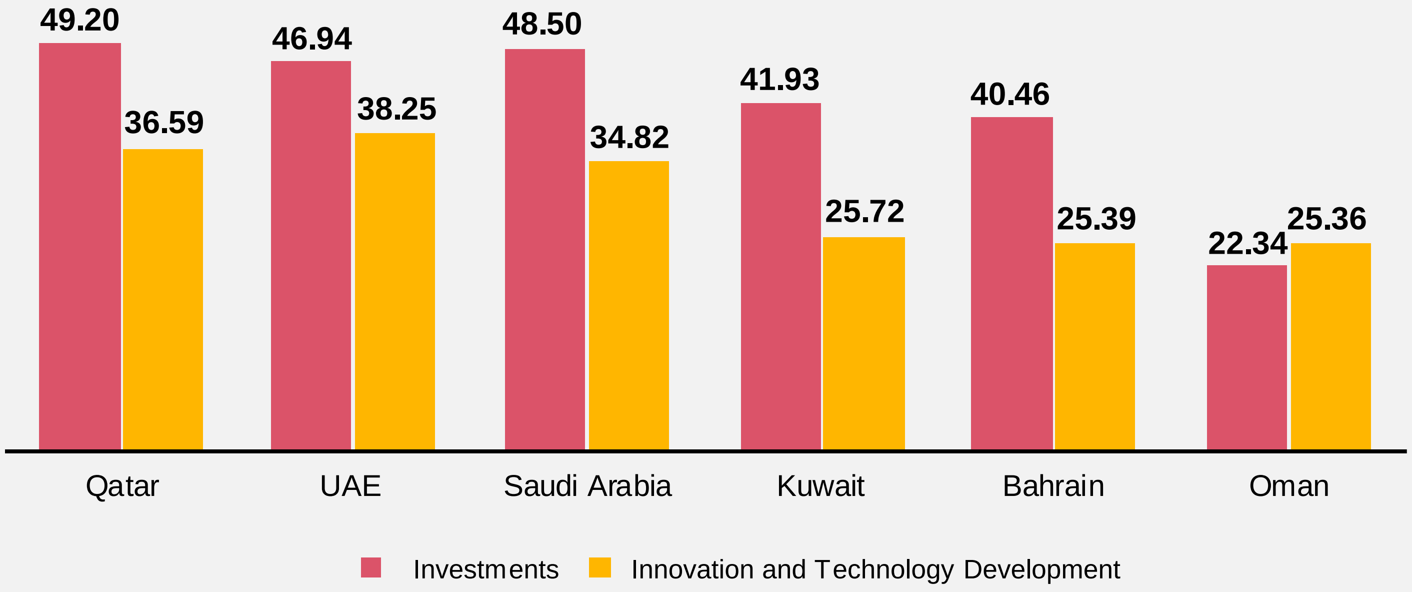
Accelerating autonomous sustainability monitoring through satellite data in Saudi Arabia

December 2024

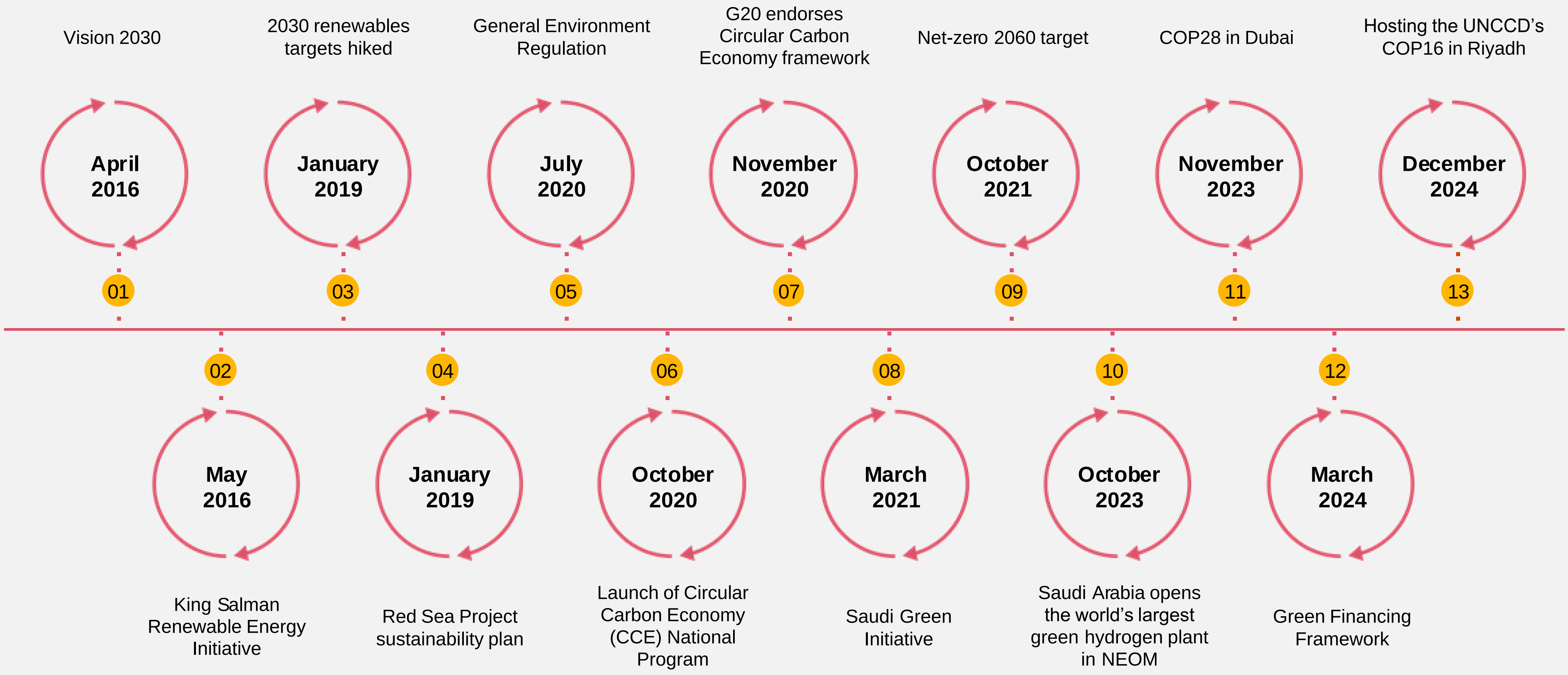
01 Sustainability in the Middle East

Sustainability has emerged as a key objective for numerous nations striving to balance social welfare, environmental preservation and economic growth. As nations embed sustainability targets into their strategic plans, the emphasis on building robust and dynamic economies becomes clear. Qatar, the UAE and Saudi Arabia are at the forefront of green investment and technological advancement in the Middle East, showcasing a steadfast commitment to sustainable development. These nations have fostered a conducive environment for green growth through substantial financial investments in clean energy projects, innovative advancements in green technology and regulations that promote further investment.



Source: MEAESS, 2023

Within the GCC, sustainability is a cornerstone of Saudi Arabia's Vision 2030. Initiatives like the Saudi Green Initiative and the National Renewable Energy Program aim to reduce oil dependency, promote renewable energy, and expand green spaces through efforts such as planting 10 billion trees and designating protected areas. The Kingdom is also advancing food security through sustainable farming and integrating eco-friendly practices into its giga projects, which are redefining urban development. These efforts not only emphasise environmental stewardship but also highlight the move towards autonomous sustainability monitoring - leveraging innovative technologies to ensure measurable and resilient environmental outcomes across the region.



02 Bridging tradition and technology

Traditional sustainability monitoring in the Middle East is deeply rooted in the region's cultural and ecological practices. Communities have historically managed resources through methods like seasonal migrations and advanced irrigation systems such as qanats or falajs, showcasing indigenous knowledge in water conservation and agricultural sustainability.

However, these practices face growing challenges. Urbanisation and population growth, economic growth, and climate change are straining natural resources, while shifting weather patterns disrupt traditional systems optimised for historical conditions. Integrating modern monitoring techniques with traditional knowledge is essential to strengthen environmental resilience. Monitoring systems that have existed for the last decade mostly rely on manual data collection and are often costly, labour-intensive, and prone to inaccuracies. The fragmented nature of data limits comprehensive insights into environmental changes.

The abundance of connected data sources has driven the adoption of advanced monitoring tools that integrate technologies like sensors, satellite imagery, AI, and machine learning (ML). These tools enable continuous, real-time analysis of vast datasets, Identifying patterns, detecting anomalies, and predicting trends with unprecedented speed and accuracy. This capability is essential for sustainability monitoring, allowing enterprises and governments to make informed decisions, reduce ecological impacts, and improve resource management.

The move towards autonomous sustainability monitoring

Autonomous systems enable businesses and governments to monitor, assess, and improve their environmental impact, energy usage, and resource management. Networks of sensors and data collection devices deployed across facilities, locations, or equipment capture real-time data on energy consumption, water use, waste generation, greenhouse gas emissions, and other key sustainability indicators. This data is transmitted to a centralised platform, where AI and ML algorithms analyse it to generate actionable insights and recommendations for improving sustainability performance. Satellite imagery can also be incorporated to provide additional sustainability metrics.

Autonomous sustainability monitoring offers significant benefits by enabling organisations to identify opportunities to reduce their environmental footprint, conserve resources, enhance operational efficiency, and cut costs. For example, it can pinpoint areas of excessive energy use or water consumption and suggest optimisation strategies.

Furthermore, these systems can issue real-time alerts when sustainability metrics exceed set thresholds, facilitating prompt action to address or prevent issues. They also generate detailed reports and dashboards, providing insights into sustainability performance over time, helping organisations track progress and demonstrate accountability to stakeholders.

Autonomous sustainability monitoring refers to the use of advanced technologies, such as Artificial Intelligence (AI), Machine Learning (ML), Internet of Things (IoT), and different types of data like satellite data, to automatically track, analyze and report on sustainability metrics without or with minimum human intervention. This approach enables continuous near-real-time assessment of environmental and resource management practices, ensuring adherence to the sustainability goals.

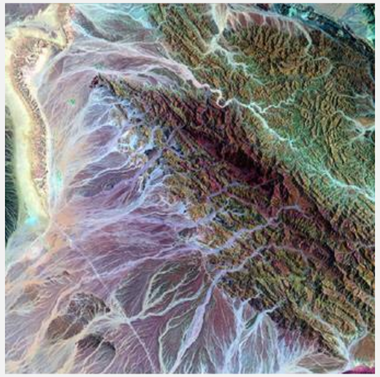
Unlocking the power of satellite data for sustainability

Satellite data has become an invaluable tool for monitoring sustainability metrics, offering extensive coverage and diverse resolutions for applications in agriculture, urban planning, and natural resource management. Advances in satellite and remote sensing technology enable precise, efficient tracking of ecosystems, land use changes, vegetation health, and climate trends, eliminating the need for manual interventions. This technology provides stakeholders with actionable insights, supporting data-driven decision-making and targeted interventions to promote long-term sustainability.

By enabling large-scale, continuous monitoring, satellite data ensures timely detection of anomalies or changes requiring immediate attention. Recent advancements have also made autonomous monitoring more accessible and cost-effective, positioning satellite technology as a powerful enabler of sustainable development initiatives across the region.

It is essential to understand what type of data is needed to derive the needed insights for a given problem that stakeholders face. One data type is various satellite imagery, which can be categorised in multiple ways, and used for different purposes or applications. The following table categorises satellite imagery based on the type of sensor, spectral bands, and spectral range.

	Type of sensor	Spectral band	Spectral range
Optical (Multispectral)	Passive	3-10 bands, including visible, near-infrared (NIR) and shortwave infrared (SWIR)	Visible spectrum (~400 - 700 nm) NIR (~700 - 1,400 nm) SWIR (~1,400 - 2,500 nm)
Optical (Panchromatic)	Passive	Single high-resolution band in visible spectrum	Visible spectrum (~400 - 700 nm)
RADAR (SAR - Synthetic Aperture Radar)	Active	X (3.8–2.4 cm) band C (7.5–3.8 cm) band L (30–15 cm) band	Microwave region (~1–30 GHz)
Thermal	Passive	1-3 bands in the thermal infrared (TIR) region	~3–14 micrometers (µm) mid-wave infrared (MWIR) and long-wave infrared (LWIR)
Hyperspectral	Passive	May range from 100 – 200 bands	From visible (~400 nm) to the shortwave infrared (~2,500 nm)
LiDAR (Light Detection and Ranging)	Active	Single wavelength, often in the near-infrared range (~1,064 nm)	NIR (~1,000–1,500 nm)

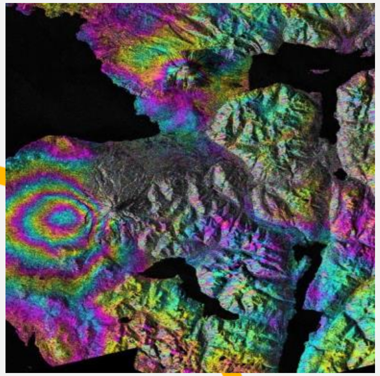


Multispectral imagery is the most popular commercially available satellite imagery, capturing images in multiple distinct spectral bands spread across different wavelengths. The typical visible spectral bands included in this imagery are Red, Green, and Blue; near-infrared (NIR) and shortwave infrared (SWIR) bands from the non-visible range. It is widely used in many sectors like agriculture, forestry, and environmental monitoring to gather rich information on the Earth's surface that the human eye cannot perceive.

Source: Landsat, 30m

Panchromatic imagery is sometimes called black-and-white satellite imagery. It captures data in a single high-resolution band, typically in the visible light spectrum. Since it provides detailed spatial information, panchromatic imagery is used in urban planning, infrastructure mapping, feature extraction (roads, vegetation areas, etc.), and more. Panchromatic imagery is also fused with Multispectral imagery to enhance the spatial resolution of the imagery using a process called Pan-sharpening.

Source: Sentinel SkySat

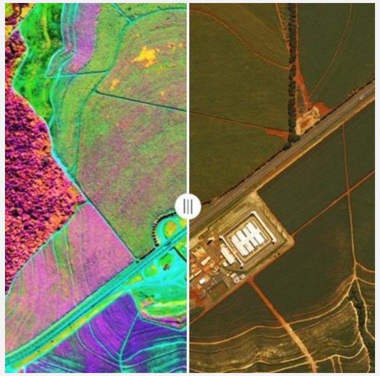


Synthetic Aperture Radar (SAR) imagery uses an active radar sensor that is not dependent on sunlight and can, therefore, capture images in the dark through cloud and rain cover. The all-weather, day-and-night capture capability enables SAR imagery to be highly dependable in applications like flood detection. InSAR helps identify early signs of landslides, surface deformation following earthquakes, etc. SAR imagery can detect glacial movements, ocean wave patterns, and oil spillage.

Source: NASA

Thermal imagery captures infrared radiation (heat) emitted by different objects on Earth's surface. This imagery can capture variations in temperature and heat emissions that are usually not captured in optical imagery. Due to its special ability to capture temperature variations, this imagery is widely used for wildfires, disaster monitoring, energy audits, crop health monitoring, etc.

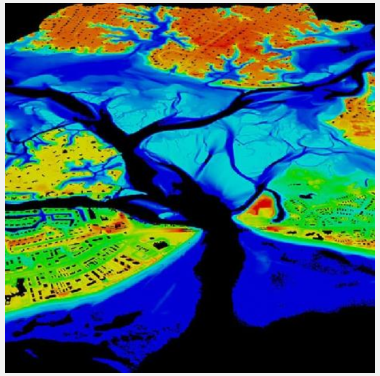
Source: SatVu



Hyperspectral imagery captures images in 100s of bands across the electromagnetic spectrum, producing one of the most detailed spectral information. This allows hyperspectral imagery to detect objects & materials precisely. Due to its capacity to capture information in multiple bands, hyperspectral imagery is used to identify traces of minerals and geological features, monitor the environment, and classify forest types, trees, etc.

Source: Planet Labs

Light Detection and Ranging (LiDAR) imagery uses active sensor laser pulses to create three-dimensional high-resolution point cloud data of the Earth's representation. Depending on the type of application, LiDAR uses infrared wavelengths to capture land-based features like land-based surveys, urban structures, forests, etc., or the green light spectrum, also known as Bathymetric LiDAR, to capture underwater surfaces like seabeds, riverbeds, etc. LiDAR surveys have also been successfully used in archaeological and heritage surveys to create digital 3D models.



Source: SatSure

Distinct types of satellite imagery provide insights into different sectors, thus helping us build a better understanding of evidence-based sustainability problems. This fact- and evidence-based approach allows for wiser decision-making and the formulation of effective policies dealing with issues of environmental protection, climate change, and sustainable development.

These satellite-based insights and data from various sources help track and assess sustainability aspects like pollution levels, heat pockets, climate change, etc., thus powering autonomous sustainability monitoring.

Challenges in deploying autonomous sustainability monitoring tools

There are still multiple challenges when it comes to deploying autonomous sustainability monitoring tools. Some include technical and operational matters, regulatory issues, and ethical considerations. Implementation of autonomous sustainability monitoring tools usually involves using satellite data, data analytics, Artificial Intelligence (AI), Internet of Things (IoT) devices, etc., which may involve multiple challenges that need to be handled for successful implementation. Some of these key challenges are as follows:

01 Gaps in data and accuracy:

The data provided by external sensors may have gaps, noises, outliers, inconsistencies, etc., thus affecting the overall accuracy of the monitoring tools. Data fusion from multiple heterogeneous sources also presents the risk of data standardization.

02 Infrastructure and deployment cost:

The infrastructure may include sensors, communication networks, and deployment costs in remote and harsh environments like forests, oceans, and deserts. Scalability across large areas is also complex.

03 Regulations and policies:

There are no standard policies and regulations for environment monitoring tools in multiple geographies. Some countries are defining and amending their definition of sustainability, which creates more ambiguity.

04 AI and ML biases:

If the training data used in the model had not covered all possibilities, then ML may introduce a bias toward ideal conditions. Since the autonomous sustainability monitoring tools include ML algorithms, there are no human interventions, which makes it difficult to understand how certain decisions are made.

05 Social and community engagement:

Autonomous sustainability monitoring tools rely on multiple technologies to make decisions, which may not consider social and community engagement, which can create mistrust in the community's solutions.

Implementing a technological framework that standardises the unification of disparate data sets can address some of these challenges.

Technological framework for autonomous sustainability monitoring

The application of advanced tech frameworks is essential for the efficacy of autonomous sustainability monitoring, especially as entities aim to maximise their sustainability efforts. By merging assorted elements such as sensors, satellite images, machine learning, and AI/ML, it becomes possible to collect and analyse data in near real-time, which allows for targeted insights concerning things like resource usage and greenhouse gas emissions.

Below is an example of a high-level technological framework that can be used to establish an autonomous sustainability monitoring system.

01 Data collection

Securing and implementing data collection technologies to enable comprehensive monitoring and establishing baseline metrics. Understanding the context is essential for evaluating ecosystem impacts. Choosing the most appropriate technology (like drones, satellites, bioacoustics, eDNA, IoT sensors) to gather specific data essential for assessing habitat risks.

02 Data ingestion and fusion:

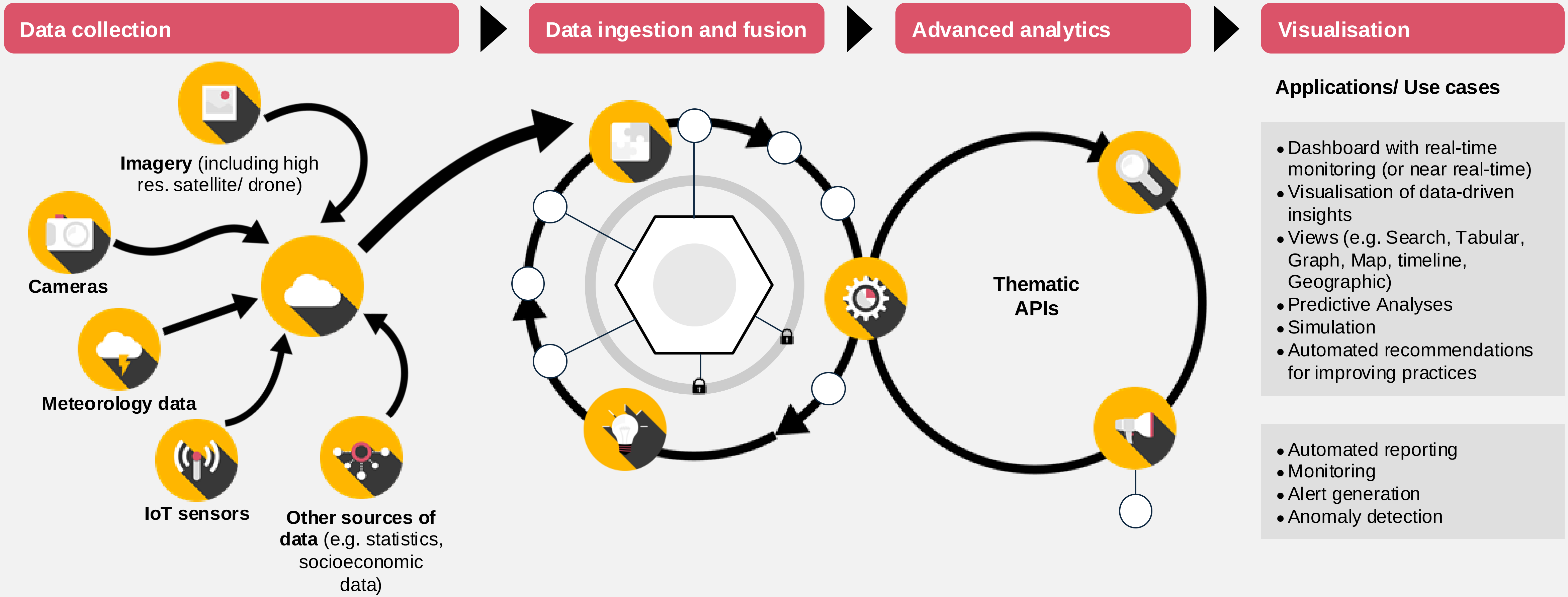
Connecting diverse data points from various data sources and harmonising data into a unified and scalable engine where data can be analysed. This is one of the most important stages where data from heterogeneous sources are fused together as per business requirements. Satellite data is fused with ground based spatial and non-spatial data to derive more insights about assets, phenomena or environment.

03 Advanced analytics:

Developing models (ML/AI) for identified use cases, running experiments, and refining prediction models to enhance future forecasting. This can include anomaly detection, pattern recognition and predictive analytics.

04 Visualisation:

Simulating, visualising and interacting with data, facilitating informed decision-making. Using 2D and 3D visualizations to display data insights, trends and predictions, as well as enabling immersive experiences to understand complex environmental interactions and scenarios.



When designing a framework, other considerations can include data governance and ethics layers, including data privacy, regulatory and ethical considerations, and feedback and adaptation to enable continuous monitoring, scalability, and flexibility. A successful framework must be underpinned by a highly modular and flexible technical architecture that can scale to multiple use cases or applications in various regions. This technical architecture would be centered around several principles and components to ensure scalability, interoperability, and adaptability.

Something very complex can be decomposed into multiple microservices that can handle specific functionalities, such as spatial analysis or data visualization. Plug-and-play services consisting of modules that can be easily added, removed, or modified are among the most critical components. This way it is possible to scale and deploy at a large scale. Such technical architecture provides a robust foundation that efficiently supports multiple applications, adapts to evolving requirements, and integrates easily with new technologies and datasets.

In Saudi Arabia, such a technological framework can be implemented in various sectors, with urban planning and agriculture being the most prominent examples.

03 **Autonomous insights:** Enhancing sustainability in urban development and agriculture

Applications of sustainability monitoring in urban development

As cities worldwide keep expanding, they use over two-thirds of the world's energy and produce over 70% of carbon emissions worldwide. Urban environmental stresses, driven by growing urban populations, demand innovative approaches to resource management and strategies to mitigate ecological impacts.

Integrating autonomous monitoring technologies in urban environments offers a practical approach to enhancing sustainability and environmental management. These cutting-edge systems leverage a network of sensors and advanced machine-learning algorithms to collect and analyse real-time data on key sustainability metrics, such as energy usage, greenhouse gas emissions, and water consumption. These innovations provide actionable insights by pinpointing inefficiencies, empowering cities and businesses to optimize resource management and reduce environmental impact.

Additionally, autonomous sustainability monitoring is crucial in tracking air quality and managing waste, aligning with urban mobility and environmental quality standards. By using real-time data, stakeholders can react quickly to urban issues, lowering traffic, allocating resources as efficiently as possible, and improving people's quality of life. There is an emerging trend where cities utilise technology to monitor environmental effects and implement immediate corrective actions, signifying a shift toward resilience and responsibility in sustainable practices. This paves the way for a smarter, more sustainable future.

Utilising platforms that aggregate various data increases policies' effectiveness in developing smart, eco-friendly cities. Ultimately, successfully deploying these technological advancements requires collaboration between the public and private sectors, ensuring comprehensive accountability in pursuing global sustainability goals.

In Saudi Arabia, both state-backed projects and local startups are leveraging emerging technologies to transform urban infrastructure to support a greener, smarter future. The Saudi Green Initiative leverages AI-driven monitoring and real-time data analytics to optimise urban energy use and protect critical resources, addressing the Kingdom’s unique sustainability challenges tied to its energy sector. KSA-based startups are also implementing AI and IoT for sustainable urban solutions, driving the Kingdom's shift towards smarter, greener cities.

01

NEOM:

As part of its Vision 2030, Saudi Arabia is developing NEOM, a smart city that aims to be a model for sustainability. NEOM plans to incorporate advanced technologies for autonomous monitoring, including AI-powered systems to manage energy consumption, water distribution, and waste management. The city is also expected to rely on renewable energy sources, primarily solar and wind.

02

The Red Sea Project:

This tourism development integrates autonomous sustainability initiatives to preserve the marine and coastal environment. The project employs drones and autonomous underwater vehicles to monitor coral reefs and marine life, ensuring minimal environmental impact. These technologies help in tracking biodiversity and managing conservation efforts effectively.

03

KAUST (King Abdullah University of Science and Technology):

KAUST is involved in various research projects focused on sustainability and environmental monitoring. The university employs autonomous systems and AI to study the Red Sea's ecosystem, including real-time data collection on sea temperatures and salinity levels, which are crucial in understanding climate change impacts.

04

Ma'aden's Remote Monitoring:

The Saudi Arabian Mining Company, Ma'aden, leverages remote sensing technologies and autonomous systems to monitor environmental compliance and manage natural resources. These systems help track air and water quality impacts from mining operations, promoting more sustainable mining practices.

05

Green Riyadh:

As part of the Riyadh Urban Development Strategy, the Green Riyadh initiative aims to plant millions of trees to improve air quality and reduce temperatures in the city. The project uses IoT sensors and autonomous watering systems to monitor soil moisture and optimize irrigation, ensuring efficient water use.

Saudi Arabia has been making significant advancements in its major urban development projects, utilizing technology to manage resources efficiently and promote environmental conservation. Here are a few notable examples. These initiatives demonstrate Saudi Arabia's commitment to leveraging technology for sustainable development, aligning with its broader goals under Vision 2030. The next step will be to accelerate the adoption of technology to monitor the Kingdom's progress more holistically and autonomously.

Applications of sustainability monitoring in agriculture

Technological advancements alone cannot address all of these challenges; however, they can be essential in combating some of them. The rising intricacy of agricultural requirements prompts a necessary transition towards elaborate methodologies that elevate both productivity and sustainability. The application of technologies such as (IoT) and (AI) results in optimising crop management practices alongside resource allocation, ensuring efficient outcomes. There is a pressing need for innovative solutions, especially in the realm of water, nutrient use efficiency, and sustainability metrics. Furthermore, networks of sensors, satellite imagery, and ML/ AI-driven methodologies allow for the real-time observation of crop vitality and environmental conditions, which aids in making decisions based on data that could alleviate environmental issues. Inventive strategies like the modified Particle Swarm Optimisation exemplifies the capability of technology to alter conventional farming methods, promoting the incorporation of sustainable aims within agricultural systems and aiding in the development of a more robust food system in a comprehensive sense.

01

Precision farming:

Satellite imagery allows for precise monitoring of crop health, soil moisture levels, and nutrient deficiencies. By analyzing this data, farmers can tailor their irrigation and fertilization practices to the specific needs of their crops, reducing water and chemical use while maximizing yields.

02

Drought management:

Satellite data aids in the early detection of drought conditions, allowing for timely interventions to mitigate crop losses. By monitoring soil moisture and vegetation indices, satellites provide insights into the onset and severity of droughts, enabling farmers to adapt their practices accordingly.

03

Crop mapping and forecasting:

Satellites offer detailed maps of crop distribution and growth patterns, essential for planning and forecasting agricultural production. This information is critical for ensuring food security and managing supply chains in a country with limited arable land.

04

Water resource management:

Satellite data is crucial for monitoring and managing water resources. By tracking water movement across landscapes, satellites help identify areas of overuse or inefficiency in irrigation systems, optimizing water use and reducing wastage.

05

Environmental monitoring:

Satellite technology contributes to environmental sustainability by monitoring deforestation, desertification, and land degradation. This data helps assess the impact of agricultural practices on the environment and supports strategies to combat environmental challenges.

Adopting these technologies cultivates a more robust agricultural structure, which is vital for satisfying the dietary requirements of a growing populace while advancing environmental well-being. Saudi Arabia has established several projects, initiatives, and software to improve agricultural sustainability monitoring. These activities are consistent with Vision 2030, which seeks to increase food security, optimise resource use, and promote environmental resilience. Saudi Arabia is working to address water scarcity, climate resilience, and sustainable production through various innovative technologies and collaborative programmes.

Some important programmes and case studies that demonstrate the country's dedication to promoting sustainable and efficient agriculture are included below:

01 **Palnear** uses AI and IoT sensors to monitor water quality and detect leaks in real time, substantially reducing wastage and improving water consumption. This technology helps NEOM achieve its sustainability goals by tackling water scarcity, improving resource management, and harmonising with Saudi Arabia's Vision 2030 emphasis on water efficiency and environmental sustainability.

02 **Topian** integrates vertical farming and hydroponic technology, considerably lowering water consumption and promoting sustainable agriculture, hence complementing Saudi Arabia's Vision 2030 aims. Topian promotes climate-resilient food security, which increases agricultural innovation in NEOM. Furthermore, the incorporation of AI-powered robotics, such as self-driving tractors and robotic pollinators equipped with disease detection systems, improves production efficiency and fosters a local ecosystem for agricultural innovation, contributing to Vision 2030's goals of scalable, sustainable food production.

03 **Estidamah's** greenhouse technologies incorporate efficient irrigation methods, such as drip and subsurface systems, to significantly reduce water usage and improve agricultural water efficiency, aligning with its mission to promote sustainable agriculture in Saudi Arabia. This approach supports Vision 2030's goals for water conservation and sustainable resource management. Furthermore, Estidamah's automated fertilizer management system uses advanced controls to regulate fertilizer levels based on crop needs, optimizing water and nutrient use within protected agriculture systems. By focusing on resource efficiency, Estidamah addresses critical water scarcity challenges, contributing to Saudi Vision 2030's sustainability objectives in agriculture.

04 **Remote Sensing and Drone Technology (Ministry of Environment, Water, and Agriculture)** employs drones and satellite imagery to track soil and crop health, facilitating ecosystem assessment and data-driven agriculture. This invention improves decision-making processes and supports Saudi Vision 2030 by building a resilient agricultural economy.

Examples of applications:

- Biomass monitoring
- Carbon capture & content assessment
- Crop yield prediction
- Environment impact monitoring
- Climate services for agriculture
- Vegetation monitoring
- Pastureland management
- Soil condition monitoring
- Weather forecasting

Future implications

Saudi Arabia is advancing sustainability by integrating satellite technology for efficient and automated environmental monitoring. This approach combats desertification, tracks vegetation cover, and supports initiatives like the Saudi Green Initiative and Red Sea protection programs, aligning with Vision 2030 goals of ecological security and ecosystem sustainability. Advanced satellite systems enable real-time data analysis and progress tracking, enhancing accountability, transparency, and decision-making - key elements for sustainable development.

Modern technologies, such as AI and machine learning, complement satellite data by providing real-time insights and enabling proactive responses to environmental changes. These innovations are transforming conservation efforts, allowing Saudi Arabia to rapidly address challenges and implement sustainable practices. Early-stage projects in autonomous monitoring and spatial analysis are already demonstrating their potential to protect ecosystems and support biodiversity.

To maximise the effectiveness of these technologies, collaboration among researchers, scientists, policymakers, and technology experts is essential. Advancements in remote sensing, machine learning, and cloud computing will further refine these systems, ensuring decision-making is grounded in robust scientific data. By adopting these methods, Saudi Arabia is positioning itself as a global leader in environmental stewardship and sustainable development.

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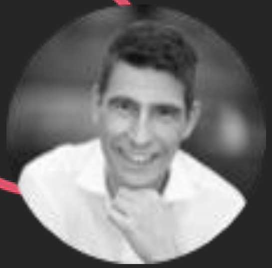

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