, such as sandstorms and high temperatures.

Figure 9: Saudi Arabia's Positioning across Emerging Technologies, Global Rank in No. of Patents & Publications (2019-2024)

TECHNOLOGY SPOTLIGHT

3.3.1 AI VISION FOR EARLY PEST / DISEASE ALERTS

Fixed or drone mounted multispectral cameras stream images into convolutional neural networks trained on annotated leaf datasets. The system flags mildew, mites or nutrient stress three days before human scouts, generating geotagged heatmaps and treatment prescriptions. Early intervention reduces pesticide volumes, crop losses and labor-intensive manual scouting passes, saving operational costs.

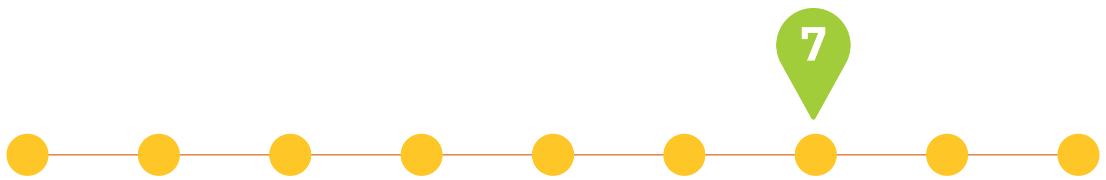
AI Vision for Early Pest / Disease Alerts

AI vision for early pest/disease alerts uses fixed cameras (and sometimes multispectral/ hyperspectral sensors) plus deep-learning models to continuously scan greenhouse crops and sticky traps, flagging pests or symptoms before outbreaks take hold. Recent research shows robust performance of vision models for greenhouse pest/disease identification, enabling precise, early interventions instead of blanket sprays (Nature). Hyperspectral pipelines can even detect plant stress and diseases at pre-symptomatic stages, which is critical for high-value controlled-environment agriculture (Nature, Frontiers). Overall, tying AI alerts to Integrated Pest Management (thresholds, biocontrol's, targeted treatments) turns detection into measurable risk reduction and safer production (Open Knowledge FAO).

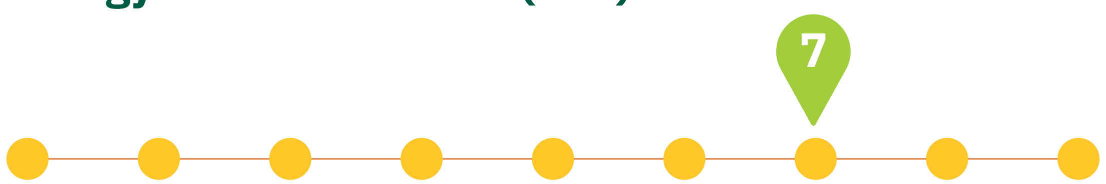
Technology and National Capability Maturity

AI-vision pest/disease systems have been demonstrated in operational greenhouses — multi-week deployments and commercial 24/7 monitoring meet the "prototype in operational environment" bar (TRL 7). However, wider qualification is constrained by generalization/validation gaps across crops, lighting, and sites, so the category hasn't consistently reached TRL 8-9 (ScienceDirect, Frontiers). Domestic R&D capacity, expanding CEA operators, and national data / AI infrastructure create conditions for pilot-to-early commercial adoption in greenhouses (CRL 7). However, specialized in-country manufacturing and validated, at-scale deployments are still limited (KAUST-CoreLabs, TIME).

Capability Readiness Level (CRL)



Technology Readiness Level (TRL)



Capability Readiness Level (CRL) and Technology Readiness Level (TRL) descriptions are in the Glossary

Global Key Players

01 Fermata (Croptimus)

02 iUNU (LUNA)

03 ecoation

04 PATS Indoor Drone Solutions

05 Trapview (Efekt d.o.o.)

06 Semios

07 Prospera (Valmont)

08 Wageningen University & Research (WUR)

09 Chinese Academy of Agricultural Sciences

10 Purdue University / Z-Trap

Technology Potential

AI vision turns protected farming from periodic scouting into continuous, automated detection, flagging pests and symptoms early enough to cut losses, optimize IPM actions, and reduce chemical dependence.

Advantages

- **Earlier, targeted interventions:** Continuous camera monitoring and deep learning detect pests/symptoms sooner than manual rounds, enabling threshold-based, localized treatments that lower pesticide use and avoid outbreaks, improving worker safety and yields. Greenhouse Grower
- **Pre-symptomatic stress/disease insight:** Hyperspectral/vision pipelines can spot disease signatures before visible symptoms, letting growers act days earlier and avoid broad-spectrum sprays or crop losses in high-value greenhouses. Nature
- **Operational efficiency and ROI:** 24/7 computer-vision platforms reduce scouting labor and translate plant/ sticky-trap data into actionable decisions — case studies report yield gains and reduced crop loss once alerts are tied to irrigation/IPM playbooks. iunu.com

Disadvantages

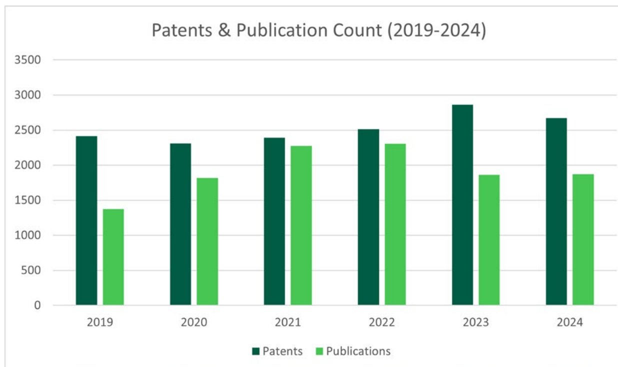
- **Domain shift & generalization risk:** Model accuracy can degrade across crops, cultivars, lighting, and camera setups; robust cross-site validation and adaptation are needed before scaling beyond pilot greenhouses. ScienceDirect
- **Hardware and autonomy constraints:** Camera-trap systems face cost, power, and image-quality limits; fully automated identification still needs improvement, especially for small or occluded insects. SpringerLink
- **Complex data/analytics burden:** High-dimensional imagery requires calibration, labeling, and expert oversight; integrating alerts into IPM programs and decision thresholds remains non-trivial for many growers. blog.ecoation.com

Latest Developments

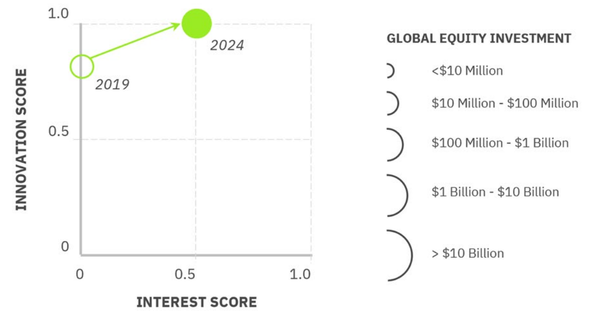
A wave of 2024–2025 research and product moves is pushing AI vision from pilots to scaled greenhouse deployments, with sharper models, standardized hardware, and serious commercial momentum.

Key Innovation Signals

- **Scale-up capital hits the space:** iUNU raised $20M (Apr 2025) to expand its LUNA AI platform, signaling investor confidence in computer-vision monitoring for high-value greenhouse crops and accelerating go-to-market and engineering. producegrower.com
- **Enterprise adoption via seed–tech partnership:** BASF Vegetable Seeds partnered with iUNU (Mar 2025) to apply LUNA AI for continuous plant performance monitoring in lettuce — evidence that major input providers are embedding AI vision into customer offerings. nunhems.com
- **End-to-end IPM suites mature:** Biobest's GreenTech 2025 showcase combined smart detection (Trap-Eye) with biological controls and automated dispersion — a fuller pipeline from monitoring to intervention for thrips management in protected crops. Biobest Group
- **New smart trap scanners launch:** Royal Brinkman and Robtelli unveiled Robcam (Jun 2025), a battery/mains-powered microscope-camera system that scans traps daily and uses AI to identify pests and beneficials, reducing labor and speeding IPM response. AgroPages
- **Model robustness gets attention:** A 2025 study showed sticky-trap color and imaging device significantly affect deep-learning accuracy, underscoring the need for hardware/lighting standards when scaling AI monitoring across greenhouses. Wiley
- **Accuracy gains on tiny insects:** 2025 work improved YOLOv10n for yellow sticky-trap detection with dataset and pipeline refinements, achieving strong performance suitable for near-real-time deployment in greenhouse monitoring devices. MDPI



The figure below is investment development of the technology against Innovation score vs Interest score



Insights and Statistics

AI vision is shifting protected agriculture from manual scouting to continuous, quantified risk detection, cutting losses, tightening IPM timing, and scaling across a vast greenhouse footprint.

Key Stats & Facts

- **Pest pressure is economically massive:** Up to 40% of global crop production is lost to pests and diseases each year, costing >$220 billion, underscoring the value of earlier, automated detection in controlled environments. Open Knowledge FAO
- **Pre-symptomatic diagnosis is feasible:** Hyperspectral + ML pipelines detected tomato leaf disease before visible symptoms, boosting classification performance 26–37% versus raw spectra — evidence that AI vision can move interventions forward in time. Nature
- **High model accuracy is achievable in greenhouses:** Recent work reported F1-scores of 0.92/0.90 and counting precision ~0.90 for pest detection/quantification, indicating operationally useful performance for automated monitoring. ScienceDirect
- **Hardware choices affect accuracy:** Sticky-trap color and imaging device significantly influenced deep-learning classification results — standardization is essential when scaling AI monitoring across sites. Wiley
- **The addressable market is huge:** Latest estimates peg global greenhouse area at ~3.72 million ha (with ~70,000 ha high-tech), implying large-scale demand for automated scouting technologies. topsectortu.nl
- **Operational payoffs are tangible:** Early imaging-based detection has been associated with 20–30% lower pesticide costs and about 25% lower IPM costs in commercial greenhouse cases, improving margins alongside crop health. Greenhouse Grower

Technology Adoption

AI vision in protected agriculture is moving from pilots to scaled rollouts, pulled by IPM economics, fresh capital, and tightening pesticide policies, while Saudi localization hinges on data governance, desert-proof hardware, and standardization for model robustness.

Current State

- **Venture-backed scaling:** iUNU raised $20M (Apr 2025) to expand its LUNA AI greenhouse platform — evidence of investor confidence and funding to accelerate multi-site deployments across high-value crops. GeekWire
- **IPM suite integration:** Biobest showcased an end-to-end thrips program at GreenTech 2025, combining AI scouting (Trap-Eye) with biocontrols and automated release, signaling mainstream integration from monitoring to action. Biobest Group
- **Policy tailwinds:** The EU's Farm-to-Fork targets a 50% cut in pesticide use/risk by 2030, pushing growers toward precision, early-warning tools, especially in high-intensity greenhouses. European Commission

Requirements for Localization

- **Data residency & privacy compliance:** Deployments must be aligned with Saudi PDPL and its Implementing Regulations — governing personal/operational data handling, cross-border transfers, and controller obligations, favoring on-shore processing and clear consent/governance. SDAIA
- **Desert-ready hardware & O&M:** Design for dust storms, heat, and low humidity — sealed optics, auto-cleaning, scheduled maintenance — validated by Saudi studies showing significant dust-storm impacts across Riyadh, Jeddah, and Dammam. MDPI
- **Standardized imaging for robust AI:** Sticky-trap color and device standards must be formulated to prevent accuracy loss from domain shift; recent research shows trap color and imaging device materially affect deep-learning performance. Wiley

Outlook

AI vision will move from point tools to integrated, multimodal IPM "autopilots" in protected agriculture — yet success hinges on model robustness, economics, and policy stability.

Future Trajectory

- **Multimodal sensing becomes standard:** Greenhouse monitoring will fuse RGB* with multispectral/hyperspectral and fluorescence to detect stress pre-symptomatically, improving reliability across crops and enabling earlier, smaller interventions that cut chemical use and loss. ScienceDirect
- **Foundation models drive generalization:** Large, cross-crop vision models with fine-tuning and few-shot learning will reduce per-site labeling, accelerating deployments and improving performance under varied cultivars and lighting — key for multi-facility growers. MDPI
- **Edge AI architectures mature:** Device-edge-cloud designs will handle on-camera inference for low latency and privacy, with the cloud used for retraining and fleet analytics, making always-on alerts practical at scale. MDPI

Key Uncertainties

- **Model robustness under domain shift:** Accuracy can drop with different trap colors, cameras, and conditions; without standards and adaptation, fleet-wide performance may lag pilot results. Wiley
- **Policy signal volatility:** Europe's withdrawal of the SUR pesticide-reduction proposal in 2024 weakens immediate regulatory pull, adding demand uncertainty for early-warning tech despite ongoing IPM goals. Food Safety
- **Adoption economics & integration:** Up-front hardware, labeling, and integration with grower workflows remain barriers—IoT/AI ag reviews flag cost, connectivity, and maintenance as persistent hurdles for commercial rollout. ScienceDirect

* RGB refers to standard imaging channels that, when fused with multispectral or hyperspectral sensing, enhance stress detection in crops.

Source: NEOM

Local Case Study

TOPIAN Glasshouses (NEOM Oxagon)

NEOM's Oxagon is piloting climate-resilient food production in harsh desert conditions where heat, humidity swings, and biosecurity risks can trigger outbreaks like powdery mildew and mites. Traditional scouting is labor-intensive and periodic, creating detection gaps that raise losses and chemical use. To localize supply and build resilience, NEOM's food company TOPIAN opened a high-tech, four-hectare greenhouse in Oxagon to trial advanced technologies at production scale, targeting nearly 4,000 tons annually while developing AI-driven predictive models for efficient operations and replication across the region (NEOM, Arab News, Zawya).

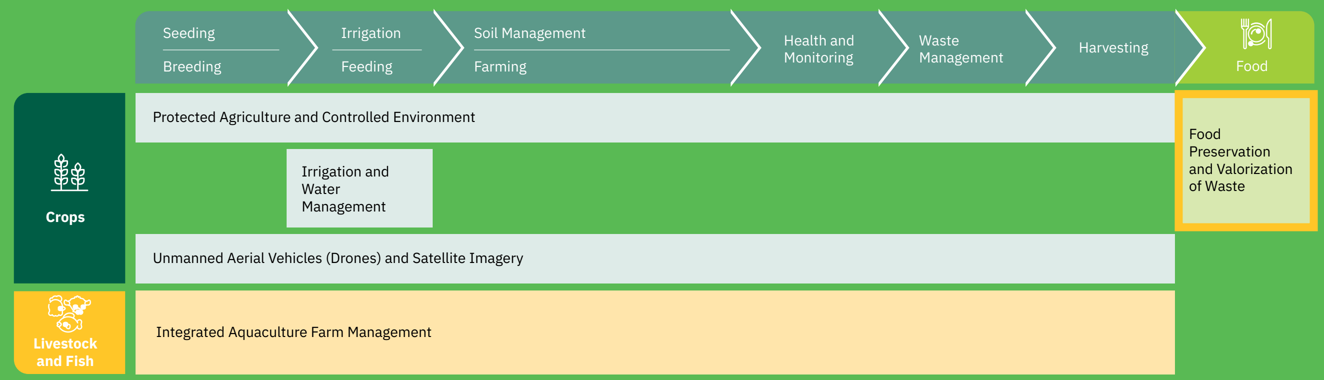
Within Oxagon's greenhouse, TOPIAN integrates a multi-camera network, combining visible (RGB) views of canopy and traps with thermal imaging — streaming to cloud models that rank disease and pest risk by zone. The pipeline feeds NEOM's program of AI modeling/predictive analytics, enabling growers to triage hotspots, schedule targeted interventions, and continuously retrain models with local data. Thermal streams highlight canopy temperature anomalies consistent with early mildew pressure; RGB streams flag insect signatures and symptom patterns. The architecture aligns with TOPIAN's stated intent to use advanced technology and AI modeling in its climate-resilient assets for operational efficiency (NEOM, Zawya).

By shifting from periodic rounds to always-on analytics, the glasshouse surfaces risks earlier than manual scouting, tightening time-to-intervention, reducing unnecessary sprays, and building a high-resolution dataset for Saudi-specific IPM. The Oxagon facility anchors local production (target ~4,000 t/y), supports workforce upskilling, and creates a transferable blueprint for additional NEOM and Kingdom sites as AI predictive models mature. Public disclosures confirm commissioning, production goals, and the AI-modeling mandate; quantified detection-lead metrics are being developed as the program scales (NEOM, Arab News, Zawya).

TECHNOLOGY PRIORITY GROUP FOCUS

3.4 FOOD PRESERVATION & VALORIZATION OF WASTE

Food loss and waste is a major issue in the food sector, and technologies addressing it provide solutions like converting it into useful applications, delaying food spoilage, deterioration or contamination, and extending food shelf life. They enable reducing food losses and greenhouse gas emissions, especially methane.



Frontier Technologies in Food Preservation & Valorization of Waste

COLD-CHAIN & ATMOSPHERE CONTROL	NON-THERMAL PRESERVATION & DECONTAMINATION	SMART PACKAGING & PRODUCT-LIFE INTELLIGENCE	WASTE-TO-VALUE & CHAIN-OF-CUSTODY
Controlled Atmosphere Storage (TRL 9)	High Pressure Processing (HPP) (TRL 9)	Blockchain Traceability for Waste Minimization (TRL 7)	Enzymatic Protein Hydrolysates (TRL 8)
IoT Enabled Cold Chain Monitoring (TRL 8)	Cold Plasma Decontamination (TRL 7)	Active & Intelligent Nano Packaging (TRL 7)	Bioplastics from Agro Waste (TRL 7)
Solar Powered Modular Cold Rooms (TRL 7)	Pulsed Electric Field (PEF) Preservation (TRL 8)	Edible Bio Coatings (TRL 8)	Advanced Anaerobic Digestion (TRL 8)
			Biochar from Plant Residues (TRL 7)
			Insect Bioconversion (TRL 7)
			Mycelium / Precision Fermentation Upcycling (TRL 7)

The definitions of the listed technologies are in the glossary

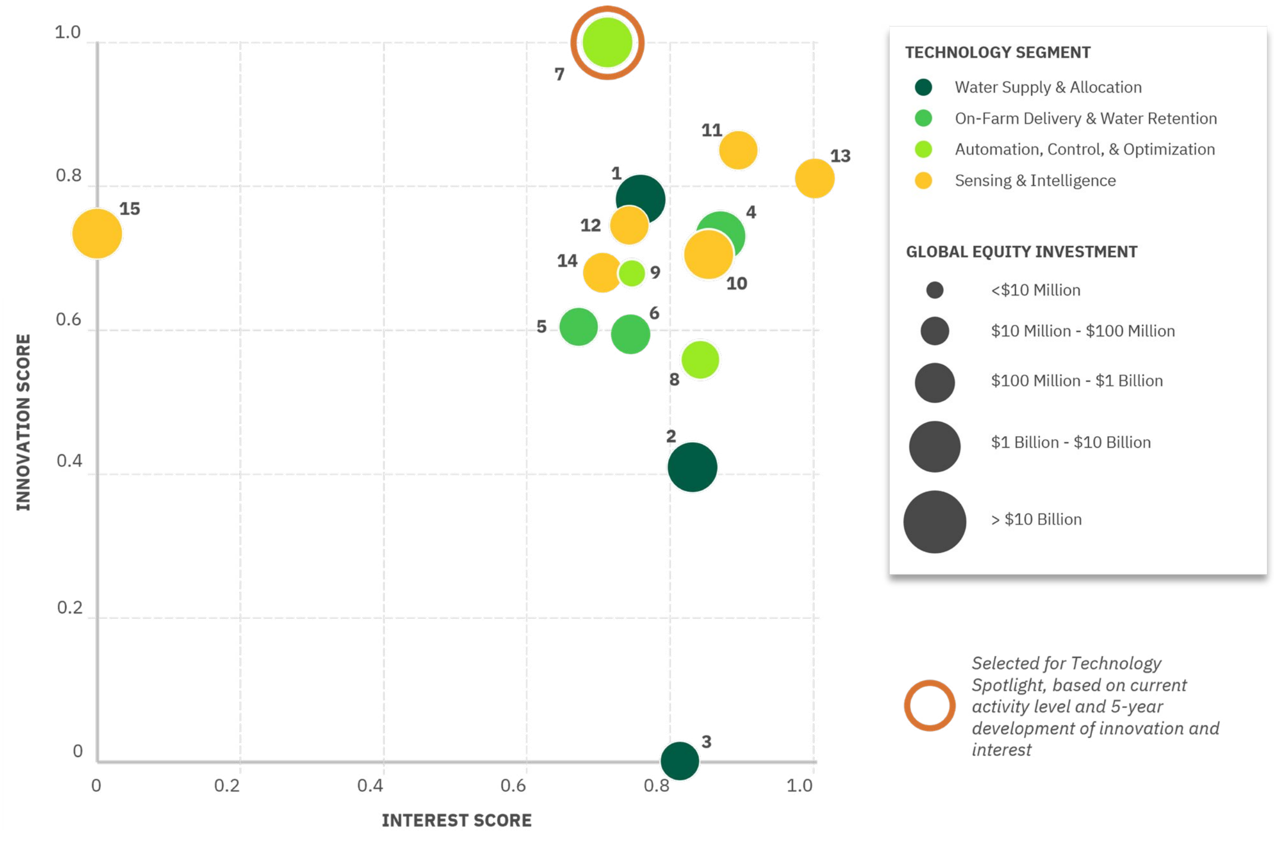
Innovation, Interest, and Investment by Technology (2024)

To assess the development of each emerging technology, our team collected data on four tangible measures of activity: **news publications, patents, research publications,** and **investment.**

For each measure, we used a defined set of data sources to find occurrences of keywords associated with each of the 15 technologies, screened those occurrences for valid mentions of activity, and indexed the resulting numbers of mentions on a 0–1 scoring scale that is relative to the technologies studied:

- The **innovation score** combines the patents and research scores. The patents score is based on a measure of patent filings, and the research score is based on a measure of research publications.
- The **interest score** reflects the number of global news publications, relative to the technologies studied (While we recognize that an interest score can be inflated by deliberate efforts to stimulate news coverage, we believe that each score fairly reflects the extent of discussion and debate about a given technology).
- **Investment** depicts the flows of funding into companies linked with the technology, including private-market and public-market capital raises (venture capital and corporate M&A, including joint ventures), private equity (including buyouts and private investment in public equity), and public investments (including IPOs).

Figure 13: Chart representing Innovation Score vs Interest Score across all 15 technologies



1 – Controlled-Atmosphere Storage
2 – IoT-Enabled Cold-Chain Monitoring
3 – Solar-Powered Modular Cold Rooms
4 – High-Pressure Processing (HPP)
5 – Pulsed Electric Field (PEF) Preservation
6 – Cold-Plasma Decontamination
7 – Edible Bio-Coatings
8 – Active & Intelligent Nano-Packaging
9 – Blockchain Traceability for Waste Minimization
10 – Advanced Anaerobic Digestion
11 – Enzymatic Protein Hydrolysates
12 – Biochar from Plant Residues
13 – Bioplastics from Agro-Waste
14 – Insect Bioconversion
15 – Mycelium / Precision-Fermentation Upcycling

Based on the scoring methodology of the McKinsey Tech Report

Note: Innovation and interest scores for the 15 trends are relative to one another. All 15 trends exhibit high levels of innovation and interest compared with other topics. While some technologies may have applications outside of agriculture, this analysis considered only patents, publications, news, and investments in the agriculture context.

Technologies Trending in Innovation Output and Public Interest

Static innovation and interest scores snapshot technological vitality, but momentum reveals trajectory. Tracking growth or decline exposes breakouts before rivals, flags waning hypes, guides timing of subsidies, calibrates capacity-building, and aligns infrastructure budgets with future demand. Dynamics safeguard against sunk costs and amplify the impact of the resources in the EWA ecosystem.

Looking into the global growth rates in patents, publications, and news published on the technologies studied over the past 5 years, particularly the growing momentum in the segment **Waste-to-Value & Chain-of-Custody** is evident. In particular, the following technologies display high growth rates across all three measures examined:

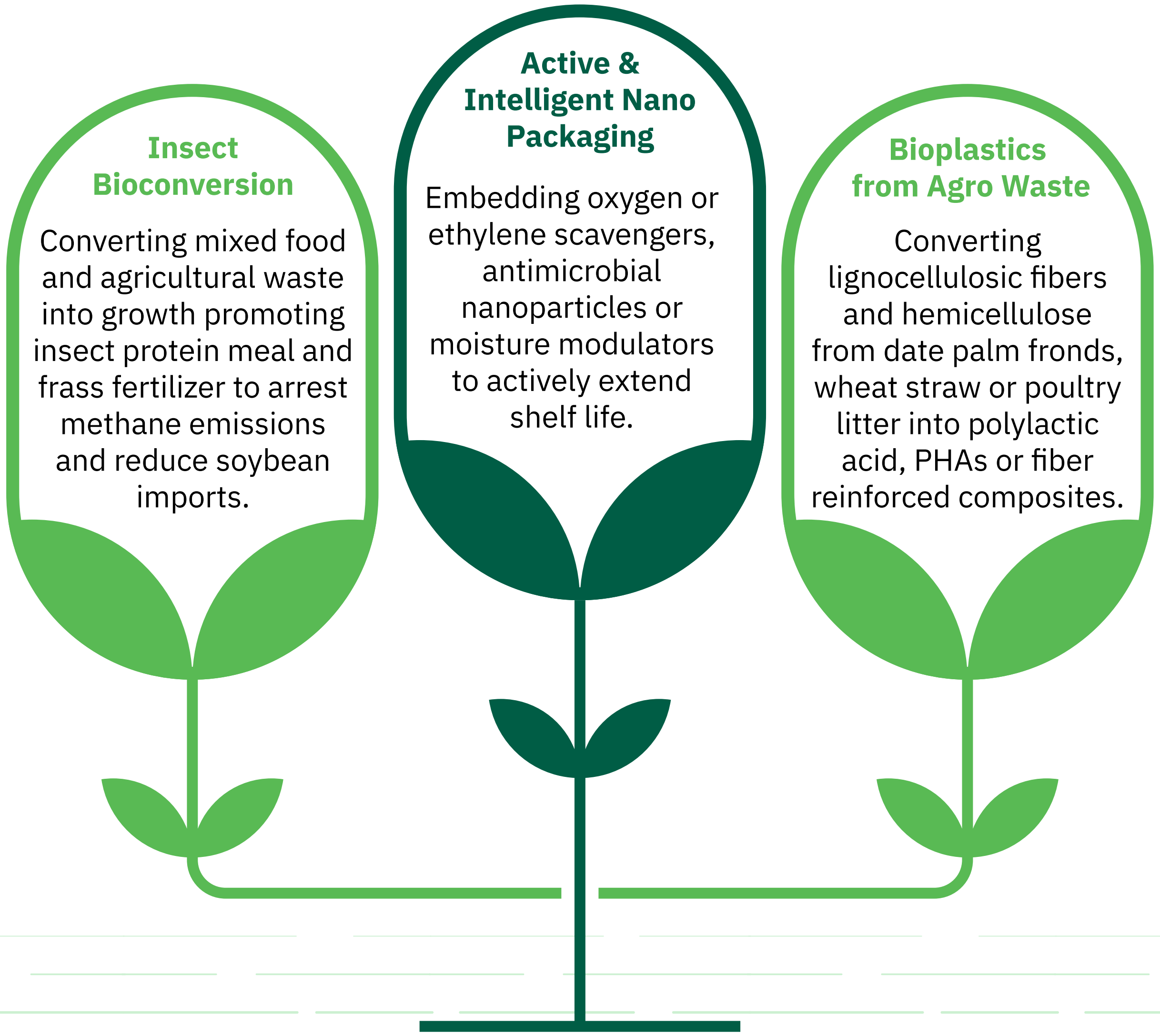
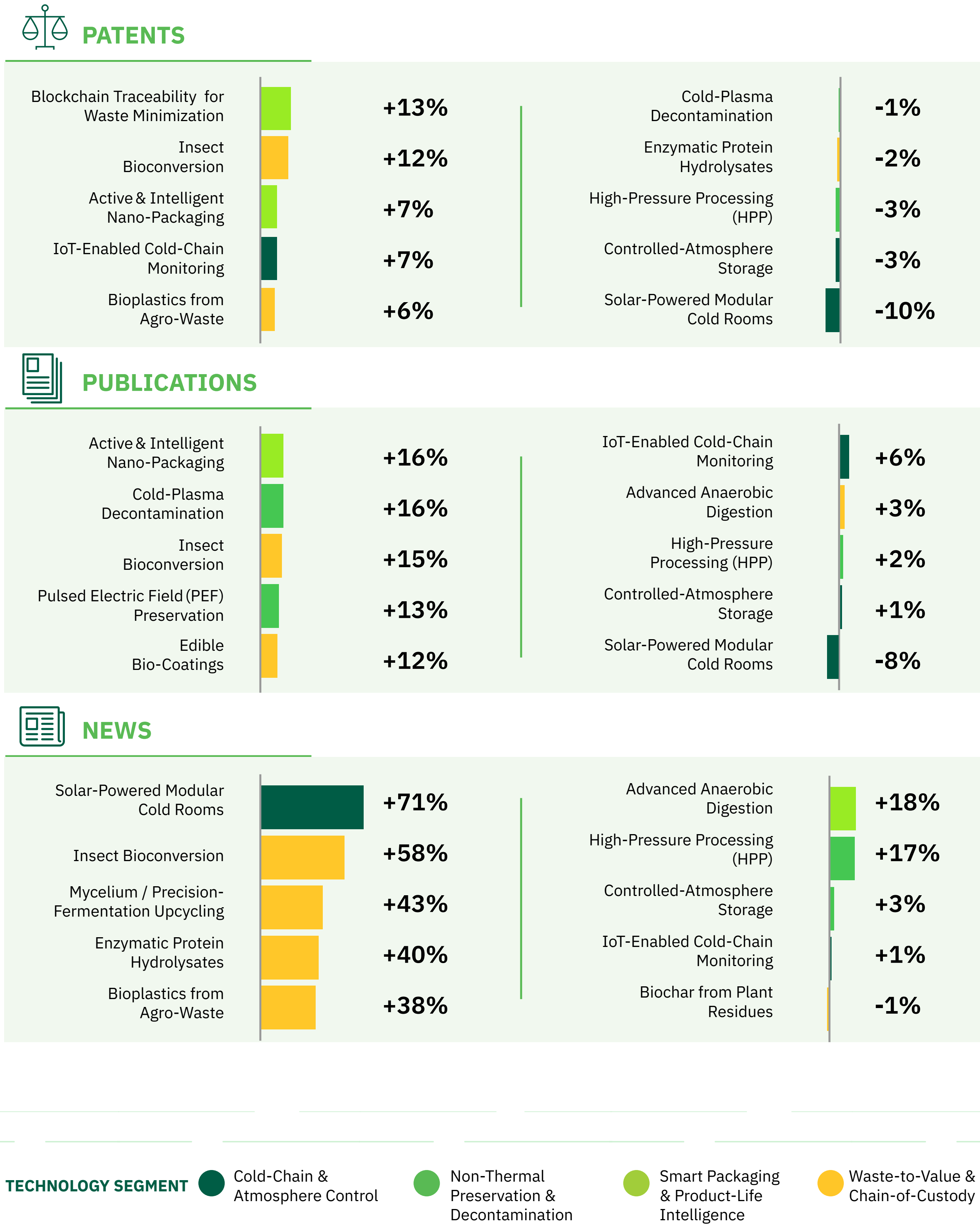


Figure 14: Continuous Annual Growth Rate of Patents, Publications, and News (2019-2024), Top 5 and Bottom 5 Technologies



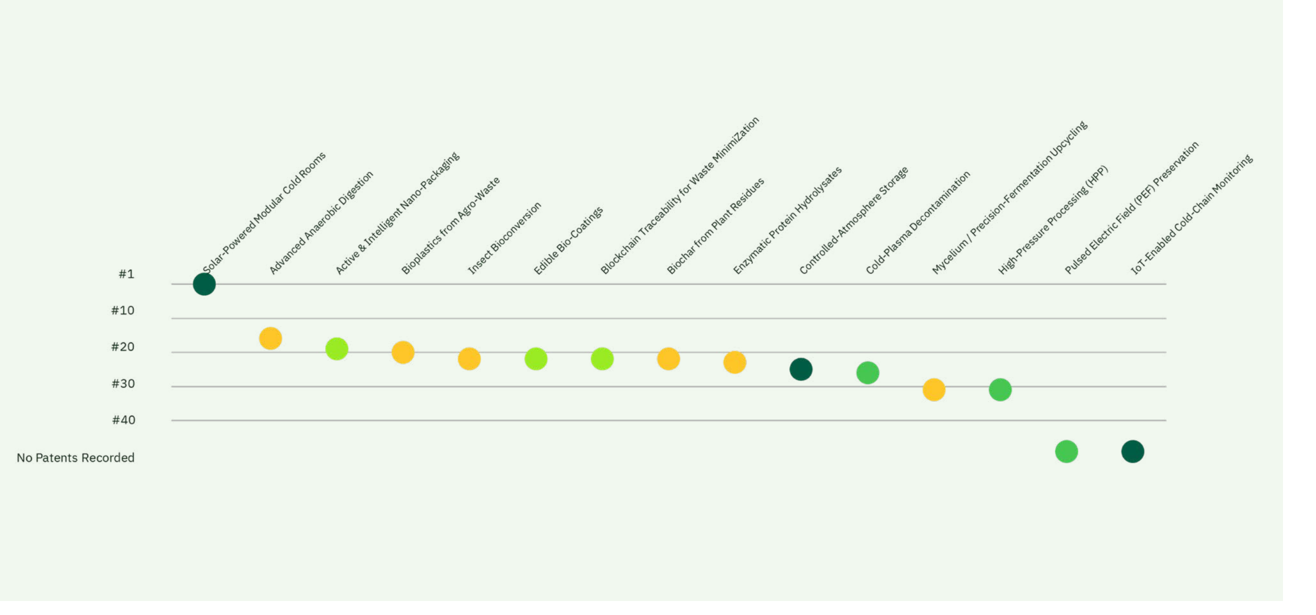
Overview of National RDI Output

Overall, Saudi Arabia is in a mediocre competitive position in the technologies investigated. Regarding **Patents**, compared to the overall Global Patent Rank (27th), our nation ranks in the global Top-20 for only four of the technologies surveyed, and Top-10 in one of the key emerging technologies in the field. Notably though, for the technology **Solar-Powered Modular Cold Rooms**, our country ranks #1 globally in patents registered between 2019 and 2024.

Regarding **Publications**, the positioning is more promising with a Top-10 ranking in 20% of the technologies observed and a Top-20 ranking in two-thirds of the technologies. The positioning is especially strong in the segment **Waste-to-Value & Chain-of-Custody**, especially in areas of valorizing plant residues. In addition, Saudi Arabia is ranked in the global Top-20 for all technologies in the segments **Cold-Chain & Atmosphere Control** and **Smart Packaging & Product-Life Intelligence**, pointing toward capability development in food preservation. Nevertheless, according to experts in the food preservation and valorization of waste those technologies face challenges related to costs (integrating technologies in the production line), regulatory compliance, consumer acceptance, and availability of raw material. Despite the fact that this TPG demonstrates robust scientific research capabilities, experts state that there is a decline in the expansion of its industrial activities.

Figure 15: Saudi Arabia's Positioning across Emerging Technologies, Global Rank in No. of Patents & Publications (2019-2024)

PATENTS



PUBLICATIONS

TECHNOLOGY SEGMENT
- Cold-Chain & Atmosphere Control
- Non-Thermal Preservation & Decontamination
- Smart Packaging & Product-Life Intelligence
- Waste-to-Value & Chain-of-Custody

TECHNOLOGY SPOTLIGHT

3.4.1 EDIBLE BIO-COATINGS

Spray on coatings made from chitosan, alginate, nanocellulose or plant proteins form breathable barriers that slow respiration and block pathogens. Natural essential oils or probiotics can be incorporated for extra antimicrobial effect. Coatings are halal compliant, leave no plastic waste, add minimal cost and already lengthen citrus and tomato storage.

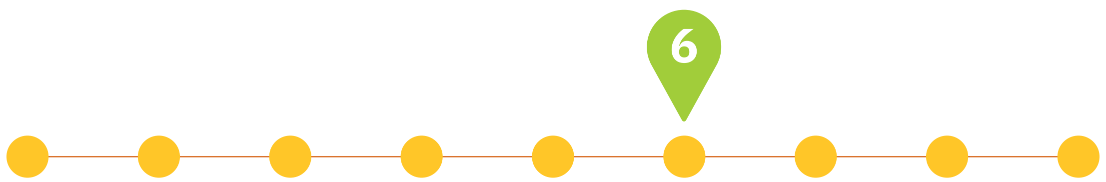
Edible Bio-Coatings

Edible bio-coatings are ultra-thin, food-grade layers applied to fresh produce (and some meats) using biopolymers—polysaccharides (e.g., pectin/alginate), proteins, or lipids, often enhanced with natural antimicrobials like chitosan or essential oils. They create a semi-permeable barrier that moderates moisture and gas exchange, slowing respiration and oxidation while suppressing microbes. The result: longer shelf life, reduced weight loss and spoilage, and fewer cold-chain dependencies—direct levers for Saudi Arabia to cut post-harvest losses, stabilize supplies in heat, and build local packing/processing jobs. Commercial systems mimic the fruit's own cuticle to retain moisture and keep oxygen out; peer-reviewed studies repeatedly show shelf-life extension and safety when using approved, food-grade inputs (PMC, PMC, digicomply.com, PubMed).

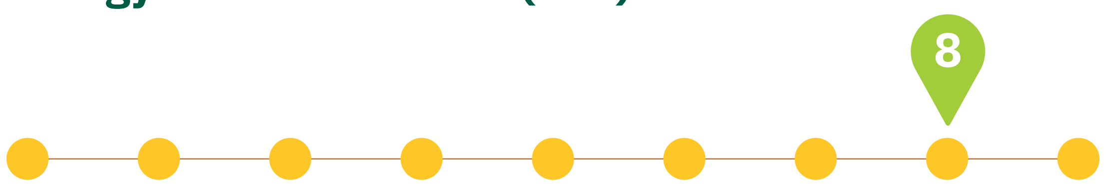
Technology and National Capability Maturity

Edible bio-coatings are system-complete and qualified in operational settings TRL 8, with peer-reviewed efficacy, European Food Safety Authority (EFSA) approvals for key actives (e.g., chitosan), and live commercial deployments extending shelf life. Adoption remains uneven and QA/labeling harmonization is ongoing, so routine operation is not universal (EFSA, MDPI). Saudi universities are actively publishing on edible coatings for local crops, Saudi Food & Drug Authority (SFDA) provides a regulatory path for food additives, and KAUST reports local shrimp-shell valorization into ~135 t/year chitosan. Large-scale domestic manufacturing and deployment remain limited, so market readiness not yet pervasive (CRL 6) (Saudi Food and Drug Authority, KAUST).

Capability Readiness Level (CRL)



Technology Readiness Level (TRL)



*Capability Readiness Level (CRL) and Technology Readiness Level (TRL) descriptions are in the Glossary

Global Key Players

01 Apeel Sciences

02 Mori

03 Sufresca

04 AgroFresh Solutions

05 Mantrose-Haeuser / AgriCoat NatureSeal

06 Liquidseal

07 Wageningen University & Research (WUR)

08 UC Davis Postharvest Research & Extension Center

09 Agricultural Research Service

Technology Potential

Ultra-thin, food-grade coatings form semi-permeable barriers on produce, slowing respiration, moisture loss and microbial spoilage — cutting post-harvest waste and packaging dependence when correctly specified and applied.

Advantages

- **Shelf-life extension & waste reduction:** Coatings modulate gas and water exchange to delay ripening and oxidation, extending freshness and reducing shrink especially valuable in hot climates and long supply chains. PMC
- **Packaging and cold-chain relief:** As edible, active barriers, coatings can complement or partially replace conventional packaging, lowering material use while preserving quality during distribution. Wiley
- **Built-in antimicrobial action:** Biopolymers like chitosan and natural additives disrupt microbial membranes, suppressing spoilage organisms and enhancing safety without synthetic preservatives. PMC

Disadvantages

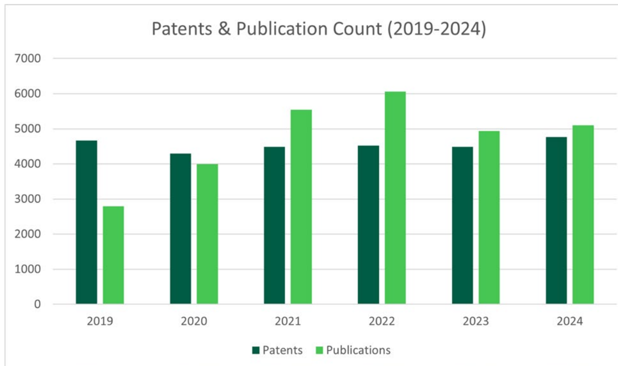
- **Risk of off-flavors if mis-specified:** Over-tight gas barriers can induce anaerobic respiration, ethanol buildup and flavor defects; permeability must match crop physiology and storage. Wiley
- **Allergen & labeling complexity:** Some formulations use allergenic inputs (e.g., shellfish-derived chitosan, milk proteins); jurisdictions treat edible films as food, requiring clear allergen disclosure. cot.food.gov.uk
- **Variable efficacy & integration cost:** Performance varies by crop, coating type and application; scale-up demands QA, equipment, and operator training, raising operational complexity versus lab results. ScienceDirect

Latest Developments

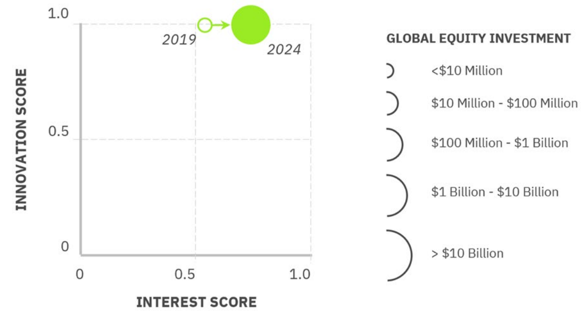
The past year brought regulatory green lights, new biomaterials, and scaling signals, while a labeling/misinformation flare-up pushed producers toward greater transparency.

Key Innovation Signals

- **EU toxicology clarity on chitosan:** EFSA's 2025 review found no toxicological concerns for chitosan/chitosan-HCl at approved uses, strengthening regulatory certainty for antimicrobial bio-coatings in Europe. EFSA
- **US expands GRAS uses (mushroom chitosan):** FDA accepted a 2025 supplement to GRN 997, widening approved uses of mushroom-derived chitosan, broadening formulation options for edible coatings in the U.S. US Food and Drug Administration
- **Silk-protein antifungal advances:** 2025 research shows silk-protein–based edible coatings with antifungal functionality can preserve strawberries, pointing to protein biopolymers as clean-label, high-performance alternatives. ScienceDirect
- **Seafood shelf-life push:** Startup BioDefense reported 2–3× extension of whole-fish shelf life with invisible edible coatings — an emerging application beyond produce. AgFunderNews
- **Transparency under the spotlight:** Industry leader Apeel publicly addressed 2025 misinformation and labeling concerns, signaling a sector-wide pivot to clearer communication and claims substantiation. thepacker.com



The figure below is investment development of the technology against Innovation score vs Interest score



Insights and Statistics

Evidence shows edible bio-coatings can materially cut post-harvest losses, slow ripening and microbes, and are advancing under clearer regulations, supporting commercial scale-up.

Key Stats & Facts

- **Food loss is big and addressable:** About 14% of global food is lost between harvest and retail; fruits and vegetables are among the most affected—prime targets for coatings that slow respiration and spoilage. IFPRI
- **Market momentum is real:** The edible films & coatings market is projected to reach ~$5.16B by 2030, signaling investor and buyer appetite across produce categories. Mordor Intelligence
- **Regulatory risk is easing:** EFSA (2025) found no toxicological concerns for chitosan/chitosan-HCl at approved uses, strengthening the safety case for antimicrobial edible coatings in the EU. EFSA
- **Measured waste cuts in retail:** A case study reports 60% lower softening and 30% less water loss in avocados with coating, effectively doubling the ripeness window, translating to fewer write-offs. International Food Waste Coalition
- **Physiology benefits are quantifiable:** 0.5% nano-chitosan coatings on apples reduced ethylene and eliminated the climacteric peak, slowing ripening and extending storage life under cold conditions. MDPI
- **Beyond produce — seafood gains:** Reviews show chitosan-based coatings can deliver ~3× shelf-life extension for ready-to-eat fish at 4 °C, indicating cross-category efficacy when formulations are dialed in. MDPI

Technology Adoption

Worldwide adoption is real and growing, driven by retailer deployments, big-ticket funding, and clearer EU/U.S. safety signals, while Saudi localization hinges on SFDA compliance, packhouse integration, and building local biopolymer supply.

Current State

- **Retail-scale rollouts are visible:** Apeel remained a 2025 "Game Changer," reflecting ongoing, multi-category retail commercialization and market traction across produce. FreshFruitPortal.com
- **Incumbents expanded portfolios:** AgroFresh's VitaFresh Botanicals platform offers plant-based edible coatings at commercial scale for citrus, avocados, mangos and more — evidence of mainstream supplier adoption. AgroFresh
- **Capital has validated the category:** Apeel's $250M Series E (2021) at a >$2B valuation signaled investor confidence and funded global scaling of coating deployments. Axios

Requirements for Localization

- **Regulatory & labeling compliance first:** SFDA strictly enforces GSO limits for food additives and bilingual labeling — coatings must map to SFDA classifications and documentation to clear import/market approval. USDA Apps
- **Integrate at packhouses within a growing cold chain:** Coatings should be applied in grading/packing lines and paired with an expanding cold-chain infrastructure that's growing rapidly through 2033, facilitating nationwide rollout. Grand View Research
- **Develop local biopolymer feedstocks:** Saudi's NAQUA generates large shrimp-shell streams; KAUST reports ~135 t/year chitosan potential, supporting in-Kingdom coating formulations and resilience of supply. KAUST

Outlook

Expect smarter, cleaner biopolymer coatings to mature technically and gain regulatory tailwinds, while scale hinges on crop-specific performance, transparent labeling, and dependable biomaterial supply.

Future Trajectory

- **Protein & silk platforms go mainstream:** New protein-based antifungal coatings (e.g., silk fibroin systems) show strong preservation in berries, pointing to scalable, clean-label matrices beyond polysaccharides/ lipids with better mechanical strength and inherent bioactivity. ScienceDirect
- **From passive barrier to "smart" active layers:** Reviews foresee nanocomposite carriers and controlled-release actives, plus intelligent/indicator functions, enabling finer gas/moisture tuning and antimicrobial dosing for diverse commodities. ScienceDirect
- **Regulatory tailwinds broaden options:** EFSA's 2025 opinion finding no toxicological concerns for chitosan/ chitosan-HCl at approved uses reduces uncertainty for antimicrobial biopolymer coatings in Europe, supporting faster approvals and procurement. EFSA

Key Uncertainties

- **Public trust and labeling:** High-visibility misinformation flare-ups around coatings show perception risk; producers may need clearer on-pack claims, disclosure, and third-party validation to sustain retail adoption. thepacker.com
- **Safety nuance & crop-specific tuning:** 2025 reviews affirm safety for most ingredients at use levels but note that not all formulations fit every commodity; poor gas-barrier matching can trigger off-flavors, demanding rigorous QA and specification. Wiley
- **Supply and cost resilience:** Market growth relies on steady, affordable bio-feedstocks and processing; if biopolymer inputs tighten or stay pricey, scale could stall despite demand forecasts. Grand View Research

Source: AI-generated image created using Google Gemini, prompt-based synthesis.

Local Case Study

Taif University

Apricots from Taif bruise and deteriorate quickly, even under chilled logistics, leading to moisture loss, surface decay, softening, and rapid downgrades. Smallholders and packers needed a low-cost, food-grade intervention that could be added to existing dip/spray lines, extend storability beyond two weeks, and preserve consumer-visible quality (firmness, color, flavor) for supermarket distribution. Prior literature flags apricots as highly climacteric with short shelf life and sensitivity to cold storage, underscoring the need for a barrier plus antimicrobial approach that works at 4–5 °C without chemical residues or packaging overhauls (PMC).

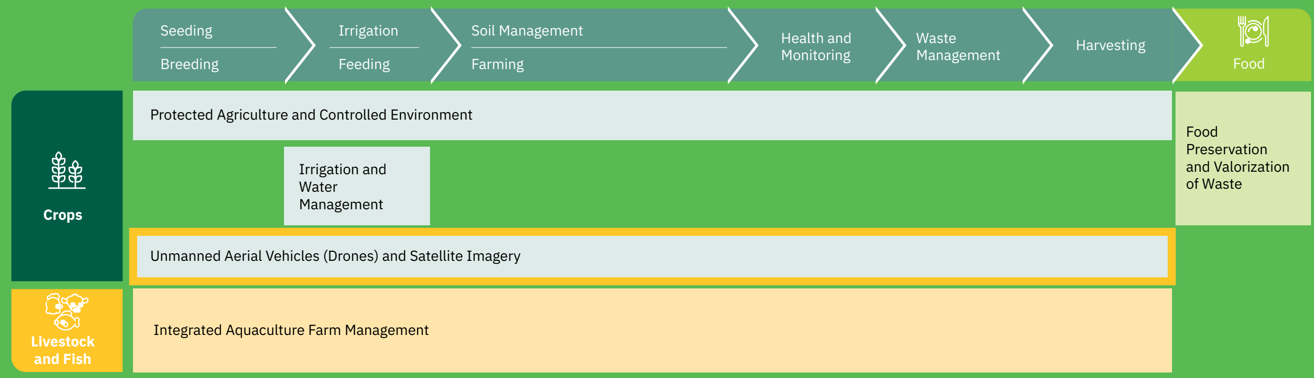
Taif University researchers partnered with local growers to trial an edible nano-chitosan dip at low percentages on freshly harvested apricots, applied post-wash in a packhouse-compatible workflow. Chitosan nanoparticles create a semi-permeable film that slows respiration and moisture loss while exerting antimicrobial action, the team benchmarked nanoparticle coatings against conventional chitosan and uncoated controls under cold storage. Similar nano-chitosan systems at 0.5–1% have been validated internationally for 4 °C storage, informing concentration choices and QA. The method fits existing equipment, adds minimal cycle time, and relies on food-approved inputs sourced or formulated in-Kingdom (PMC, Europe PMC).

The pilot extended cold-storage life to ~30 days at 4–5 °C, maintaining significantly higher firmness, lower weight loss and decay, and better sensory acceptability versus controls. Results align with peer-reviewed findings: Taif University's study reports 30-day cold-storage viability and improved quality indices with chitosan nanoparticles, while external studies at similar concentrations corroborate microbial suppression and texture retention at 4 °C. For growers, the intervention reduces shrink and widens shipping windows; for retailers, it stabilizes quality with minimal operational change, making it a pragmatic waste-reduction lever for Saudi supply chains (PMC, PubMed).

TECHNOLOGY PRIORITY GROUP FOCUS

3.5 UNMANNED AERIAL VEHICLES (drones) & SATELLITE IMAGERY

Unmanned aerial vehicles (UAVs or drones) bring several advantages to the agriculture sector, especially since they can be remotely controlled or pre-programmed to fly autonomously. Drones provide a wide range of services in agriculture, from improving water usage, increasing irrigation efficiency, to more effectively managing water resources.



Frontier Technologies in Unmanned Aerial Vehicles (drones) and Satellite Imagery

SATELLITE CONSTELLATIONS & ON-ORBIT ANALYTICS	UAV SENSING PAYLOADS & MODALITIES	UAV PLATFORMS & INFRASTRUCTURE	FIELD OPERATIONS & ACTUATION
High Revisit, Sub Meter CubeSat Imagery (TRL 8)	Thermal Imaging Drones (TRL 8)	Unified Drone & Sat Imagery SaaS Platforms (TRL 8)	Swarming Spray & Scout Drones (TRL 7)
Next Gen SAR Satellites (TRL 7)	Multispectral Sensor Kits (TRL 8)	Edge AI Drones (TRL 7)	Drone Based Aerial Seeding (TRL 7)
Methane & GHG Tracking Satellites (TRL 7)	UAV LiDAR (TRL 8)	BVLOS Corridors (TRL 7)	Electrostatic Spray Drones (TRL 7)
On Orbit Edge Computing & ML (TRL 6)		"Drone in a Box" Docks (TRL 7)	
Hyperspectral Imaging Satellite Constellations (TRL 8)			

The definitions of the listed technologies are in the glossary

Innovation, Interest, and Investment by Technology (2024)

To assess the development of each emerging technology, our team collected data on four tangible measures of activity: **news publications, patents, research publications,** and **investment.**

For each measure, we used a defined set of data sources to find occurrences of keywords associated with each of the 15 technologies, screened those occurrences for valid mentions of activity, and indexed the resulting numbers of mentions on a 0–1 scoring scale that is relative to the technologies studied:

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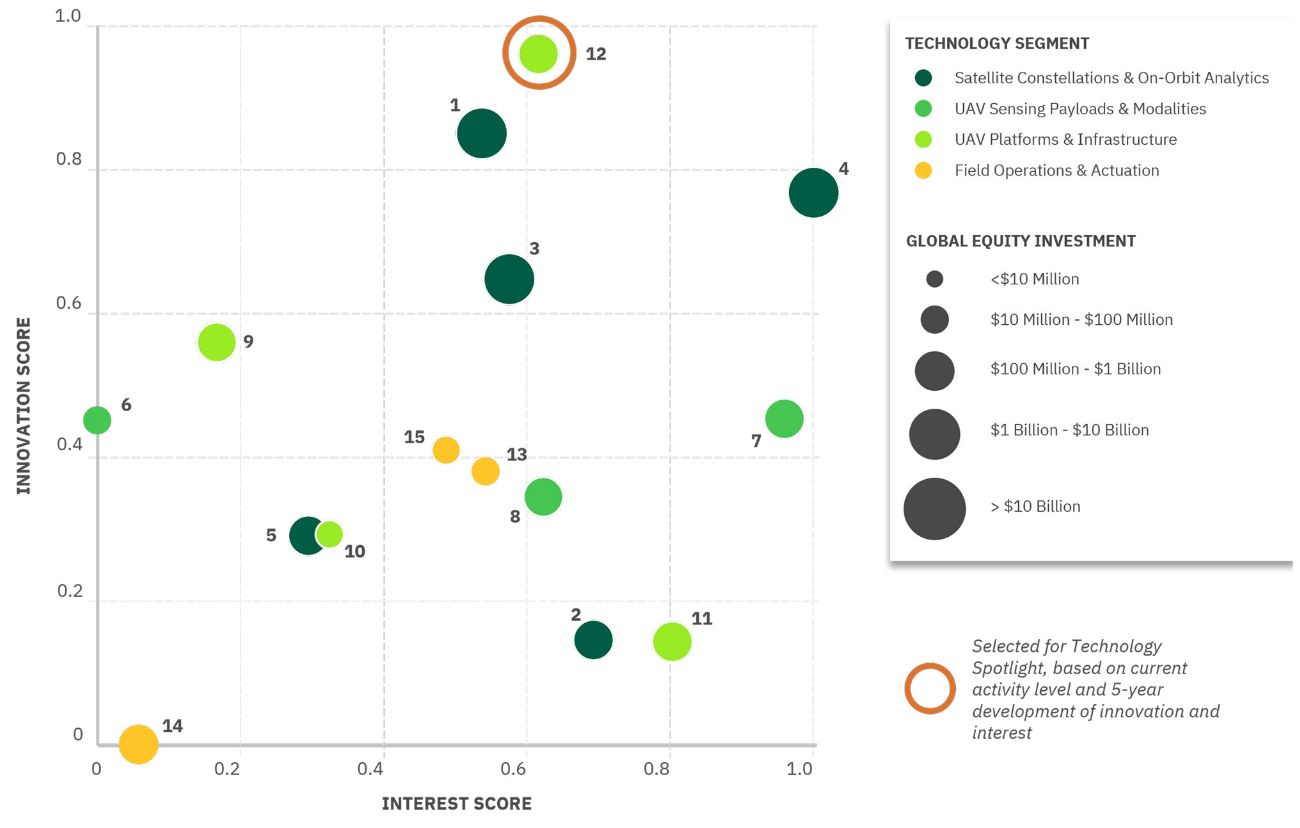
Figure 16: Chart representing Innovation Score vs Interest Score across all 15 technologies



1 – High-Revisit, Sub-Meter CubeSat Imagery
2 – Hyperspectral Imaging Satellite Constellations
3 – Methane & GHG-Tracking Satellites
4 – Next-Gen SAR Satellites
5 – On-Orbit Edge Computing & ML
6 – Multispectral Sensor Kits
7 – Thermal-Imaging Drones
8 – UAV LiDAR
9 – Unified Drone-&-Sat Imagery SaaS Platforms
10 – BVLOS Corridors
11 – "Drone-in-a-Box" Docks
12 – Edge-AI Drones
13 – Drone-Based Aerial Seeding
14 – Electrostatic Spray Drones
15 – Swarming Spray & Scout Drones

Based on the scoring methodology of the McKinsey Tech Report

Note: Innovation and interest scores for the 15 trends are relative to one another. All 15 trends exhibit high levels of innovation and interest compared with other topics. While some technologies may have applications outside of agriculture, this analysis considered only patents, publications, news, and investments in the agriculture context.

Technologies Trending in Innovation Output and Public Interest

Static innovation and interest scores snapshot technological vitality, but momentum reveals trajectory. Tracking growth or decline exposes breakouts before rivals, flags waning hypes, guides timing of subsidies, calibrates capacity-building, and aligns infrastructure budgets with future demand. Dynamics safeguard against sunk costs and amplify the impact of the resources in the EWA ecosystem.

Looking into the global growth rates in patents, publications, and news published on the technologies studied over the past 5 years, no segment is particularly standing out for growing or declining momentum. On the level of individual technologies, the following display high growth rates across all three measures examined:

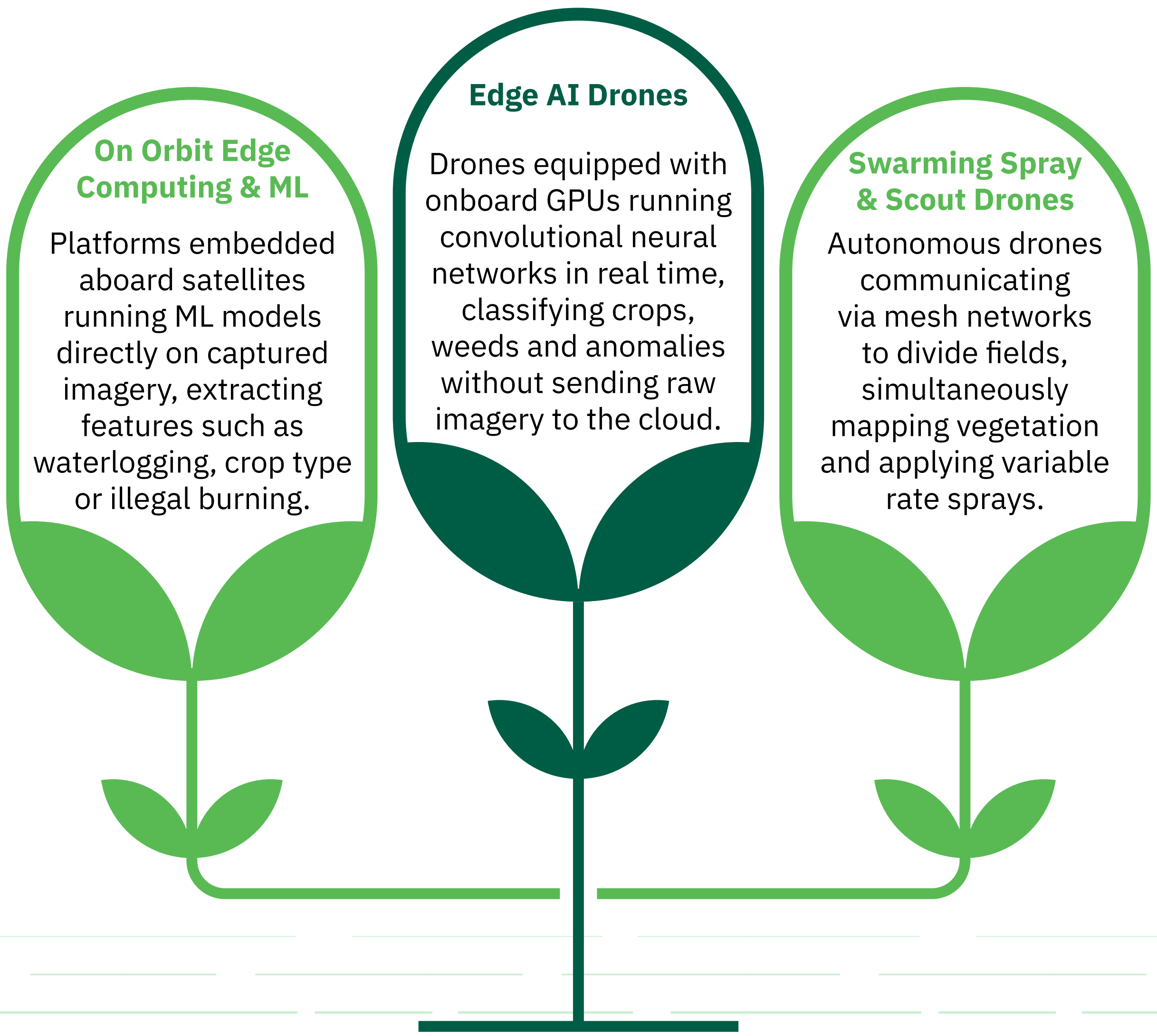
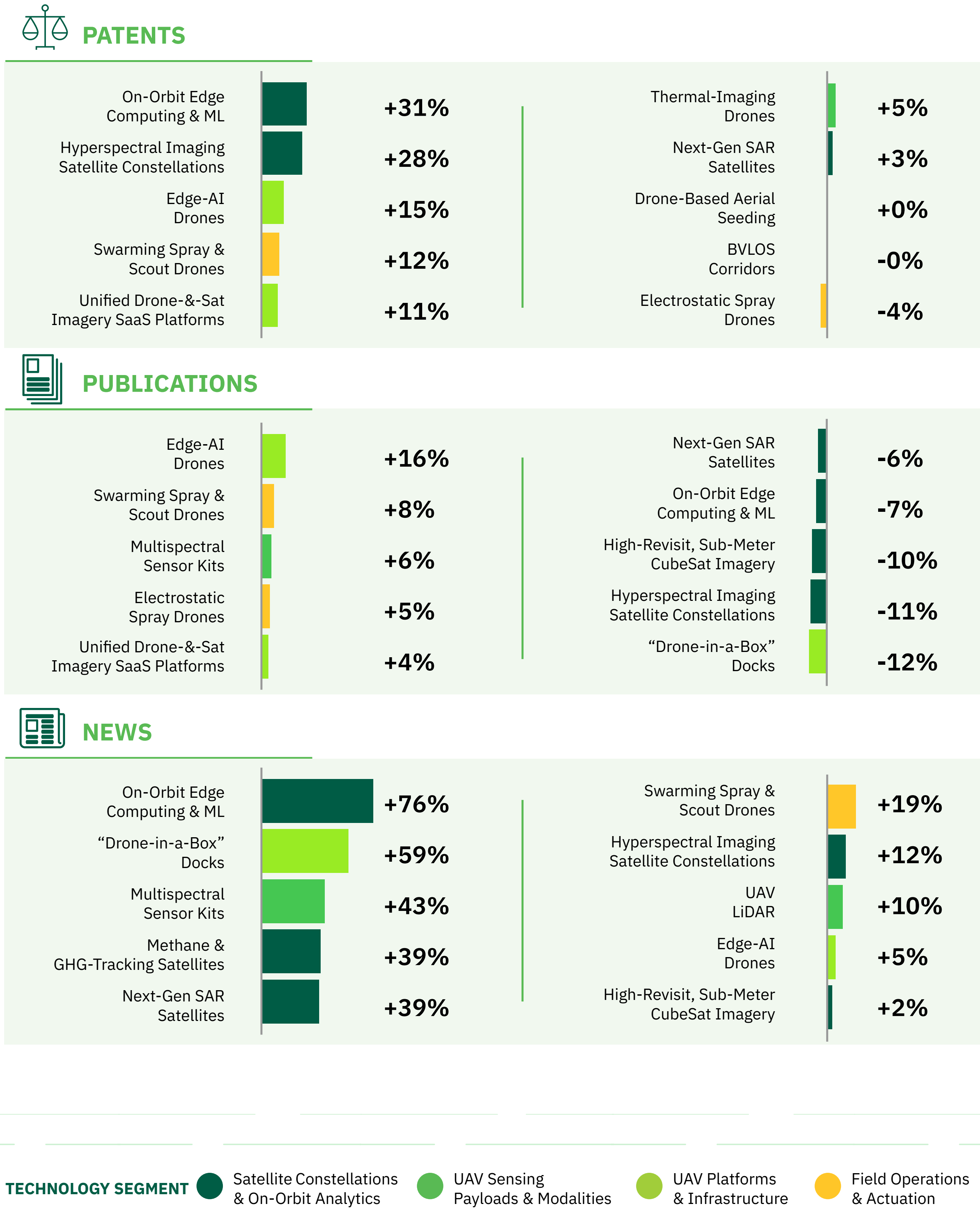


Figure 17: Continuous Annual Growth Rate of Patents, Publications, and News (2019-2024), Top 5 and Bottom 5 Technologies



Overview of National RDI Output

In the research benchmarking, Saudi Arabia's position is split. Regarding **Patents**, compared to the overall Global Patent Rank (27th), our nation ranks in the global Top-20 for around half of the technologies surveyed, and Top-10 in two of the key emerging technologies in the field. The country takes a strong position, especially in the segment **UAV Platforms & Infrastructure**. For 7 of the 15 technologies observed, no patent registrations were recorded between 2019-2024, though.

Regarding **Publications**, the positioning is overall more promising as while there is no Top-10 ranking in any of the technologies observed, Saudi Arabia ranks Top-20 globally in ~75% of the technologies listed. Most notably, recent investments into digital technologies have placed Saudi Arabia in the global leadership group for scientific publications in the segment **Monitoring & Analytics**. As scientific publication activity is a major early indicator for innovation potential in the future, the outlook toward 2030 and beyond is promising, especially considering the large potential for efficiency gains and sustainable water usage that digital tools, AI, and advanced analytics offer.

Figure 18: Saudi Arabia's Positioning across Emerging Technologies, Global Rank in No. of Patents & Publications (2019-2024)

PATENTS

PUBLICATIONS

TECHNOLOGY SEGMENT: Satellite Constellations & On-Orbit Analytics · UAV Sensing Payloads & Modalities · UAV Platforms & Infrastructure · Field Operations & Actuation

TECHNOLOGY SPOTLIGHT

3.5.1 EDGE-AI DRONES

Multirotor drones equipped with onboard GPUs run convolutional neural networks in real time, classifying crops, weeds and anomalies without sending raw imagery to the cloud. This edge processing cuts latency, bandwidth and privacy risk, enabling fully autonomous scouting missions that finish detection and prescription in a single rapid daily flight.

Edge-AI Drones

Edge-AI drones are UAVs that run AI models on-board (vision, navigation, mapping) instead of streaming to the cloud. That local inference slashes latency, saves bandwidth, and improves resilience and data privacy (IBM, arXiv). Hardware platforms such as NVIDIA Jetson and Qualcomm Flight RB5 5G pack GPU/AI accelerators into low-SWaP mission computers so drones can detect obstacles, classify targets, and plan paths in real time (NVIDIA, Qualcomm). Commercial systems like Skydio show this in practice: onboard “Spatial/Autonomy AI” performs 360° sensing, obstacle avoidance, and in-field 3D scanning without offloading (skyio.com). For agriculture and environment, edge-AI drones enable rapid crop/water-stress scouting, pest and livestock detection, and infrastructure inspections even beyond reliable networks, delivering faster decisions, lower data costs, and safer operations that scale (Milvus).

Technology and National Capability Maturity

Edge-AI drones already fly autonomous, on-board-AI missions in the field (e.g., public-safety/utility deployments), but agriculture-specific scale-out still faces cost, battery, and real-time processing hurdles so maturity stops short of routine, standardized roll-out (TRL 7) (WIRED, MDPI). Saudi Arabia has solid RDI and governance foundations and emerging local UAV co-production, enabling pilots and early services. However, edge-AI compute and most airframes are imported, constraining localization and scale economics today (CRL 5) (General Authority of Civil Aviation, KAUST, SAMI-AEC).

Capability Readiness Level (CRL)

5

Technology Readiness Level (TRL)

7

*Capability Readiness Level (CRL) and Technology Readiness Level (TRL) descriptions are in the Glossary

Global Key Players

01 Skydio

02 Shield AI

03 Percepto

04 Exyn Technologies

05 DJI (Enterprise)

06 Parrot

07 Auterion

08 NVIDIA (Jetson)

09 Qualcomm (Flight RB5 5G)

10 Univ. of Zurich / ETH Zurich (RPG)

Technology Potential

On-board inference lets drones perceive, decide, and act in real time without constant connectivity — unlocking faster, safer, and more scalable operations across agriculture, environment, and infrastructure.

Advantages

- **Real-time autonomy in denied/ patchy comms:** On-drone AI enables navigation and mission execution when GPS or links are unreliable, cutting latency and manual workload while improving safety and coverage for field tasks. Shield AI
- **Higher inspection productivity & quality:** Autonomous capture and on-board perception automate complex scans, producing consistent datasets and rapid digital twins for assets or fields with minimal pilot skill. skydio.com
- **Lower bandwidth, better privacy/ resilience:** Processing data at the edge reduces backhaul, costs, and exposure of sensitive imagery while enabling decisions when networks are congested or offline. IBM

Disadvantages

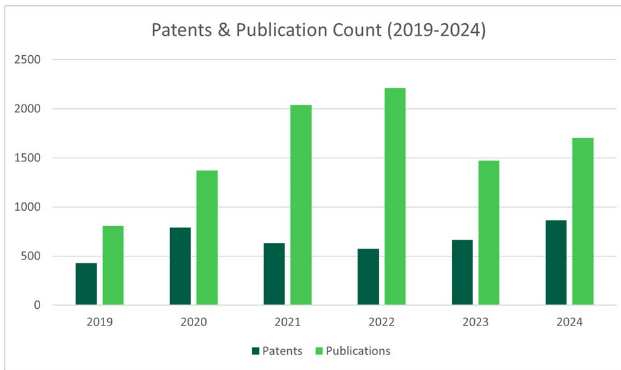
- **SWaP/energy limits cap endurance & model size:** Edge compute adds power and thermal load; limited onboard energy constrains flight time and inference budgets, demanding careful optimization and task scheduling. MDPI
- **Regulatory friction for autonomy at scale:** Routine BVLOS and high-autonomy operations face evolving approval pathways and qualification requirements, slowing widespread deployment despite technical readiness. Federal Aviation Administration
- **Model robustness under distribution shift:** Vision and control models can degrade in novel conditions; new approaches aim to improve generalization, but reliability still requires careful validation and adaptation. science.org

Latest Developments

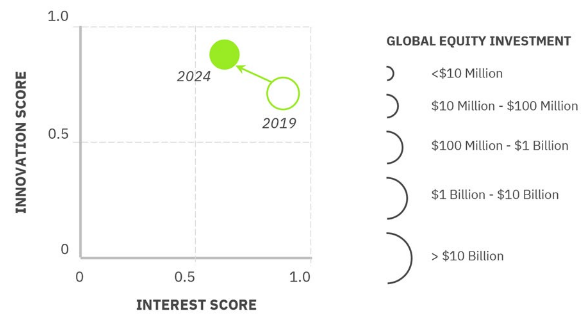
Edge-AI drones are accelerating thanks to sharper onboard compute, maturing autonomy stacks, and policy shifts that normalize remote, beyond-visibility operations — pushing real deployments from pilots to scaled programs.

Key Innovation Signals

- **BVLOS normalization moves from waivers to rules:** The Federal Aviation Administration's (FAA) new BVLOS NPRM proposes a predictable path for routine low-altitude BVLOS (incl. agriculture/aerial surveying), a catalyst for persistent, edge-autonomous operations at scale. Federal Aviation Administration
- **Edge autonomy at mass scale in conflict zones:** Auterion will supply 33,000 AI guidance kits to Ukraine, enabling onboard vision-lock targeting despite jamming — evidence of large-volume, field-hardened edge AI deployments. Financial Times
- **Rapid commercial autonomy iteration:** Skydio's 2025 X10D "Asimov" updates deliver navigation/communications improvements for tactical ISR, showing fast, continuous gains in on-drone perception and decision-making. skydio.com
- **Docked, fully remote inspections expand:** An FAA waiver now permits fully remote, dock-based inspections across the U.S., validating persistent edge-AI drone ops without on-site pilots for utilities and infrastructure. DRONELIFE
- **Autonomy surpasses human pilots:** An autonomous drone beat human champions at an international racing event, underscoring real-world advances in high-speed onboard perception-control that translate to tougher field missions. Tech Xplore
- **Cheaper, stronger edge compute hits market:** NVIDIA's $249 Jetson Orin Nano Super boosts accessible onboard AI performance for small UAVs, lowering cost barriers for startups and applied robotics teams. Wall Street Journal



The figure below is investment development of the technology against Innovation score vs Interest score



Insights and Statistics

Edge-AI is translating into measurable gains: higher onboard compute, expanding BVLOS approvals, and real-world productivity/ROI — moving autonomous drone ops from demos to dependable, at-scale workflows.

Key Stats & Facts

- **Triple-digit TOPS on tiny airframes:** Jetson Orin NX delivers up to 157 TOPS in 10–40W, ~5× AGX Xavier, enabling multi-model perception, tracking, and planning entirely onboard small UAVs. NVIDIA
- **5G robotics SoC with on-device AI:** Qualcomm's RB5 platform provides ~15 TOPS AI, optional 5G, Wi-Fi 6, and support for multiple concurrent cameras, powering vision-heavy autonomy without the cloud. Qualcomm
- **BVLOS activity is scaling fast:** By Oct 2024, FAA had issued 190 BVLOS waivers, with 44,166 flights by BEYOND participants, expanding the operational envelope where edge-autonomous drones deliver value. oig.dot.gov
- **Autonomy beats human champions:** In Nature, the "Swift" AI drone recorded the fastest race time, ~0.5 s quicker than the best human pilot — evidence of high-speed, real-world perception-control maturity. Nature
- **Proven ROI in inspections:** Stantec cut bridge-inspection time from 10 days to 5 and halved costs (-50%) using autonomous capture and on-drone perception, showing tangible efficiency from edge-AI workflows. skydio.com
- **Docked ops become lighter and simpler:** DJI Dock 2 is 75% smaller and 68% lighter than its predecessor, easing site deployment for persistent, remote, edge-autonomous missions. DJI

Technology Adoption

Edge-AI drones are moving from flashy demos to regulated, scaled operations driven by BVLOS policy shifts, docked remote ops, and wartime acceleration — yet localization in Saudi Arabia hinges on airspace approvals, data rules, and local-content economics.

Current State

- **BVLOS rulemaking normalizes scale:** The FAA's BVLOS NPRM sets a predictable, performance-based path for routine low-altitude BVLOS (incl. agriculture/survey), replacing ad-hoc waivers and unlocking persistent, edge-autonomous operations. Federal Aviation Administration
- **Enterprise remote ops go national:** Broad BVLOS waivers now permit fully remote, dock-based inspections across the U.S., signaling commercial readiness for autonomous, on-drone AI workflows in utilities and infrastructure. DRONELIFE
- **Wartime scaling proves edge autonomy:** Ukraine will field 33,000 Auterion AI "strike kits," showing mass production and field hardening of onboard perception/decision systems — technology maturity that spills over into civil markets. Financial Times

Requirements for Localization

- **Airspace approvals & ops categories:** Edge-AI missions (incl. BVLOS/autonomous) must align with General Authority of Civil Aviation Regulations (GACAR) Part 107 categories, permits, and definitions, requiring operator certification, risk cases, and conformance with Saudi aviation safety rules. General Authority of Civil Aviation
- **Datasovereignty&privacycompliance:** On-drone sensing and video must meet PDPL and Implementing Regulations — governing processing, retention, and cross-border transfers, necessitating Saudi-hosted pipelines or approved safeguards for any external processing. SDAIA
- **Local-content economics & procurement:** Government and SOE adoption will weigh Local Content and Government Procurement Authority (LCGPA) local-content mandates — pushing in-Kingdom assembly, maintenance, and services so vendors need credible localization plans to win tenders at scale. engine.strategicgears.com

Outlook

Edge-AI drones will gain endurance, autonomy, and regulatory legitimacy — yet success hinges on battery breakthroughs, rulemaking timelines, and supply-chain geopolitics.

Future Trajectory

- **Cheaper, stronger onboard AI:** Low-cost embedded GPUs make multi-model perception and planning standard on small UAVs, moving analytics from the cloud to the airframe and unlocking denser, faster missions at scale. NVIDIA
- **BVLOS normalization unlocks persistent ops:** A proposed FAA BVLOS rule shifts from ad-hoc waivers to performance-based approvals, enabling routine long-range inspections, surveying, and ag missions driven by on-drone inference. federalregister.gov
- **Endurance jumps with next-gen batteries:** Solid-state chemistries promise higher energy density and safety than Li-ion, extending flight times and payload headroom for compute-heavy autonomy, if manufacturing scaling stays on track. DRONELIFE

Key Uncertainties

- **Regulatory timing & harmonization:** Final BVLOS requirements, equipage, and operational categories remain in flux; delays or restrictive provisions could slow nationwide deployment and investment pacing. Federal Aviation Authority
- **Europe's U-space rollout complexity:** Implementation details, service provider readiness, and local integration with ATC vary across states, affecting cross-border scalability of autonomous, docked operations. EASA
- **Geopolitics & compliance headwinds:** Security reviews, potential import restrictions, and evolving Remote ID/airspace rules can reshape vendor access, costs, and fleet roadmaps, especially for widely used platforms. theverge.com

Source: terra drone

Local Case Study

KAUST CEMSE & Prince Sultan University

Field scouting in Saudi agriculture demands fast detection of crop-stress indicators across large, arid plots where connectivity is intermittent and manual image review is too slow and costly. Traditional cloud-offloaded AI pipelines choke on bandwidth and latency, delaying action when heat and water stress evolve hourly. Researchers in the Kingdom targeted a solution that would (1) run detection and tracking on the aircraft, (2) geolocate findings precisely, and (3) transmit only what matters to save airtime and protect data. This set the stage for AERO, an on-drone edge-AI "UAV brain" aimed at precision remote sensing in real operating conditions (MDPI).

The team built AERO around Jetson Xavier AGX as the edge computer, executing YOLOv4/YOLOv7 object detection fused with DeepSORT tracking and TensorRT acceleration directly onboard. The system follows a cloud-edge hybrid: the drone performs real-time perception and reports detected objects with coordinates to the cloud without redundant video, minimizing bandwidth. Inference performance reached ~15.5 FPS on-airframe while maintaining low false positives (0.7%) and few identity switches (1.6%). This architecture suits agricultural use cases because it prioritizes timely, georeferenced "events" over raw streams, enabling action even when the backhaul is weak (MDPI, DOAJ).

AERO demonstrates that edge-AI drones can deliver operationally relevant detection, tracking, and geo-localization for agricultural targets in Saudi settings while slashing data transfer needs. By pushing perception to the edge, the platform reduces latency and cost, and makes routine, repeatable sorties feasible for crop-stress scouting, asset inspections, and other remote-sensing tasks. The work led from Prince Sultan University with knowledge exchange across the KAUST CEMSE ecosystem anchors a national capability path for autonomous agri-analytics and offers a blueprint for local SMEs to productize services (MDPI, KAUST CEMSE, Prince Sultan University).

04

LEADERSHIP INSIGHTS

Innovating for a Sustainable Future: Estidamah on Agricultural Technology Advancements

In tackling extreme water scarcity, harsh climates, and import dependency, Saudi Arabia is redefining agricultural resilience through advanced technologies. Controlled Environment Agriculture, precision irrigation, and biotechnology are not just solutions—they're strategic enablers of sustainable food systems. We're pioneering emerging domains like saline agriculture, circular bioeconomy, and microalgae-based protein production to future-proof our food supply. Guided by Vision 2030 and backed by over $17.3 billion in government-approved funding, our innovation roadmap unfolds in three phases: rapid tech scale-up (2025–2028), localization and export (2028–2032), and global leadership in integrated, carbon-negative systems (2032–2035). Projects like NEOM and the Red Sea serve as live labs for zero-waste, climate-smart agriculture. Our ambition is clear: to transform Saudi Arabia into the 'Silicon Valley of Desert Agriculture'—a global hub for scalable, arid-climate solutions that secure nutrition and sustainability for future generations.

Dr. Khalid Al-Ruhailee
General Director of the National Center for Research and Development of Sustainable Agriculture – Estidamah

Innovating for a Sustainable Future: NEOM TOPIAN on Agricultural Technology Advancements

Saudi Arabia's path to agricultural transformation is shaped by unique challenges among them, water scarcity and a reliance on traditional open-field farming. Transitioning toward high-efficiency technologies like protected agriculture, precision irrigation, and digital monitoring will be essential. However, adoption hinges on building farmer confidence through demonstrable, economically viable results. An emerging but underappreciated frontier is aquaculture. With high feed efficiency and alignment with the Kingdom's Red Sea assets, it presents a scalable, climate-resilient protein source. Innovations such as submersible cages and closed containment systems, already underway, are unlocking new potential in this space. Investment in agriculture innovation is currently driven by large producers who absorb the bulk of the risk. For broader inclusion, especially among SMEs, the ecosystem must evolve—introducing risk-sharing frameworks, accessible financing, and incentives tied to measurable impact. Looking ahead, Saudi Arabia is cultivating a structured innovation ecosystem through platforms like Ibtikar and Estidamah, which unite government, industry, academia, and innovators. Over the next decade, we expect protected agriculture to dominate, digital compliance tools to become standard, and aquaculture technologies to advance rapidly. To position itself as a global leader, the Kingdom must align its natural constraints and economic goals with targeted innovative strategies. With coordinated action across policy, finance, and regulation—particularly through integrative platforms like SAFTA—Saudi Arabia can emerge as a global benchmark for sustainable agriculture in desert climates.

Woody Ang (WooTeck)
Director of Food Ecosystems – NEOM TOPIAN

Innovating for a Sustainable Future: Tanmiah on Agricultural Technology Advancements

Saudi agriculture is operating under structural pressures—water scarcity, climate volatility, import dependency, and rising biosecurity risk—which make innovation not optional but fundamental. To stay competitive and resilient, we must shift from reactive farming to predictive, data-driven, resource-efficient systems. The technologies priority groups highlighted in this report—AI-powered predictive irrigation, IoT and AI-enabled farm management, food preservation and waste valorization, and edge-AI drones for monitoring—directly address the Kingdom's challenges. They help us use less water, stabilize yields, safeguard animals and plant health, and extract more value from every unit of input. Yet two emerging areas remain overlooked: alternative feed ingredients as a national resilience lever, and climate and carbon-accounting frameworks tailored to desert agriculture and protein systems, which could unlock future green-finance opportunities. Looking ahead, the next 5–10 years will bring two major shifts: moving from isolated pilots to integrated decision platforms that combine IoT, imagery, genetics, and market data; and moving from imported solutions to technologies co-developed for arid climates. Saudi Arabia is well-positioned to become a global testbed—attracting specialized funds, enabling public–private consortia, and drawing innovators who want to prove their solutions in one of the world's most demanding environments. To lead globally, the Kingdom should own the agenda for desert agriculture and halal protein systems, build living labs and regulatory sandboxes, deploy targeted capital through national funds, invest in multidisciplinary talent, and ultimately export knowledge—not just commodities. With continued alignment among MEWA, industry, investors, and research institutions, Saudi Arabia can evolve from being 'a difficult place to farm' into a global benchmark for climate-resilient, high-performance agriculture."

Muhammad Abbas Khan
Chief Strategy Officer in Tanmiah

Innovating for a Sustainable Future: Green Dunes in Agricultural Technology Advancements

Saudi Arabia is navigating a critical transformation in agriculture, driven by the urgency to enhance water efficiency, increase productivity, and overcome labor shortages—all under the broader objectives of Vision 2030. Emerging technologies such as AI-powered irrigation, precision farming, and controlled-environment agriculture are proving essential in this shift. We're also closely watching frontier innovations like autonomous farm ecosystems and gene-editing tools, which could redefine the sector over the next decade. Investment momentum is high, guided by national priorities and supported by government frameworks. The private sector, too, is recognizing the long-term value of scalable, sustainable technologies. As the market grows more data-driven and automated, partnerships—like our Saudi Japanese Italian collaboration—will be key in localizing and transferring global agri-tech solutions. By establishing excellence centers and investing in R&D and manufacturing, Saudi Arabia can lead the future of sustainable agriculture in arid regions worldwide.

Shebley Al-Noimi
Director in Green Dunes

05

APPENDIX

Interviews – Questions for Private Sector Leader

Dr. Khalid Al Ruhailee - Estidamah
General Director of the National Center for Research and Development of Sustainable Agriculture

1. What are the key agriculture-related challenges, and how do technologies play a role in overcoming them?

The core challenges are fourfold: Extreme Water Scarcity (consuming about 80% of national water), Harsh Climatic Conditions (average temperatures exceeding 50℃), high Food Import Dependency (creating supply chain vulnerability), and pervasive Soil Degradation (salinization and low organic matter). Innovative technologies are our strategic solution: for example, Controlled Environment Agriculture (CEA) delivers up to 90% water savings; Precision Irrigation and IoT optimize real-time resource allocation; and Biotechnology enables rapid propagation of climate-adapted, disease-resistant varieties. Ultimately, the integration of Solar Power and AI-driven Farm Management transforms these environmental constraints into competitive advantages, positioning Saudi Arabia as a global testbed for climate-resilient food production.

2. What is not yet in everyone's radar, and you are closely following?

In addition to significant advances in CEA and digital support systems, we are strategically monitoring and pioneering three crucial emerging domains that will redefine our agri-food system resilience. First, Saline Agriculture and Halophyte Cultivation represent an untapped potential for coastal MENA regions, leveraging seawater-based integrated aquaponics to unlock marginal lands, moving beyond traditional freshwater conservation. Second, Agricultural Waste Valorization and Circular Bioeconomy involve maximizing value from agricultural residues, from converting date palm fiber into rockwool alternatives to producing biochar and biopesticides, which directly addresses soil health and carbon sequestration. Critically, we are also advancing the Development and Testing of Biofertilizers and Biopesticides derived from bio-sources to enhance sustainable, low-chemical farming. Finally, Microalgae and Precision Fermentation represent a revolution in protein production, requiring minimal land and water, an area where early Saudi investment can establish regional nutritional security leadership.

3. What drives investments in agriculture innovation in Saudi Arabia?

Investment is fundamentally driven by a powerful policy-commercial synergy. The Vision 2030 Policy Framework provides decisive government support, exemplified by the Agricultural Development Fund (ADF) approvals exceeding $17.3 Billion and offering up to 75% financing for CEA projects. This commitment is amplified by the Food Security Imperative and the strict Water Conservation Mandate (Qatrah program), making agritech investment strategically mandatory. Furthermore, the Demonstrated ROI in harsh climates by pioneers like Pure Harvest and Red Sea Farms validates commercial viability, and the immediate, large-scale Megaproject Integration (NEOM, Red Sea Project) creates essential anchor demand and innovation testbeds for localized food systems.

4. How do you see the market for agriculture innovation evolving in the next 5-10 years?

We foresee a three-phase transformation: Phase 1 (2025-2028) focuses on Technology Adoption and Scale-Up, driven by rapid deployment of smart greenhouses and triple investment in vertical farming.

Phase 2 (2028-2032) marks a pivot to Technology Localization and Export, where the Kingdom shifts from importing to domestically manufacturing components, establishing Saudi Arabia as the regional hub for desert-adapted solutions. Finally, Phase 3 (2032-2035) will witness the maturation of Integrated Systems and Circular Bioeconomy Leadership, positioning the Kingdom as the global reference for arid-climate sustainable agriculture, integrating aquaponics, waste valorization, and carbon-negative practices.

5. How can Saudi Arabia position itself as a global leader in agriculture innovation?

Saudi Arabia must strategically leverage its Extreme Climate as an Innovation Catalyst, as technologies proven here are inherently scalable globally. Our strategy requires building a World-Class Innovation Infrastructure, including specialized National Agricultural Innovation Centers and an "Agriculture Technology Park." We must capture Intellectual Property and Standards Leadership by prioritizing local patenting and leading international standards development for arid-climate agriculture. This effort is secured through Strategic International Partnerships and the establishment of a Saudi Agri Tech Venture Fund to co-invest globally. Crucially, we must Demonstrate at Megaproject Scale by using NEOM and The Red Sea Project as living laboratories to create zero-waste, carbon-neutral blueprints, while simultaneously investing in Human Capital through large-scale training programs and specialized visa categories to attract global talent. Our objective is to become the "Silicon Valley of Desert Agriculture."

Interviews – Questions for Private Sector Leader

Woody Ang (WooTeck) -NEOM TOPIAN
Director of Food Ecosystems

1. What are the key agriculture-related challenges, and how do technologies play a role in overcoming them?

Saudi Arabia's agricultural transformation is fundamentally constrained by water scarcity and the heavy reliance on open-field cultivation, which remains the dominant production model. Farmers often hesitate to adopt modern systems because greenhouses represent the largest capital investment they will make, and they require confidence that technology is both reliable and economically viable.

The next wave of progress will depend on:

- Water-efficient technologies (protected agriculture, improved climate control, precision irrigation, digital monitoring).
- Demonstrable results that build farmer confidence, particularly technologies linked to crops with strong domestic demand, stable yields, and predictable operating costs. Where technology clearly improves water productivity and commercial outcomes, adoption accelerates.

2. What is not yet in everyone's radar, and you are closely following?

A major shift is coming in aquaculture as a core protein pathway and complementary alternative for the Kingdom. While consumption today is still dominated by poultry, beef, and lamb, aquaculture offers the highest feed conversion ratio, strong climate resilience, and aligns with Saudi Arabia's long Red Sea coastline. This has been proven via MEWA's focus on the National Livestock & Fisheries Development Program (NLFDP).

Topian's upcoming deployments by Q1 2026 including submersible sea cages and closed containment systems in Duba are capable of managing temperature and bypassing thermocline layers illustrate how innovation can unlock a new, scalable protein source. This transition is underway but not yet widely appreciated on a national scale. However, we believe this is just the beginning and the potential can be fully unlocked in the years ahead.

3. What drives investments in agriculture innovation in Saudi Arabia?

Currently, innovation risks are primarily carried by larger producers and companies. Smaller farmers often lack the financial buffer and risk appetite to trial nascent technologies; they wait for solutions that have already reached commercial proof of concept.

Three factors shape investment behavior:

- Risk concentration among large incumbents.
- Capital intensity of modern agriculture systems.
- Operational complexity that requires skilled labor and after-sales support.

Enabling SMEs to participate will require structured risk-sharing mechanisms enabled by the Government / larger companies, accessible financing for technologies, and incentives tied to verified improvements in both water savings, and in data that can inform investments into market-viable crops.

4. How do you see the market for agriculture innovation evolving in the next 5-10 years?

Saudi Arabia is moving toward a model where innovation is tested, validated, and scaled within structured environments that bring together government, industry, academia, and innovators.

A pivotal enabler we have embarked on is the development of innovation platforms such as Ibtikar, established with Saudi Greenhouses (SGH) and hosted at the University of Tabuk (UT). These platforms demonstrate the "quadruple helix" model in action; integrating commercial players (SGH / Topian), research institutions (UT), talent pipelines (UT), and regulatory partners (MEWA).

In the next 5-10 years, we expect:

- Protected agriculture to become the default production system for key crops.
- Rapid growth in aquaculture technologies, particularly warm-water CCS and offshore systems, and even RAS systems.
- Digital monitoring and verification to become standard across subsidies and compliance.
- More innovation-driven partnerships shaping commercial decision-making.

5. How can Saudi Arabia position itself as a global leader in agriculture innovation?

Saudi Arabia can lead globally by aligning its natural constraints, economic ambitions, and innovation toolkit around performance, resilience, and measurable value.

Key opportunities include:

- **Incentivize deployment over acquisition**, moving toward performance-linked incentives that reward verified water savings and yield protection.
- **Accelerate protected agriculture adoption** through clear technology standards, financing routes, and technical support systems.
- **Expand innovation testbeds and centers** such as Ibtikar and Estidamah across regions to attract global innovators to trial desert-climate solutions.
- **Champion climate-aligned proteins**, especially aquaculture, where the Kingdom has natural strategic advantage.
- **Strengthen regulatory clarity for modern agriculture,** including new greenhouse standards, aquaculture systems, biotechnology / gene-editing, and digital monitoring of water use.

With coordinated policy, financing, and regulatory action especially through platforms such as SAFTA that bring all players together to establish tangible partnerships, the Kingdom has inherent potential to become a global reference point for sustainable, desert-climate agriculture and food-system innovation.

Interviews – Questions for Private Sector Leader

Muhammad Abbas Khan – Tanmiah
Chief Strategy Officer

1. What are the key agriculture-related challenges, and how do technologies play a role in overcoming them?

From our perspective at Tanmiah, the main structural challenges are:

- Water scarcity and climate stress – Growing feed and food in arid and semi-arid environments forces us to produce more with less water, under higher temperature volatility. Since our operations consume water, we are always on the lookout for technologies to make water consumption more efficient.
- Dependence on imported inputs – Especially grains and protein meals like soybean, which exposes us to price shocks, logistics risk, and geopolitical disruptions.
- Productivity and biosecurity – We must continuously lift yields and efficiency while managing disease risks in animal and plant systems.

The technology priority groups you highlight align directly with these challenges:

- Irrigation and Water Management (AI-powered predictive irrigation) can radically improve water-use efficiency for forage, feed crops, and integrated farming systems. In a country like Saudi Arabia, predictive models linked to soil moisture, weather, and crop stage are no longer "nice to have"; they are essential to sustaining production over the long term.
- IoTs and use of AI in farming helps de-risk production, especially in the context of broiler and breeder farming. Early detection of disease and stress is key to protecting yield and reducing vaccination use.
- Food Preservation and Waste Valorization can extend shelf life, reduce cold-chain losses, and help convert by-products into feed or other high-value inputs—something we already see as strategically important in the poultry and red-meat sectors.
- UAVs and Satellite Imagery (edge-AI drones) – I have seen some startups in KSA offering a scalable way to monitor large land areas, crop health, grazing conditions, and even farm-level water use, feeding data into more precise decision-making. This has huge potential in the Kingdom and is directly linked to food security goals of V2030.

In short, the combination of sensing, AI, and controlled environments is how we move from reactive agriculture to predictive, resource-efficient, and resilient systems.

2. What is not yet on everyone's radar, and you are closely following?

There are two areas we are watching very closely that are not yet mainstream in most discussions:

1. **Alternative feed ingredients as a strategic lever, not a niche experiment** For a country that imports most of its feed ingredients, shifting part of the protein or energy base to locally cultivable resources (e.g., moringa, camelina, desert-adapted crops, algae, insects, or upgraded by-products) is not just an R&D topic—it is a national resilience topic. The full ecosystem (agronomy, processing, feed formulation, and animal performance data) still needs to be built, but the potential is significant. There is also a strong requirement to build regulatory eco system and hence the role of MEWA and SFDA is crucial to support those players who are investing in this area.
2. **Climate and carbon accounting tailored to arid agriculture and protein systems** As global markets and financiers move towards emissions accountability, we will need robust, region-specific models to quantify emissions, sequestration, and circularity in livestock and desert agriculture. Done well, this could unlock new forms of green finance and incentives for Saudi producers. Again, the role of CMA becomes critical in leading this initiative and those stakeholders with good ESG practices, MSCI ratings etc must be incentive which could come in the form of non-monetary and monetary benefits such as access to cheaper capital.

3. What drives investments in agriculture innovation in Saudi Arabia?

In Saudi Arabia, agriculture innovation is being driven by a strategic convergence of:

- Food security and resilience – Ensuring reliable, high-quality access to food in a volatile global environment is clearly a national priority. Anything that reduces import dependency, especially for strategic commodities (feed grains, protein, water-intensive crops), is of high interest.
- Vision 2030 and economic diversification – AgriFood and AgriTech are now seen as part of the Kingdom's diversified growth engine, creating jobs, attracting FDI, and generating exportable capabilities (not just exportable products).
- Water and climate constraints – Limited renewable water resources and increasing climate stress mean that "more of the same" is not an option. Innovation is not a luxury; it is the only viable path to sustainable growth in the sector.
- For companies like Tanmiah, the business case is reinforced by operational economics: technologies that reduce water per unit of protein, stabilize feed cost, or lower mortality and waste typically have clear payback. When combined with ESG expectations and upcoming disclosure requirements, innovation becomes part of preserving long-term license to operate and access to capital.

4. How do you see the market for agriculture innovation evolving in the next 5–10 years?

Over the next 5–10 years, I expect agriculture innovation—globally and in Saudi Arabia—to move through two shifts:

- **From pilots to platforms** We will move beyond scattered pilots of AI irrigation, drones, or sensors into more integrated platforms where data from multiple sources (IoT, imagery, farm records, genetics, markets) is combined into a "decision engine" for farmers, integrators, and policymakers. The winning solutions will be those that solve multiple pain points at once: water, labor, yield, and risk.
- **From imported technologies to co-created solutions for arid climates** Saudi Arabia will increasingly co-design technologies rather than simply import them. For example, AI-powered irrigation models tuned to local soils and microclimates; or pest-detection models trained on regional crops and pests. Partnerships between Saudi companies, universities, and global innovators will be central. We have recently seen the strategic relationship between US and Saudi Arabia and the technological influx from USA would shape the landscape for good in KSA.

In that context, the market for Agrifood innovation in Saudi Arabia will likely:

- Attract specialized funds and venture builders focused on desert and halal food systems.
- See more public–private consortia around shared infrastructure (e.g., protected agriculture clusters, aquaculture zones, feed-ingredient value chains).
- Become a regional magnet for start-ups that want to prove their solutions in one of the world's most challenging, but well-capitalized, environments.

5. How can Saudi Arabia position itself as a global leader in agriculture innovation?

Saudi Arabia can lead by focusing on the areas where its challenges become its competitive advantage:

- **Own the "desert agriculture and halal protein" agenda globally** Few countries combine extreme climate, water constraints, large-scale protein demand, and strong capital availability. If the Kingdom positions itself as the place where solutions for hot, dry, resource-constrained environments are developed and scaled, those solutions will be relevant to many parts of Africa, the Middle East, South Asia, and even Southern Europe.
- **Create living labs and regulatory sandboxes** Establish reference sites and "living labs" for the five technology groups you outlined—where start-ups, corporates, and researchers can test AI irrigation, controlled environment systems, bio-coatings, and edge-AI drones under real Saudi conditions. Pair this with agile regulatory sandboxes for new inputs, biologicals, feed ingredients, and digital tools.
- **Deploy targeted capital and incentives** Use PIF, SALIC, ADF, and commercial banks in a coordinated way to de-risk innovation (through soft finance, offtake guarantees, and concessional capital for strategic areas like water-saving technologies and novel feed sources). Reward projects that show measurable improvement in water use, emissions intensity, and food security metrics.
- **Invest in talent and cross-disciplinary skills** Agriculture innovation now sits at the intersection of biology, data science, engineering, and business. Saudi Arabia can lead by developing specialized programs and centers of excellence that train "agri-systems leaders"—people who understand both the technology and the production realities on the ground.
- **Export knowledge, not just commodities** As Saudi solutions mature, the Kingdom can export methodologies, platforms, and standards—from desert greenhouse designs and predictive irrigation models to halal-compliant supply-chain systems and circular feed solutions. This would position Saudi Arabia not only as a food importer/exporter, but as a knowledge and technology exporter for climate-resilient food systems.

Interviews – Questions for Private Sector Leader

Shebley Al-Noimi – Green Dunes
Director

1. What are the key agriculture-related challenges, and how do technologies play a role in overcoming them?

One of the primary challenges we observe in the agriculture sector is the increasing pressure on water resources, productivity, and labor availability. Climate variability continues to affect crop performance, while traditional farming systems struggle to maintain consistency and efficiency.

Advanced technologies particularly AI-driven irrigation, controlled-environment agriculture, and precision farming allow us to optimize water consumption, enhance yield predictability, and reduce dependency on manual labor.

Through our multi-national partnership (Saudi, Japanese, and Italian), we integrate proven global technologies with localized solutions tailored to Saudi Arabia's environmental conditions.

2. What is not yet on everyone's radar, and you are closely following?

We are closely tracking the emergence of fully autonomous farm ecosystems that integrate robotics, AI-enabled sensing, and automated decision-making. While still in early development, these technologies will redefine future farm operations. We also follow rapid advancements in microbial-based soil enhancement and gene-editing tools that increase crop resilience. These innovations have the potential to become major disruptors in the next decade, yet they remain under-discussed in many markets.

3. What drives investments in agriculture innovation in Saudi Arabia?

Investment is primarily driven by national priorities related to food security, resource efficiency, and economic diversification under Saudi Vision 2030. The agriculture sector is transitioning from traditional methods to advanced, technology-enabled systems, and the government continues to create a supportive regulatory and financial environment. Additionally, the private sector sees strong long-term value in scalable technologies such as AI-powered irrigation, protected agriculture, aquaculture innovations, and waste-to-value solutions.

4. How do you see the market for agriculture innovation evolving in the next 5–10 years?

We expect the market to grow rapidly, becoming more data-centric, automated, and sustainability-driven. Saudi Arabia will increasingly adopt technologies that reduce production volatility, improve resource-use efficiency, and enhance resilience to climate challenges. Drones, edge-AI systems, genomic tools, and controlled-environment agriculture will become standard components of modern farms. Furthermore, global partnerships such as the collaboration between Saudi, Japanese, and Italian entities in our company will accelerate technology transfer and localization.

5. How can Saudi Arabia position itself as a global leader in agriculture innovation?

Saudi Arabia can strengthen its global position by continuing to invest in research, local manufacturing of agri-tech solutions, and international partnerships. Establishing regional excellence centers for AI-based agriculture, aquaculture engineering, and desert farming technologies will attract both talent and capital. By focusing on scalable innovation, pilot-to-deployment pipelines, and export-ready technologies, the Kingdom can become a reference point for sustainable agriculture in arid regions worldwide.

Selection Criteria Scorecard

	Technology	Segment	Technology Readiness Level	Spotlight Score
		TPG 1		
1	AI-Powered Predictive Irrigation	Automation, Control, & Optimization	8	59
2	Autonomous Irrigation Robots & Drones	Automation, Control, & Optimization	7	58
3	Digital Twin Irrigation Management Platforms	Automation, Control, & Optimization	7	51
4	Soil-Moisture Sensing	Sensing & Intelligence	9	46
5	Offgrid & Portable Desalination Units	Water Supply & Allocation	7	34
6	Super Absorbent Hydrogel Soil Amendments	On-Farm Delivery & Water Retention	7	32
7	GIS-Based Irrigation Mapping	Sensing & Intelligence	9	29
8	LPWAN (LoRaWAN) Smart Valve & Flow Meter Controllers	On-Farm Delivery & Water Retention	7	27
9	AI Enabled Leak Detection Analytics	Automation, Control, & Optimization	8	24
10	Inline Real Time Nitrate & Salinity Sensors	Sensing & Intelligence	7	23
11	Blockchain Enabled Water Rights Trading & Audit Platforms	Water Supply & Allocation	7	22
12	Satellite Imagery for Irrigation Monitoring	Sensing & Intelligence	7	21
13	Treated Sewage Effluent (TSE) Reuse Networks	Water Supply & Allocation	9	15
14	Agrivoltaic Drip Systems	On-Farm Delivery & Water Retention	8	14
15	Subsurface Drip Irrigation (SDI)	On-Farm Delivery & Water Retention	9	2
		TPG 2		
16	Genomic & CRISPR Enabled Breeding	Health, Genetics, & Feeds	6	60
17	AI driven Feeding & Biomass Monitoring	Precision Operations & Automation	8	53
18	Recirculating Aquaculture Systems (RAS) 2.0	Production System & Water Infrastructure	9	49

	Technology	Segment	Technology Readiness Level	Spotlight Score
19	Water Quality Sensor Networks	Precision Operations & Automation	8	37
20	Renewable-Energy-Powered RAS	Production System & Water Infrastructure	8	33
21	Nanobubble Oxygenation Systems	Production System & Water Infrastructure	7	32
22	Blockchain based Traceability Platforms	Circularity & Value Chain	7	29
23	Functional Probiotic & Postbiotic Feeds	Health, Genetics, & Feeds	8	29
24	Sludge Valorisation	Circularity & Value Chain	7	29
25	Autonomous Net Cleaning & Inspection Robots (ROV/AUV)	Precision Operations & Automation	8	27
26	Aquaculture Digital Twins	Precision Operations & Automation	7	24
27	Integrated Multi Trophic Aquaculture (IMTA)	Circularity & Value Chain	7	24
28	Biofloc Technology (BFT)	Production System & Water Infrastructure	8	21
29	Satellite & UAV Algae and Water Quality Monitoring	Precision Operations & Automation	7	19
30	AI based Health Diagnostics	Health, Genetics, & Feeds	7	2
		TPG 3		
31	AI Vision for Early Pest/Disease Alerts	Sensing, Automation, & Control	7	76
32	Blockchain traceability for CEA produce	Crop Performance & Assurance	8	60
33	On site CO_2 Capture & Enrichment	Crop Performance & Assurance	7	43
34	AI-based Climate Control	Sensing, Automation, & Control	8	38
35	Antimicrobial & IR Reflective Films	Crop Performance & Assurance	7	30
36	Industrial Waste Heat Integration	Climate & Energy Optimization	6	28
37	Electrochromic Smart Glass	Climate & Energy Optimization	7	24

Selection Criteria Scorecard

	Technology	Segment	Technology Readiness Level	Spotlight Score
38	Agrivoltaics for Greenhouses	Climate & Energy Optimization	8	24
39	PCM Thermal Batteries	Climate & Energy Optimization	7	21
40	Energy Recovery HVAC	Climate & Energy Optimization	8	20
41	Autonomous Greenhouse Robots	Sensing, Automation, & Control	7	13
42	Tunable Spectrum LED Lighting	Crop Performance & Assurance	9	12
43	Low Energy Aeroponics	Water & Nutrient Circularity	7	10
44	Closed Loop Fertigation	Water & Nutrient Circularity	8	9
45	AWG Greenhouse Systems	Water & Nutrient Circularity	6	8
	TPG 4			
46	Edible Bio Coatings	Smart Packaging & Product-Life Intelligence	8	83
47	Insect Bioconversion	Waste-to-Value & Chain-of-Custody	7	59
48	Bioplastics from Agro Waste	Waste-to-Value & Chain-of-Custody	7	54
49	Enzymatic Protein Hydrolysates	Waste-to-Value & Chain-of-Custody	8	53
50	Blockchain Traceability for Waste Minimization	Smart Packaging & Product-Life Intelligence	7	52
51	Active & Intelligent Nano Packaging	Smart Packaging & Product-Life Intelligence	7	50
52	Biochar from Plant Residues	Waste-to-Value & Chain-of-Custody	7	48
53	Cold Plasma Decontamination	Non-Thermal Preservation & Decontamination	7	42
54	Advanced Anaerobic Digestion	Waste-to-Value & Chain-of-Custody	8	39
55	Pulsed Electric Field (PEF) Preservation	Non-Thermal Preservation & Decontamination	8	39
56	Mycelium / Precision Fermentation Upcycling	Waste-to-Value & Chain-of-Custody	7	38

	Technology	Segment	Technology Readiness Level	Spotlight Score
57	IoT Enabled Cold Chain Monitoring	Cold-Chain & Atmosphere Control	8	35
58	Controlled Atmosphere Storage	Cold-Chain & Atmosphere Control	9	33
59	High Pressure Processing (HPP)	Non-Thermal Preservation & Decontamination	9	30
60	Solar Powered Modular Cold Rooms	Cold-Chain & Atmosphere Control	7	1
	TPG 5			
61	Edge AI Drones	UAV Platforms & Infrastructure	7	83
62	Next Gen SAR Satellites	Satellite Constellations & On-Orbit Analytics	7	41
63	High Revisit, Sub Meter CubeSat Imagery	Satellite Constellations & On-Orbit Analytics	8	39
64	Unified Drone & Sat Imagery SaaS Platforms	UAV Platforms & Infrastructure	8	36
65	Swarming Spray & Scout Drones	Field Operations & Actuation	7	36
66	Multispectral Sensor Kits	UAV Sensing Payloads & Modalities	8	34
67	Methane & GHG Tracking Satellites	Satellite Constellations & On-Orbit Analytics	7	33
68	On Orbit Edge Computing & ML	Satellite Constellations & On-Orbit Analytics	6	32
69	Thermal Imaging Drones	UAV Sensing Payloads & Modalities	8	26
70	Hyperspectral Imaging Satellite Constellations	Satellite Constellations & On-Orbit Analytics	8	26
71	UAV LiDAR	UAV Sensing Payloads & Modalities	8	20
72	Drone Based Aerial Seeding	Field Operations & Actuation	7	16
73	BVLOS Corridors	UAV Platforms & Infrastructure	7	16
74	Electrostatic Spray Drones	Field Operations & Actuation	7	15
75	“Drone in a Box” Docks	UAV Platforms & Infrastructure	7	11

Glossary

Maturity-Technical Readiness Level (TRL)

TRLs are used as a method of assessing the maturity of a technology being developed. It has a scale from 1-9 (from basic principles and research to actual proven systems and full commercial application)

TRL1	TRL2	TRL3	TRL4	TRL5	TRL6	TRL7	TRL8	TRL9
Basic Technology Research	Applied Research	Critical Function	Laboratory Testing of prototype component or process	Laboratory Testing of Integrated system	Prototype System Verified	Pilot System Demonstrated	Commercial Design	Full Commercial Deployment

Capability Readiness Level (CRL)

CRL is a scale that assesses the market readiness and economic viability of a technology, ranging from 1 to 9. It focuses on the business model, market validation, and the commercial need for the technology, ensuring that the solution meets market demands and has a viable business case. Unlike TRL, CRL is more subjective and requires detailed market analysis.

CRL1	CRL2	CRL3	CRL4	CRL5	CRL6	CRL7	CRL8	CRL9
Basic science capabilities and facilities are limited in KSA	• Small-scale basic science completed in KSA, by local and foreign personnel • Necessary lab equipment physically located in the KSA; with limited dependence on out sourcing	• Multiple KSA labs are fully capable of conducting appropriate basic science. • Research output from local labs widely published and cited in Int'l peer reviewed journals	Functional applied science applications of relevant tech completed at a small scale in either Saudi labs, or by tech-focused KSA companies (e.g., MNCs and National Champions)	• Functional tech. modules built in several Saudi labs and/or companies. • Findings widely published. • Large group of skilled Saudi scientists, engineers, and technologists enabled	• Saudi labs or companies have produced Minimum Viable Products (MVP) of fully functional tech components. • MVPs demonstrated in public forums and conferences	• In-country manufacturing capacity exists at scale. • If it is a Technology-based service, it can be deployed and provisioned nationwide	• In-country manufacturing capacity exists at cost levels comparable to similar systems. • Tech-based service, it can be deployed and provisioned worldwide	• In-country manufacturing capacity has produced scale quantities sold nationwide and internationally • Tech-based service deployed in multiple countries.

sources:

1. TRL – Definition is designed by NASA https://esto.nasa.gov/files/trl_definitions.pdf.There is detailed description for hardware and software https://www.nasa.gov/pdf/458490main_TRL_Definitions.pdf
2. CRL – Definitions are designed by RADIA National Mission Guidebook

Glossary

3.1 IRRIGATION & WATER MANAGEMENT

	Terminology	Description
1	AI-Powered Predictive Irrigation	Cloud edge platform that ingests real time weather, soil moisture and crop stage data, then uses machine learning models to predict plant water demand and trigger valves only when and where needed. Cuts water, energy and labor, raises yields, and generates audit trails for regulators and insurers. Supports desalination supply planning and compliance with policies.
2	Autonomous Irrigation Robots & Drones	GPS guided ground rovers and multi rotor drones carry sprayers, micro valve actuators or moisture sensors, traversing fields day or night without operators. Platforms combine machine vision and AI path planning to target micro zones, reduce compaction versus tractors and deliver precise water doses. Robotics tackles labor shortages, boosts smallholder productivity and safety significantly.
3	Digital Twin Irrigation Management Platforms	Virtual replicas of wells, canals, pumps and field networks ingest real time sensor data and historical hydrology to simulate flows, predict failures and optimize scheduling. Scenario testing identifies leakage hotspots, energy peaks and policy impacts before field execution. Digital twins accelerate permitting, reduce non revenue water and guide investment prioritization, capital allocation.
4	Soil-Moisture Sensing	Low cost wireless probes, such as those using graphene, TDR or capacitance, can be used to detect minute volumetric water content and electrical conductivity at multiple depths. Data transmit via LoRa or NB IoT into dashboards guiding irrigation schedules. Accurate, maintenance light hardware enables deficit irrigation, prevents salinity buildup and informs AI models for larger water accounting systems across farm networks.
5	Offgrid & Portable Desalination Units	Compact reverse osmosis or membrane distillation skids powered by photovoltaic panels and energy recovery devices produce 5–50 m³ per day of irrigation grade water from brackish wells or seawater. Units deploy rapidly to remote farms, emergency drought zones or mobile greenhouses, expanding cultivated area, supporting livestock, and reducing tanker trucking emissions and costs significantly.
6	Super Absorbent Hydrogel Soil Amendments	Cross linked polymer granules absorb hundreds of times their weight in water, slowly releasing moisture and dissolved nutrients to roots. Applied within planting rows, hydrogels reduce irrigation frequency, improve seedling survival, mitigate salinity peaks, and decrease fertilizer leaching. Biodegradable formulations developed from cellulose or chitosan minimize microplastic accumulation concerns in soils.
7	GIS-Based Irrigation Mapping	Geographic Information Systems combine land use, soil texture, topography, climate and infrastructure layers to delineate irrigated areas, calculate water demand and prioritize investment. High resolution spatial analysis guides canal rehabilitation, pump sizing and subsidy targeting. Open source datasets and cloud platforms democratize access, underpinning national dashboards and district level extension services decision-making.
8	LPWAN (LoRaWAN) Smart Valve & Flow Meter Controllers	Battery powered LoRaWAN nodes retrofit onto valves and flow meters, enabling remote on/off control, pulse metering and pressure regulation across vast fields. Long range communication and mesh networking minimize gateway costs. Automated shutdowns on leaks, theft alarms and integration with AI schedulers lower non revenue water and labour, boosting resilience and safety margins.
9	AI Enabled Leak Detection Analytics	Acoustic, pressure and flow sensors stream data into machine learning models that distinguish leak signaturesLPWA from normal transients in buried plastic (PE or PVC) pipelines. Algorithms rank leak probability, estimate loss volume and dispatch repair crews before surface breakouts. Saves water, energy and road damage, and integrates with digital twin dashboards for utilities.
10	Inline Real Time Nitrate & Salinity Sensors	UV LED spectroscopic, ion selective electrode, or MEMS microfluidic probes installed directly in irrigation lines measure nitrate, potassium, pH and electrical conductivity every minute. Data feed fertigation controllers, preventing over fertilization and root burn. Compact designs with auto calibration lower maintenance, enabling closed loop nutrient management and compliance with wastewater reuse regulations and export standards.

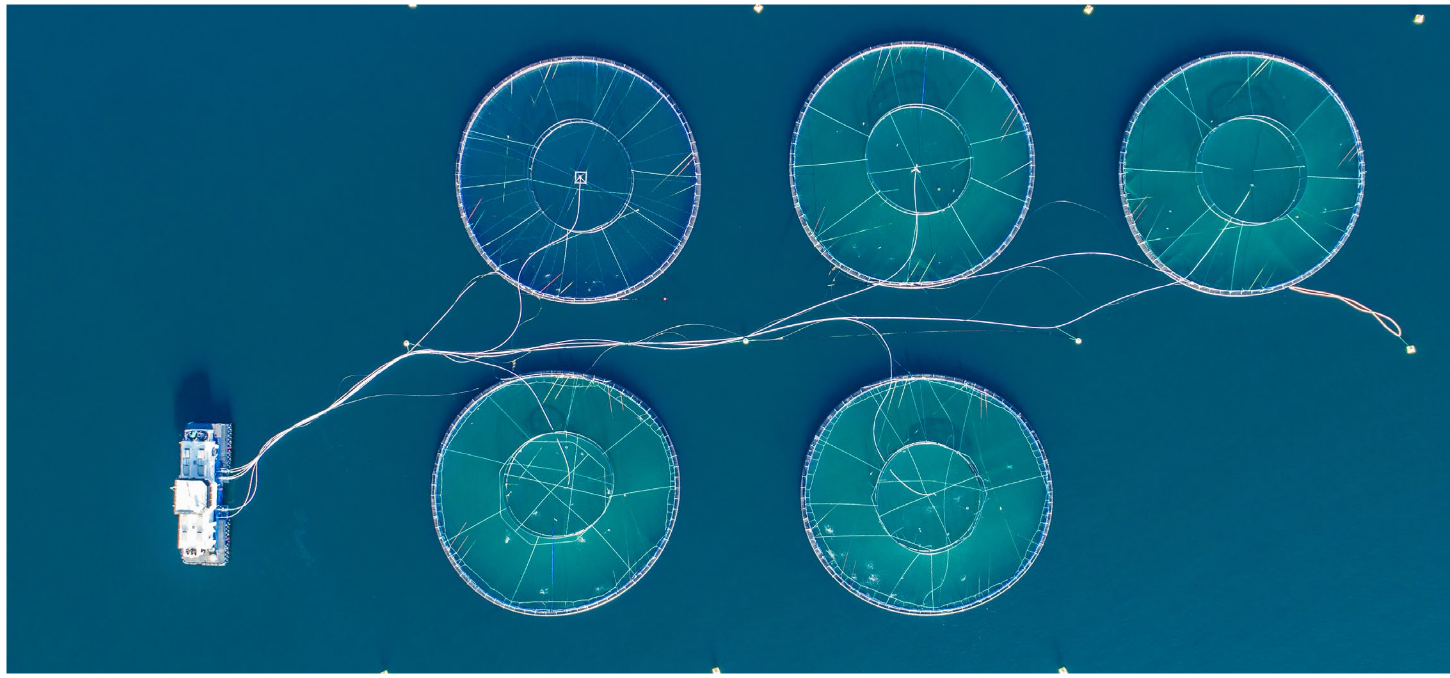
	Terminology	Description
11	Blockchain Enabled Water Rights Trading & Audit Platforms	Distributed ledger systems tokenize volumetric water allocations, record real time usage from smart meters and enable transparent peer to peer trading under evolving regulations. Immutable records deter over extraction, speed enforcement and unlock market signals that reward conservation. Integration with payment rails and digital identities reduces transaction friction for farmers and utilities across basins globally.
12	Satellite Imagery for Irrigation Monitoring	Multi spectral, hyperspectral and SAR satellite constellations deliver frequent, cloud penetrating images that estimate evapotranspiration, crop biomass and soil moisture across entire basins. Analytics detect over watering, illegal abstractions and drought stress, enabling regulators and farmers to allocate water dynamically, benchmark efficiency and support drought insurance, carbon credit programs, geospatial supply planning initiatives.
13	Treated Sewage Effluent (TSE) Reuse Networks	Purple pipe distribution grids convey tertiary treated sewage effluent, polished for salinity and pathogens, from urban plants to peri urban farms. Continuous online sensors verify quality; blending stations adjust EC and nutrient levels. Reuse cuts freshwater demand, provides nutrient rich water, reduces marine discharge, underpins circular economy targets in Saudi cities, improving resource management.
14	Agrivoltaic Drip Systems	Co locating elevated photovoltaic panels with buried drip irrigation delivers shade modulated microclimates, reducing evapotranspiration up to 50 % while generating solar power for pumps. Panel rows accommodate machinery, and smart controllers adjust flow based on real time irradiation and soil sensors. Agrivoltaics increases land productivity, diversifies farm income and cuts emissions significantly.
15	Subsurface Drip Irrigation (SDI)	Buried drip lines with pressure compensating emitters deliver water directly to root zones, halving evaporation and reducing weed pressure. Suitable for rowing crops and orchards on saline, windy or sloped fields, SDI increases yield, permits fertigation and lowers labour. Proven technology now benefits from cheaper plastic, automated flushing and Saudi subsidies.

Glossary

3.2 INTEGRATED AQUACULTURE FARM MANAGEMENT

	Terminology	Description
1	Genomic & CRISPR Enabled Breeding	Genome editing tools like CRISPR Cas9 introduce targeted mutations that confer resistance to sea lice or viral diseases, speed growth or improve fillet quality without transgenic DNA insertion. Precision broodstock programs shorten breeding cycles, reduce chemical treatments and feed usage, while rigorous containment and regulatory frameworks aim to address biosafety concerns. and acceptance.
2	AI driven Feeding & Biomass Monitoring	Machine vision cameras and acoustic sensors integrate with machine learning algorithms to count fish in real time, estimate biomass and automatically dose feed pellets or liquid feed. The platforms cut over and under feeding, improve growth rates, minimize feed waste and reduce nutrient pollution, while providing dashboard analytics for farmers and insurers accurately.
3	Recirculating Aquaculture Systems (RAS) 2.0	Second generation recirculating aquaculture systems combine high rate biofiltration, denitrification, micro screening, heat recovery heat pumps and AI process control to reuse more than 95 % of water. Energy optimized pumps and variable frequency blowers cut power demand, while closed loop wastewater valorization captures nutrients. On land facilities enable biosecure, high density production near markets year round. with reduced operating footprint.
4	Water Quality Sensor Networks	Low cost electrochemical, optical and graphene based probes measure dissolved oxygen, pH, ammonia, nitrite, salinity and temperature every minute, pushing data via LoRaWAN or 5G (sensors) to edge gateways that run anomaly detection models. Operators receive instant alerts and automated aeration or dosing commands, shrinking mortalities, energy use and labour requirements, lowering operational costs.
5	Renewable Energy	Compact reverse osmosis or membrane distillation skids powered by photovoltaic panels and energy recovery devices produce 5–50 m^3 per day of irrigation grade water from brackish wells or seawater. Units deploy rapidly to remote farms, emergency drought zones or mobile greenhouses, expanding cultivated area, supporting livestock, and reducing tanker trucking emissions and costs significantly.
6	Powered RAS	Floating or onshore recirculating farms integrate roof mounted photovoltaics, wave or wind turbines, battery storage and heat pump recovery loops, supplying low carbon power and thermal energy to filtration, lighting and HVAC. Coupling energy demand forecasting with smart inverters slashes grid dependence, lowers operating costs and helps facilities meet net zero targets. and regulations.
7	Blockchain based Traceability Platforms	Distributed ledger platforms assign tamper proof digital identities to every batch of eggs, smolt, feed and harvested fillets, recording temperature, treatments and custody transfers through QR codes or NFC tags. Immutable datasets underpin compliance with import regulations, enable rapid recalls, reward sustainable producers and give consumers verifiable provenance from hatchery to plate.
8	Functional Probiotic & Postbiotic Feeds	Feeds augmented with carefully selected probiotic strains or heat treated postbiotic metabolites improve gut microflora balance, immunity and nutrient absorption in shrimp and finfish. Formulas reduce reliance on antibiotics, enhance feed conversion ratios and survival, while yeast or lactobacillus derived bioactives confer resilience against stress, boosting harvest yields sustainably. and product quality.
9	Sludge Valorisation	High solids anaerobic digesters, hydrothermal liquefaction and algae co cultivation convert nutrient rich RAS sludge and mortalities into biogas, organic fertilizer or single cell protein. Integrated waste heat recovery and catalytic additives raise methane yield, cut disposal fees, close nutrient loops and create additional revenue streams, moving facilities toward circular, zero discharge operations. and regulatory compliance goals.
10	Autonomous Net Cleaning & Inspection Robots (ROV/AUV)	Submersible robotic vehicles equipped with rotary brushes, cavitation nozzles and AI vision autonomously patrol salmon cages, removing biofouling while simultaneously inspecting net integrity. Continuous, low-pressure cleaning reduces parasite habitat, maintains water flow, prevents escapes, and eliminates diesel vessel visits, cutting labour, fuel, and copper antifoulant usage significantly while boosting fish welfare.

	Terminology	Description
11	Aquaculture Digital Twins	Digital twin platforms create physics-based or data-driven virtual replicas of cages, tanks and surrounding waters, ingesting sensor, weather, and feeding data to forecast oxygen dynamics, biomass growth, structural loads, and disease risk. Managers can simulate 'what if' scenarios, optimize set points remotely, and integrate autonomous vehicles for inspection, reducing downtime and losses.
12	Integrated Multi Trophic Aquaculture (IMTA)	Integrated multi trophic aquaculture co cultivates fed species like finfish with extractive organisms such as seaweed, mussels or sea cucumbers that absorb dissolved nutrients and particulate waste. Properly balanced trophic ratios boost revenue diversification, improve water quality, increase overall biomass per site, and reduce environmental footprints, supporting ecosystem based farm certification and resilience.
13	Biofloc Technology (BFT)	Biofloc systems stimulate heterotrophic bacterial growth by maintaining high C:N ratios, converting toxic ammonia into microbial protein that shrimp or tilapia consume directly. Aerated tanks or lined ponds operate at high stocking densities, cut water exchange by 90 percent, recycle nutrients, lower feed conversion ratios, and diminish disease outbreaks significantly
14	Satellite & UAV Algae and Water Quality Monitoring	Combining high resolution multispectral satellites with AI enabled drones delivers near real time maps of chlorophyll, turbidity and surface temperature, predicting harmful algal blooms days in advance. Integrated dashboards issue early warning alerts, allowing farm managers to adjust feeding, harvest early, or deploy mitigation measures, safeguarding stock health and limiting economic losses for coastal farms.
15	AI based Health Diagnostics	Underwater stereo cameras capture high definition images of fish skin, eyes and behaviour; convolutional neural networks detect lesions, sea lice, deformities and stress indicators long before manual sampling. Continuous, non intrusive screening guides targeted treatments, optimizes welfare scores, reduces antibiotic use, and provides insurers and regulators with objective health records in real time.



Glossary

3.3 PROTECTED AGRICULTURE & CONTROLLED ENVIRONMENT (CEA)

	Terminology	Description
1	AI Vision for Early Pest/Disease Alerts	Fixed or drone mounted multispectral cameras stream images into convolutional neural networks trained on annotated leaf datasets. The system flags mildew, mites or nutrient stress three days before human scouts, generating geotagged heatmaps and treatment prescriptions. Early intervention reduces pesticide volumes, crop losses and labor-intensive manual scouting passes, saving operational costs.
2	Blockchain traceability for CEA produce	Distributed ledger platforms log every greenhouse batch from seed acquisition to harvest, linking sensor data, pesticide applications and cold chain conditions into tamper proof records. Smart contracts automate certification, carbon accounting and recall alerts, enhancing consumer trust, export market access and price premiums while streamlining audits for safety and sustainability frameworks in retail.
3	On site CO_2 Capture & Enrichment	Modular direct air capture or flue gas scrubber units harvest concentrated CO_2 streams, filter contaminants and inject measured doses into greenhouse atmospheres, accelerating photosynthesis up to thirty percent. Waste heat from regeneration integrates with existing boilers, improving energy balance and replacing trucked CO_2 deliveries, reducing carbon footprint and supply vulnerability in remote locations.
4	AI-based Climate Control	Edge-connected sensors, physics models and machine learning algorithms combine in a greenhouse "brain" that continually optimizes lighting, ventilation, humidity, CO_2 and fertigation. The software forecasts crop growth, weather and energy price movements, then adjusts set points minute by minute, cutting kilowatt hours, water and labor while lifting yield consistency and biosecurity margins, reducing operational cost.
5	Antimicrobial & IR Reflective Films	Polyethylene or EVA greenhouse films embedded with zinc oxide, silver or titanium nanoparticles reflect excess near infrared radiation while releasing antimicrobial ions that suppress fungal pathogens. The dual functionality lowers canopy temperatures by up to four degrees Celsius, improves light diffusion, boosts yield and extends film lifetime, reducing plastic replacement frequency significantly.
6	Industrial Waste Heat Integration	High temperature coolant streams from data centres, anaerobic digesters or power plants are piped through plate heat exchangers, delivering low cost thermal energy for greenhouse heating and CO_2 recovery. Smart valves and thermal storage smooth intermittency, cutting fossil fuel consumption, emissions and operating expense while valorizing otherwise wasted energy in cold nights.
7	Electrochromic Smart Glass	Electrochromic glazing dynamically modulates light transmission and infrared rejection via low voltage ion migration between transparent oxide layers. Automated controls tint panes within minutes based on solar intensity and crop growth stage, reducing peak cooling loads fifteen percent, mitigating photo stress and enabling precision daylight management without traditional shade curtains or screens.
8	Agrivoltaics for Greenhouses	Semi transparent perovskite or organic photovoltaic coatings replace inert glass, harvesting surplus infrared and ultraviolet radiation while letting photosynthetically active light through. Integrated power electronics feed LED lighting and cooling loads, creating net positive energy greenhouses that buffer heat peaks, monetize electricity export, and cut carbon intensity without land use conflict in arid climates.
9	PCM Thermal Batteries	Phase change material tanks absorb latent heat during daylight peaks, melting paraffin or salt hydrates, then solidify overnight to release stored energy through heat exchangers. Coupled with low grade heat sources, they stabilize greenhouse temperatures, cut fossil backup hours and integrate seamlessly with cogeneration, solar or waste heat recovery loops for climate resilience.
10	Energy Recovery HVAC	Integrated heat pump chillers use natural refrigerants such as CO_2 or ammonia and variable speed compressors to capture waste heat from lighting and dehumidification, then recycle it for water pre heating or space heating. Model predictive control harmonizes loads, achieving twenty to forty percent energy savings and lowering greenhouse gas emissions and operating expenditures significantly.

	Terminology	Description
11	Autonomous Greenhouse Robots	Camera guided, battery electric robots patrol protected crop rows executing harvesting, pollination, pruning and health scouting with millimetre precision. On board AI vision grades fruit, shares digital twins and enables predictive labour scheduling. Modular end effectors swap within minutes, turning a single robot fleet into flexible capacity that buffers labour shortages and improves worker safety.
12	Tunable Spectrum LED Lighting	Solid state fixtures using quantum dot or phosphor tuning shift photon spectra on demand to match each crop's photosynthetic peaks and circadian cues. Dynamic recipes steer morphology, flavonoid content, and flowering while trimming energy per kilogram harvested. Lifespans reach 50,000 hours and remote firmware pushes automate spectral updates with minimal maintenance downtime.
13	Low Energy Aeroponics	Plants are suspended in misting chambers where ultra fine nutrient droplets contact roots directly, maximising oxygen exposure and trimming water use by ninety five percent versus hydroponics. High frequency ultrasonic nozzles and heat recovery fans slash pumping losses, enabling low capex modular towers that double productivity per square metre and simplify bio security protocols in deserts.
14	Closed Loop Fertigation	Real time ion selective sensors measure nitrate, potassium and pH within recirculating nutrient solutions, feeding PID or AI controllers that adjust stock tank dosing pumps automatically. Closed loop logic maintains optimal electrical conductivity, slashing fertilizer use fifteen percent and eliminating disposal effluent. Cloud dashboards provide compliance traceability and proactive maintenance alerts for sustainable compliance.
15	AWG Greenhouse Systems	Atmospheric water generators condense moisture from ambient air using desiccant wheels or vapor compression, supplying pure irrigation water inside closed greenhouses. Coupled with solar thermal seawater greenhouse designs, they leverage evaporative cooling and saline evaporation ponds, enabling year round production in ultra-arid regions without groundwater abstraction or external municipal supplies supporting remote communities.

Glossary

3.4 FOOD PRESERVATION & WASTE VALORIZATION

	Terminology	Description
1	Edible Bio Coatings	Spray on coatings made from chitosan, alginate, nanocellulose or plant proteins form breathable barriers that slow respiration and block pathogens. Natural essential oils or probiotics can be incorporated for extra antimicrobial effect. Coatings are halal compliant, leave no plastic waste, add minimal cost and already lengthen citrus and tomato storage.
2	Insect Bioconversion	Insects, most prominently the black soldier fly larvae (BSF), convert mixed food and agricultural waste into growth promoting insect protein meal and frass fertilizer within fourteen days. Modular vertical racks require little land or water, arrest methane emissions, and supply domestic aquafeed, reducing soybean imports and contributing to sustainable circular economy job creation.
3	Bioplastics from Agro Waste	Processes convert lignocellulosic fibres and hemicellulose from date palm fronds, wheat straw or poultry litter into polylactic acid, PHAs or fibre reinforced composites. Recent catalysts lower reaction temperatures and eliminate toxic acids, reducing carbon footprint. Saudi made compostable packaging could meet export regulations and capture regional sustainable materials markets.
4	Enzymatic Protein Hydrolysates	Continuous reactors with immobilized proteases cleave fish, poultry or dairy by products into digestible peptides valuable for sports nutrition, functional beverages, animal feed and cosmetics. Membrane filtration tailors molecular weight fractions; process water is largely recycled. Technology monetizes slaughterhouse waste while improving amino acid bioavailability and sustainability credentials.
5	Blockchain Traceability for Waste Minimization	Distributed ledger systems record each harvest, processing, storage, and transport event, linking IoT sensor data and smart contracts. Immutable records speed recalls, enable dynamic pricing based on shelf life, incentivize waste reduction, and provide transparent halal and carbon credentials demanded by export markets, investors, and increasingly discerning domestic consumers.
6	Active & Intelligent Nano Packaging	Films embed oxygen or ethylene scavengers, antimicrobial nanoparticles or moisture modulators, actively extending shelf life. Printed freshness sensors, RFID or colourimetric dots provide real time spoilage data for logistics dashboards and blockchain ledgers. Commercial roll stock integrates seamlessly with existing flow wrap lines, protecting tomatoes, poultry and ready-to-eat products.
7	Biochar from Plant Residues	Pyrolysing date palm fronds or other biomass at 400–600 °C produces porous biochar that locks carbon for centuries and boosts sandy soil fertility and water retention. Syngas heat powers the kiln, and generated carbon credits enhance profitability. Field trials report higher crop yields and reduced irrigation demand in arid regions.
8	Cold Plasma Decontamination	Cold atmospheric plasma devices generate reactive oxygen and nitrogen species that kill surface bacteria, yeasts and moulds on produce, packaging and equipment at room temperature. Inline conveyor tunnels or handheld wands treat tonnes hourly without chemicals, saving rinse water and enabling safer berries, dates, and leafy greens exports.
9	Advanced Anaerobic Digestion	Enhanced anaerobic digesters deploy immobilized sludge, micronutrient dosing and nanoparticle catalysts to boost methane yields from municipal, agricultural and slaughterhouse residues. Integrated membrane upgrading produces biomethane vehicle fuel, while nutrient rich digestate is refined into biofertilizer, turning liabilities into multi revenue streams aligned with Saudi carbon neutral ambitions.
10	Pulsed Electric Field (PEF) Preservation	Pulsed Electric Field treatment passes micro second, high voltage pulses through pumpable liquids, electroporating microbial membranes at sub pasteurization temperatures. Energy and water demands fall sharply, nutrient retention rises, and flavour remains fresh. Pilot lines for juices, dairy and liquid eggs show rapid payback in GCC, cutting cold chain spoilage.
11	Mycelium / Precision Fermentation Upcycling	Filamentous fungi or engineered microbes ferment whey, date molasses or spent grains into mycoprotein, enzymes, flavour molecules or dairy identical proteins. Stainless steel bioreactors deliver high space time yields, require little land or water, and enable new local protein industries while valorising by-products that currently burden waste streams.
12	IoT Enabled Cold Chain Monitoring	Battery-powered sensors, such as those using GSM, LoRa, or Bluetooth, capture temperature, humidity, light, and shock inside trucks, containers, and retail fridges. Cloud analytics can flag excursions, drive route optimization, predict compressor failures and document compliance for exports. Integration with blockchain smart contracts can enable automated insurance or shelf life extension payments.
13	Controlled Atmosphere Storage	Sealed rooms or containers precisely control oxygen, carbon dioxide, humidity and temperature, often with ethylene absorbers, to slow ripening and microbial growth. New sensor automated units suit dates, mangoes and tomatoes, enabling weeks long sea transport or strategic food reserves while cutting refrigeration energy through dynamic atmosphere optimization.
14	High Pressure Processing (HPP)	High Pressure Processing subjects sealed foods to up to 600 MPa, destroying pathogens without heat. Shelf life doubles while colors, vitamins, and flavours stay fresh, ideal for premium juices, ready meals and halal meat. Modular skids fit SME plants, and energy per kilogram beats thermal retorting in hot conditions.
15	Solar Powered Modular Cold Rooms	Modular cold storage units powered by solar energy, designed to provide off-grid refrigeration for perishables and vaccines. These systems often use insulated structures, thermal storage, and hybrid compressors, and can be deployed in rural areas to reduce post-harvest losses and support sustainable development.

Glossary

3.5 UNMANNED AERIAL VEHICLES & SATELLITE IMAGERY

	Terminology	Description
1	Edge AI Drones	Multirotor drones equipped with onboard GPUs run convolutional neural networks in real time, classifying crops, weeds and anomalies without sending raw imagery to the cloud. This edge processing cuts latency, bandwidth and privacy risk, enabling fully autonomous scouting missions that finish detection and prescription in a single rapid daily flight.
2	Next Gen SAR Satellites	Next generation synthetic aperture radar missions such as NISAR provide cloud penetrating, day night images of surface roughness and moisture at ten metre resolution. Interferometric stacks reveal soil moisture and biomass changes, supporting irrigation scheduling, flood warning and accurate carbon stock monitoring even during dust storms that block optical sensors.
3	High Revisit, Sub Meter CubeSat Imagery	Low Earth orbit CubeSat networks deliver meter class images every few minutes, giving farms near real time views of field operations, pest outbreaks and security issues. High revisit rates and taskable point and shoot cameras support monitoring of variable rate applications and enforcement of groundwater withdrawal or land use regulations.
4	Unified Drone & Sat Imagery SaaS Platforms	Software as a service portals ingest both UAV and satellite data, harmonize resolutions, and apply analytics ranging from evapotranspiration to yield prediction. Single dashboards lower the skill barrier for farmers and regulators, providing tasking, processing, and reporting tools within one subscription. APIs enable insurance, fintech, agronomy apps, and marketplace integration.
5	Swarming Spray & Scout Drones	Coordinated fleets of autonomous drones communicate via mesh networks to divide fields, simultaneously mapping vegetation and applying variable rate sprays. Cloud software orchestrates tasks seamlessly. Swarming raises treated hectares per hour, lowers labour costs and enables night operations, while precise electrostatic nozzles reduce chemical use and drift into surrounding ecosystems.
6	Multispectral Sensor Kits	Low-cost modular sensors that capture data across blue, green, red, and near-infrared spectral bands to assess crop health. These sensors can be mounted on small unmanned aerial vehicles (UAVs) to generate vegetation indices such as the Normalized Difference Vegetation Index (NDVI) and the Normalized Difference Red Edge (NDRE). Open-source image processing pipelines enable the production of chlorophyll and vegetation health maps, providing affordable tools for crop monitoring in regions where access to high-resolution satellite data or commercial UAV systems is limited.
7	Methane & GHG Tracking Satellites	Miniaturized spectrometers aboard dedicated satellites measure short-wave infrared absorption to locate and quantify methane plumes from livestock, landfills and oil infrastructure down to tens of kilograms per hour. Continuous monitoring underpins emissions reduction verification and climate smart agriculture programmes. Data integrates with national inventories, carbon markets and regulatory enforcement.
8	On Orbit Edge Computing & ML	Edge computing platforms embedded aboard satellites run machine learning models directly on captured imagery, extracting features such as waterlogging, crop type or illegal burning. Only compressed insights are downlinked, slashing bandwidth costs and latency, enabling quasi real time alerting to ground users. Concept proves value for disaster response and agriculture.
9	Thermal Imaging Drones	Drones with radiometric infrared cameras detect canopy temperature differences indicating water stress, blocked emitters or disease several days before visual symptoms. Automated flights provide rapid irrigation uniformity audits and targeted cooling interventions for greenhouses and orchards in hot climates. Algorithmic thresholds translate thermal maps into clear, actionable farmer alerts reports.
10	Hyperspectral Imaging Satellite Constellations	Constellations of small satellites carrying hyperspectral cameras capture hundreds of narrow spectral bands, enabling daily maps of crop nutrients, soil chemistry, disease stress and contaminant plumes. AI analytics convert the calibrated reflectance data into actionable layers for irrigation, fertilizer and environmental compliance decisions across millions of hectares including arid zones.
11	UAV LiDAR	Unmanned aerial vehicles carrying lightweight LiDAR scanners collect dense 3 D point clouds that quantify crop canopy height, orchard volume and rangeland biomass at centimetre accuracy. The data feed yield models, carbon accounting and erosion risk assessments, complementing passive optical imagery. Recent miniaturisation slashes payload weight and battery drain significantly.
12	Drone Based Aerial Seeding	Heavy lift multirotors dispense seed pellets, beneficial insects or biocontrol agents with centimetre GPS accuracy. The method accelerates rangeland restoration, cover cropping and precision pasture renewal, reducing labour and enabling seeding in terrain inaccessible to tractors. Variable rate algorithms optimize seed density, improving germination, outcomes and carbon credit project economics.
13	BVLOS Corridors	Beyond visual line of sight flight corridors combine regulatory approvals, ground based detect and avoid radars and 5G command links to let agricultural UAVs cover tens of kilometres autonomously. Corridor infrastructure unlocks large area mapping, spraying and cargo runs that are impossible under traditional visual line of sight safety restrictions.
14	Electrostatic Spray Drones	Spray drones fitted with electrostatic charge systems impart opposite charges to pesticide droplets, causing them to wrap around leaves and stems. The technology achieves up to 90 percent drift reduction and significant active ingredient savings compared with conventional boom sprayers or manned crop dusters. Laboratory tests confirm improved canopy penetration.
15	"Drone in a Box" Docks	Weatherproof charging and data offload stations allow drones to launch, land, exchange batteries and upload mission data autonomously. Permanent rooftop or field installations enable 24/7 monitoring, security patrols and scheduled agronomic flights with minimal human intervention. Standardized APIs integrate docks with farm software, compliance auditors and emergency response networks.

Glossary

Definitions

	Term	Description
1	IUNU	IUNU is a Seattle-based agricultural technology company founded in 2013. The company specializes in precision agriculture solutions for greenhouse operations, focusing on vine crops such as tomatoes, cucumbers, and peppers
2	LUNA	LUNA AI is an advanced agricultural technology platform developed by IUNU, a Seattle-based company specializing in AI and machine vision solutions for greenhouse operations. The platform is designed to enhance the efficiency, sustainability, and profitability of controlled environment agriculture (CEA) by providing real-time, plant-level insights
3	YOLOv10n	YOLOv10n is the most lightweight variant in the YOLOv10 family, designed for edge devices and latency-sensitive real-time applications. It significantly reduces parameter count and computational cost while maintaining competitive detection accuracy. Incorporating an anchor-free detection approach and an efficient feature extraction backbone, YOLOv10n offers superior speed and deployment flexibility, making it ideal for mobile platforms, drones, and security systems
4	F1-scores	is the harmonic mean of precision and recall, providing a single metric to evaluate a model's accuracy, especially when dealing with imbalanced datasets.
5	TensorRT	TensorRT is NVIDIA's high-performance deep learning inference optimizer and runtime library

Abbreviation

	Abbreviation	Terms and description
1	M&A	Mergers and Acquisitions
2	IPOs	Initial Public Offering
3	EWA	Environment, water and Agriculture sectors
4	AI	Artificial Intelligence
5	ML	Machine Learning
6	IoT	Internet of things
7	RDI	Research, development, and innovation
8	MEWA	Ministry of Environment, water and Agriculture
9	ET	Evapotranspiration
10	FAO-SIO	Food and Agriculture Organization and Saudi Irrigation Organization
11	SDAIA	Saudi Data and Artificial Intelligence Authority
12	ASABE	American Society of Agricultural and Biological Engineers.
13	RL	Reinforcement Learning
14	CAGR	Compound annual growth rate
15	OEM	Original Equipment Manufacturer
16	TSE	Treated Sewage Effluent
17	NCM-grade	National Center for Meteorology
18	ha	Hectare
19	EC	Electrical Conductivity
20	ROI	Return on investment
21	PAIL	Precision Agriculture Irrigation Language: A data standard developed by AgGateway to ensure interoperability between irrigation equipment, sensors, and control systems.
22	FMIS	Farm Management Information System: A digital platform integrating farm data (weather, soil, irrigation, inputs, etc.) to support decision-making and automation

Glossary

Abbreviation

	Abbreviation	Terms and description
23	cross-OEM	Cross-OEM indicates interoperability between machinery, parts, or digital systems produced by different equipment manufacturers, allowing them to work together seamlessly
24	SOPs	Standard Operating Procedures
25	R-squared	R-squared is a coefficient of determination that indicates how well data points fit a statistical model (typically a regression model). Its value ranges from 0 to 1, where a higher value means the model explains a greater proportion of the variance in the observed data
26	NAQUA	National Aquaculture Group
27	JPY	Japanese Yen
28	IgM+	Immunoglobulin M positive
29	BMC	BioMed Central
30	SNP	Single Nucleotide Polymorphism
31	dnd	Dead and gene, A gene that plays a crucial role in germ cell (reproductive cell) development. Knocking out the dnd gene in fish results in sterility, which is useful for biosafety and controlling gene flow in aquaculture.
32	LD	Linkage Disequilibrium
33	GCC	Gulf Cooperation Council
34	GSO	Gulf Standards Organization
35	PE7	Bacillus subtilis
36	O	an abbreviation for the genus Oreochromis in the scientific name Oreochromis spilurus saudi.
37	SAS	Statistical Analysis System
38	HDPE	High-Density Polyethylene
39	IPM	Integrated Pest Management
40	EU	European Union
41	PDPL	Personal Data Protection Law
42	RGB	A common color model used in digital imaging and sensing. In this context, RGB refers to standard imaging channels that, when fused with multispectral or hyperspectral sensing, enhance stress detection in crops.
43	SUR	Sustainable Use Regulation
44	Ag	Agriculture
45	EFSA	European Food Safety Authority
46	QA/Labeling	Quality Assurance and Labeling
47	SFDA	Saudi Food & Drug Authority

	Abbreviation	Terms and description
48	QA	Quality Assurance
49	FDA	Food and Drug Administration
50	GRN	Generally Recognized as Safe Notice (FDA designation number for GRAS submissions) For example, “GRN 997” refers to the official record evaluating mushroom-derived chitosan as safe for food applications.
51	GPU	Graphics Processing Unit
52	low-SWaP	Low Size, Weight, and Power
53	GPS	Global Positioning System
54	FAA	Federal Aviation Administration
55	X10D	A product naming convention used by Skydio for its AI-powered drone system update. Here, it indicates the 2025 upgrade iteration with advanced autonomy and ISR improvements.
56	Asimov	Isaac Asimov’s “Three Laws of Robotics
57	ISR	Intelligence, Surveillance, and Reconnaissance
58	NX	A compact AI computing module designed by NVIDIA. It delivers up to 157 trillion operations per second (TOPS) for edge AI applications, enabling advanced perception and autonomy in small UAVs (unmanned aerial vehicles).
59	GACAR	General Authority of Civil Aviation Regulations
60	SoC	System on Chip: An integrated circuit that consolidates CPU, GPU, memory, and other essential components onto a single chip.
61	BVLOS	Beyond Visual Line of Sight: Refers to drone operations conducted outside the direct visual range of the operator. Critical for scaling autonomous UAV applications such as agriculture, surveying, and infrastructure inspections.
62	SOE	State-Owned Enterprise
63	LCGPA	Local Content and Government Procurement Authority
64	EASA	European Union Aviation Safety Agency
65	ATC	Air Traffic Control
66	CEMSE	Computer, Electrical and Mathematical Sciences and Engineering division at KAUST
67	AERO	Autonomous Edge Remote Observation
68	AGX	NVIDIA Jetson AGX, a series of high-performance AI computing modules designed for edge devices, robotics, and autonomous systems
69	DeepSORT	Deep Learning-based Simple Online and Realtime Tracking
70	RAG AI	Retrieval-Augmented Generation [RAG] AI technique combining search and AI responses

Report Participants

Dr. Bander bin Mohammed Alsaghan

Head of the General Administration of Agricultural Extension

Dr. Alaa Samy Megahed

Expert of Digital Agriculture Extension Services

Dr. Haythum Mohammed Salem

Expert of Irrigation Water Management

Dr. Karim Fikry Hammad

Expert of Soil Management

Dr. Mohamed Mohamed Toutou

Expert of Fish and Algae Aquaculture

Dr. Zakaria Fouad Fawzy

Expert of Plant Production “Protected Agriculture, Vegetable Crops, and Climate-Smart Agriculture

Dr. Amr Abdelkhalek Ahmed

Expert of Plant Production (Fruits)

Dr.Walid mohammed shehata

Expert of Agricultural Processing Industries

Dr. Wael Mahmoud Marzouk

Expert of beekeeping and honeybee rearing

Dr. Saher Jumah Albakeer

Expert of Fruit Trees

Dr. Radwan Mohammed Yakti

Expert of Plant Protection and biological control

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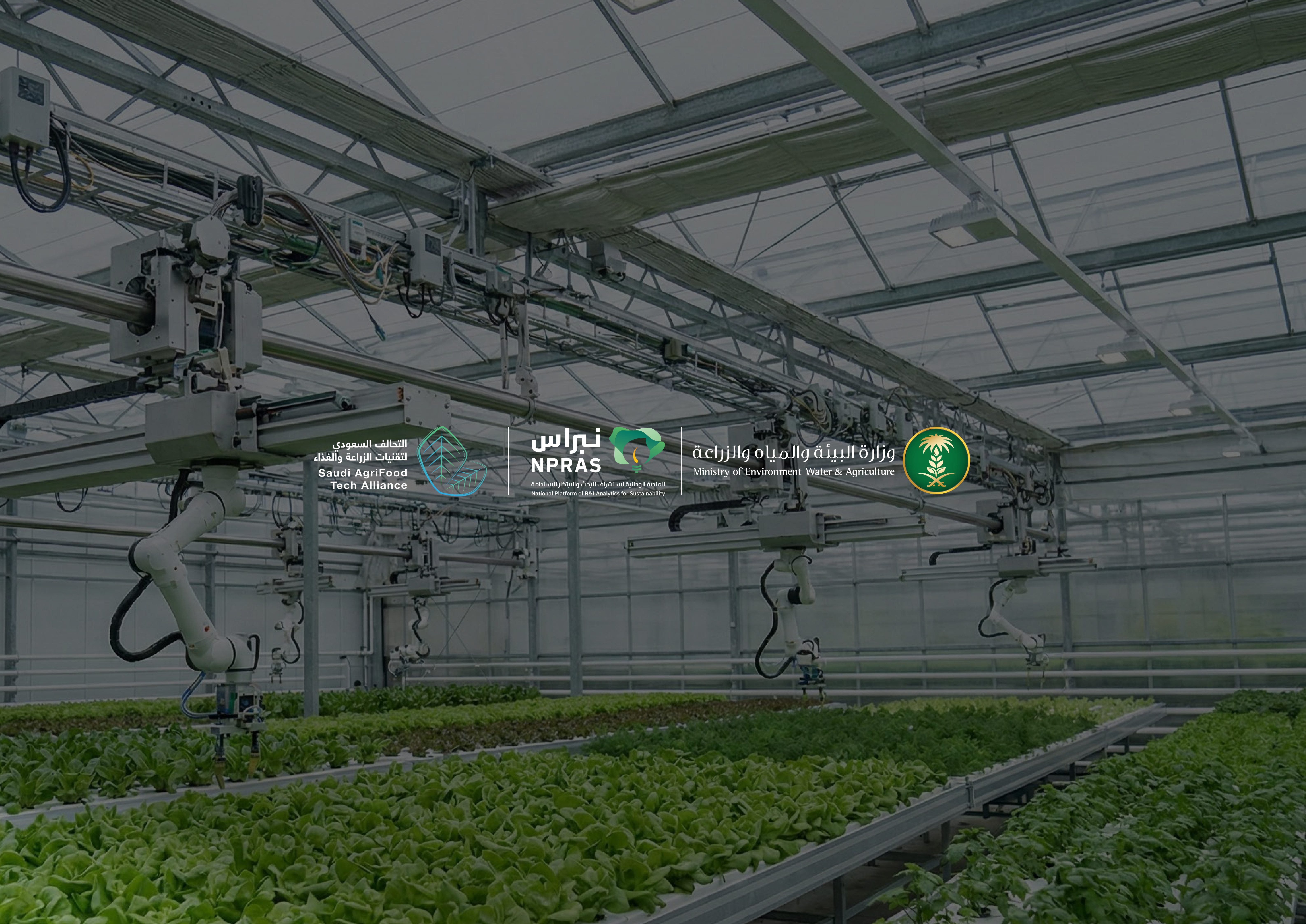

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