



Climate Resilient Agriculture in Poland

ANNEX

Technologies in soil, energy and water
management for resilient agriculture;
Dutch technological expertise

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Sustainable soil and crop management

Core practices and principles

Resilient agriculture is highly dependable on soil condition. The ability of continuously generate agri-food products without significant reliance on other markets and their inputs requires appropriate soil health. Soil provides plants with the essential nutrients, water, and root support they require to grow and thrive. Climatic conditions, time, living organisms, and, especially, the human management of soil and crop selection are some of the basic factors that affect soil health and fertility and consequently determine the agricultural production effectiveness and robustness in the long term.

In the past decades the use of mineral fertilizers and plant protection products as well as the utilization of monoculture crops has steadily increased, adversely impacting soil condition and the environment². Excessive use of chemical fertilizers alone enhances soil degradation in the form of soil organic matter reduction, soil compaction, nitrate leaching, salinity and acidity. At the same time buying fertilizers, pesticides,

etc. constitutes a considerable cost for the farmers. Their use significantly diminishes agricultural resilience, as fertilizer production takes place through fragile global value chains, while specific pesticides are often exclusive to certain companies.

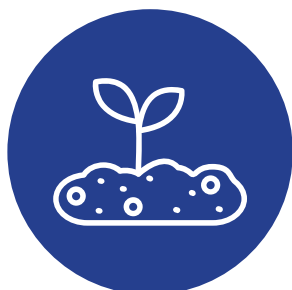
In response to this situation, a debate has emerged over the need for more sustainable soil nutrient use. New agricultural practices provide sustainable solutions for maintaining soil life, improving fertility, and feeding plants in order to promote agricultural production. Healthy soil ensures optimum moisture, significant amount of beneficial microorganisms, optimum nutrients and lower level of toxicity due heavy metals and pesticide and in result improves productivity. At the same time the diminished use of fertilizers, pesticides, etc. decreases farmers' costs and builds agricultural resilience. Let us not forget that the use of sustainable soil and crop management is beneficial for the planet as well, as it minimizes contamination and negative environmental impact.

² van den Berg, H.; Gu, B.; Grenier, B.; Kohlschmid, E.; Al-Eryani, S.; da Silva Bezerra, H.S.; Nagpal, B.N.; Chanda, E.; Gasimov, E.; Velayudhan, R.; et al. Pesticide lifecycle management in agriculture and public health: Where are the gaps? *Sci. Total Environ.* 2020, 742, 140598

Key solutions and technologies

Sustainable soil and crop management encompasses a wide range of practices that are essential to building agricultural resilience, improving yields while simultaneously cutting costs. Among these one can enumerate:

SOIL CONSERVATION



Soil conservation forms one of the fundamental principles of sustainable farming. Rather than viewing soil simply as a medium for crop production, sustainable management recognizes it as a complex living ecosystem that supports nutrient cycling, water regulation, and biodiversity. Among the main specific tools used for soil conservation are:

» **diversified crop rotation:**

alternating different crops in a field to improve soil health, reduce pest and disease pressure, and enhance nutrient cycling.

» **no-till farming/ conservation tillage:**

minimizing soil disturbance by planting crops directly into the residue of previous crops. This reduces erosion, improves water infiltration, and enhances soil structure.

» **minimizing soil compaction:**

compaction tends to squeeze out water and air pores, changing the function of soil in the ecosystem and resulting in lost yield; to counteract those negative outcomes farmers should conduct field activities only when soil is not wet or saturated and reduce the pressure put on the field (e.g. reduce the weight of equipment, reduce axle weight, increase tire size and reduce tire pressure).

» **cover cropping/ permanent soil cover:**

planting crops primarily to protect and improve the soil, rather than for harvest. Cover crops can suppress weeds, add organic matter, and prevent erosion.

SUSTAINABLE FERTILIZATION



Globally, synthetic fertilizers are behind the bulk of global food production. Standard farming often requires substantial amounts of these products to increase yields. This results in farmers' reliance on fragile global value chains and considerable costs they have to bear. At the same time a significant amount of fertilizers is not directed towards crops due to nutrient run-off that additionally negatively affects the environment³. To limit those negative effects farmers can use such tools as:

- » **Manure management:** utilizing organic waste from rearing to improve soil fertility and reduce reliance on synthetic fertilizers; actions also include basic actions e.g. putting a lid on the manure tank, which stops ammonia being lost to air.

- » **Application of compost and organic amendments:** composting is a widely used method for treating organic waste and producing a humus-like material that serves soil health.
- » **Precision agriculture for fertilization:** using GPS, sensors, and data analytics can optimize fertilizers input use and reduce waste.
- » **Use of nitrogen-fixing crops:** plants such as legumes convert nitrogen from the air into a form that is biologically useful, thus can replace synthetic nitrogen as part of the process of rebuilding soil fertility.

SUSTAINABLE PEST AND DISEASES MANAGEMENT



Pests and plant diseases are major threats to global food production. Fuelled by climate change, biodiversity loss and transnational trade, pests, weeds and diseases now cause USD 220 billion in losses annually for the global agri-food sector⁴. One option is to apply chemicals to limit pests and diseases. However, their excessive use harms the environment and human health, and results in farmers dependence on such products. An alternative is to use eco-friendly, cost-effective, and long-term solutions to control pests and diseases without harming the ecosystem:

- » **Integrated pest management (IPM):** a holistic approach to pest control that combines biological control agents, crop rotation, habitat management,

³ according to the United Nations-backed Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES).

⁴ <https://openknowledge.fao.org/items/7a20fe82-13ce-462c-8476-8267e8a5b71b>

resistant crop varieties, and continuous pest monitoring to limit pest populations; when intervention becomes necessary, preference is given to biopesticides instead of synthetic ones, as these products are generally more biodegradable, more selective toward target species, and less harmful to non-target organisms.

» **Precision agriculture for pest control:**

AI and IoT-based pest monitoring systems to track pest movements and predict infestations, as well as drone technology for precise pesticide application, reducing chemical waste and environmental damage.

» **Developing resistant crops:**

crop varieties that are resistant to pests and diseases, reduce the need for chemical interventions, making farming more sustainable and cost-effective.

» **Crop rotation and diversification:**

growing different crops in the same field over different seasons prevents the buildup of pests and soil-borne

diseases as well as disrupts pest life cycles by removing their preferred host plants.

» **Biological control agents:**

using natural enemies of pests to manage infestations, e.g. introducing or facilitating predatory insects or microbial pesticides - bacteria that targets harmful pests without affecting beneficial insects.

» **Trap cropping:**

planting sacrificial crops to attract pests away from the main crop to divert pests from attacking high-value crops and in result reduce pesticide use, as pests concentrate on easily replaceable plants instead of main crops.

Sustainable soil and crop management solutions improve soil structure, increase organic matter content, enhance water-holding capacity, and stimulate microbial activity. Healthy soils are consequently more resilient to drought, stabilize agricultural productivity in the long term and reduce dependence on costly synthetic agrochemicals. These actions improve nutrient cycling, disrupt pest and disease cycles, suppress

weed populations, supports pollinator and beneficial insects populations. This enhances ecosystem as well as farmers resilience, and reduces economic risks by limiting farmers' dependence on single commodities.

Dutch expertise in sustainable soil and crop management

Dutch farming is globally recognized as a beacon of agricultural innovation, sustainability, and productivity. Due to climate crisis and its repercussions, Dutch companies and farmers are perfecting farming techniques and agriculture technology where sustainability, precision, and productivity converge. One of the main priorities for those endeavours in Dutch agricultural context is soil health which is under considerable pressure. This is due to depleted organic matter, salinization in coastal areas, intense land use and obviously climate crisis growing impact. Soil regeneration in the Netherlands is rapidly becoming a technology-driven revolution that might be exported and replicated in other countries, such as Poland.

The Dutch have seamlessly integrated **precision farming, data-driven technology and automation** into their farming systems to increase yields, resilience, and decrease costs⁵:

» **Sensors and data collection:**

Real-time sensors, such as multi-depth probes, monitor soil moisture, temperature, acidity, salinity, nutrient content (e.g. nitrogen, phosphorus, potassium, carbon), crop health, etc. Internet of Things devices deliver continuous, hyper-local data feeds to farm management systems for granular control over irrigation and inputs. Mobile soil scanning devices use electromagnetic induction, optical sensors, ground-penetrating radars, etc. to acquire data necessary to create e.g. soil maps and nutrient variability zones.

» **Big Data and Artificial Intelligence (AI):**

Sophisticated analytics platforms aggregate field data (weather, soil, plant health) and guide fast, evidence-based decision-making for maximum output and minimal loss. These decisions concern fertilizer application, water scheduling, pest management, etc. AI solutions forecast disease risk, suggest optimal crop rotations, and tailor nutri-

ent regimes for individual fields, from predicting optimal planting schedules to adjusting greenhouse climate and nutrient dosing automatically.

» **Drones and satellite monitoring:**

High-resolution imagery unlocks insights into large field conditions, plant stress, diseases, resource allocation, enabling rapid, targeted treatment.

» **Automated machinery:**

GPS-guided tractors and robotic harvesters minimize labour and operate with greater accuracy, protecting soil structure and maximizing efficiency. Automated weeders, planters, and harvesters streamline labour and increase speed, accuracy, and safety throughout the growing season. Autonomous lightweight robots replace tractors for: weeding, seeding, soil sampling, crop monitoring and drastically reduce soil compaction during these activities.

⁵ RVO (2026): Smart Farming. How Dutch innovation, data, and design are shaping the future of open field cultivation <https://www.rvo.nl/sites/default/files/2026-02/SmartFarmingGuide.pdf>

Because the Netherlands has limited arable land, **innovative greenhouses**, has become a signature Dutch approach for producing more food per square meter⁶ and resulted in effective solutions and technologies:

- » **Controlled Environment:**
Tightly regulated temperature, humidity, and CO₂ maximize growth rates and quality while preventing disease outbreaks.
- » **Artificial Lighting:**
LED systems tuned for optimal photosynthesis, allowing round-the-clock production of greens, herbs, and fruit.
- » **Vertical farming:**
Multi-layer cropping systems and fully climate-controlled greenhouses boost production of high-demand vegetables, flowers, and fruits.
- » **Hydroponics and substrate-based cultivation:**
Use of water or substrates (e.g. stonewool, coco) instead of soil reduces soil-borne disease risks and allow for high-density urban or indoor production.

Dutch agriculture considerable advantage is the use of **closed-loop nutrient- and resilient cropping system**.

The specific practices that are used for this purpose are:

- » **Use of agricultural byproducts as fertilizers:**
Livestock manure, crop residues, and other organic wastes are reused (composted or anaerobically digested) to create fertilizer, reducing synthetic input dependence.
- » **Use of biochar:**
Biochar improves water retention, microbial diversity, carbon stability. It is used on arable land and as greenhouse substrates as well.
- » **Fertigation, closing nutrient cycles in hydroponics or greenhouses:**
Nutrient-rich effluent is treated and reused in subsequent cycles, closing the nutrient loop. Fertigation injection of fertilizers and other water-soluble products into an irrigation system enables the delivery of tailored nutrient solutions

to match the crop's developmental stage precisely.

- » **Use of bio-stimulants:**
These improve plant growth using microbial consortia, enzymes, fungi, algae extracts, etc. to fix nitrogen, solubilize phosphorus, release potassium, improve soil structure and in effect reduce dependency on chemical fertilizers. This also includes microbial seed coatings with: mycorrhiza, nitrogen fixers, growth-promoting bacteria, which all improve germination and crop resilience.
- » **Resilient cropping systems:**
Using crop varieties with stronger root systems, smart water and drainage solutions, and crop rotations that decreases risks from droughts. Focusing on crops, e.g. white lupin, quinoa, aardaker⁷, that are not only rich in plant-based proteins and resilient to climate stress but also help regenerate soil with nitrogen-fixing roots.

⁶ <https://www.wur.nl/en/research/plant/climate-smart-and-sustainable-field-cropping-systems>

⁷ <https://www.wur.nl/en/news/nwa-funding-research-quinoa-lupin-and-aardaker-promising-meat-alternatives-also-benefit-soil>

Responsible energy use in agriculture

Sustainable energy as a prerequisite of sustainable agriculture

Energy input, beyond traditional manual and animal labour, is crucial to modern agricultural production. It is a key factor in moving away from subsistence farming towards food security and added value creation. To this end, energy systems in agriculture should involve the integration of various energy sources and technologies to optimise the efficiency and stability of agricultural operations. Agriculture uses energy for numerous applications. For example fossil fuels are used for driving machinery, heating, irrigation pumps, drying grain, etc., while electricity is often used for machinery, cooling and lighting purposes⁸. Furthermore, these energy sources indirectly influence agriculture through their use in the production of fertilisers, agrochemicals etc.

Currently the main issue plaguing agri-food sector is the overreliance on fossil fuels. These markets are prone

to socio-economic shocks that result in price volatility and supply concerns. They are also susceptible to inefficiencies, e.g. engines running while idle or thermal energy run-off⁹. The switch to electrification could alleviate this shortcomings. Furthermore, transforming from a non-renewable energy-based system to a renewable-based agriculture system could additionally build resilience as the farmers becomes their own energy producers. The use of solar, wind, biogas, or hydro energy offers tremendous potential, with applications ranging from heating and cooling, post-harvest processing, to lighting technologies.

Nevertheless, the switch from non-renewable to renewable energy imposes several challenges. Many forms of renewable energy production are dependent on weather conditions. In effect there is a need to store energy for use during periods of low energy production or high demand. Furthermore, in some cases renewable energy competes for land with traditional agricultural activities. Though these are legit-

⁸ Rahman, Md & Khan, I. & Field, David & Techato, Kuaanan & Alameh, Kamal. (2022). Powering agriculture: Present status, future potential, and challenges of renewable energy applications. *Renewable Energy*. 188. 10.1016/j.renene.2022.02.065.

⁹ Studies indicate that tractors operate under idle conditions for approximately one-quarter of their working time, although this proportion could be substantially reduced through improved management practices (Lenzini, N. (2019). An updated methodology to analyse the idling of agricultural tractors. *Biosystems Engineering*. <https://doi.org/10.1016/J.BIOSYSTEMSENG.2019.09.001>).

imate concerns, the advantages of electrification based on renewable energy offers significant potential for building farmers' resilience. The limiting of greenhouse gases emissions along the way would be an added advantage to this process.

One of the aspects of energy optimization in agriculture that often remains neglected is the overall reduction of energy use. It is the crucial objective that results in lowering farmers' expenditure and building agricultural production resilience. As the energy-limiting actions seem relatively easy they are often interpreted as ineffective, while in fact they should become the primary goal for farmers seeking energy-resilience.

Limiting energy use and electrification

» **Building's thermal optimization:**

Incorporating high-quality insulation during the construction and retrofitting of agricultural facilities, e.g. warehouses, livestock buildings cold storage facilities, etc. This concerns e.g. improved wall and roofing insulation, using efficient windows and installation of self-closing doors¹⁰.

» **Heat recovery technologies:**

Collecting and reusing heat for other applications. E.g. pre-cooling systems using groundwater can lower milk temperature before mechanical refrigeration, ventilation systems in poultry and pig production can be equipped with heat exchangers that recover thermal energy from exhaust air.

» **Using low-temperature heating systems:**

Underfloor heating commonly installed in livestock facilities and agricultural buildings coupled with condensing boilers.

» **Limiting artificial lighting, using LEDs and automation technology:**

Maximizing natural daylight in farm buildings and replacing conventional incandescent bulbs with LED lamps can significantly reduce energy needs. Savings can be achieved also through automated lighting control systems equipped with motion detectors, daylight sensors, and programmable timers that ensure lighting operates only when required.

» **Efficient ventilation systems and its maintenance:**

Variable-speed drives enable fans (preferably Direct Current ones) to operate only at the airflow required under prevailing environmental conditions. Routine cleaning of dust accumulation on fan blades can reduce airflow efficiency by up to 40%¹¹.

» **Appropriate machinery selection:**

Selecting tractors with power outputs appropriately matched to their tasks improves fuel efficiency, while regular

¹⁰ Innowo (2022): Zamykamy obieg w rolnictwie – zrównoważone wykorzystanie energii w produkcji rolnej i szklarniowej

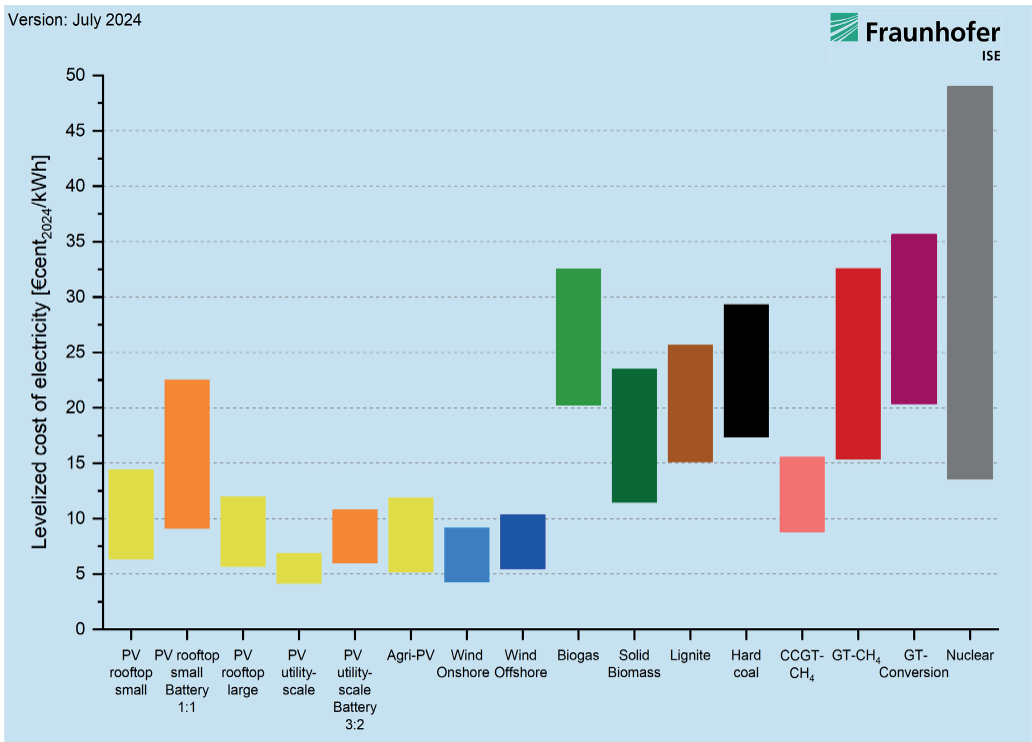
¹¹ Innowo (2022): Zamykamy obieg w rolnictwie – zrównoważone wykorzystanie energii w produkcji rolnej i szklarniowej

technical inspections ensure optimal performance. Maintaining correct tire pressure, balancing axle loads, and minimizing unnecessary engine idling further reduce fuel consumption. The adoption of multifunctional cultivation units can generate substantial savings in both fuel consumption and labour costs.

Renewable energy production

In recent years socio-economic shocks have once again confirmed the agri-food production’s significant reliance on fossil fuels. At the same time we are witnessing a rapid decline in the cost of renewable technologies. Currently solar and wind energy is less costly than traditional energy sources making renewable energy production a financially sensible choice, for the whole economy and for farmers specifically.

FIGURE 56
Levelized cost of
differnet energy
sources



Source: Kost, C. et al. (2024): Levelized Cost of Electricity Renewable Energy Technologies. Fraunhofer Institute for Solar and Energy Systems ISE.

The switch towards renewable energy production has additional advantage in the form of resilience building for farmers. These dispersed energy sources are independent from global shocks and short-term price fluctuations, while they may result in more diversified farm income. The key renewable energy solutions for agriculture are:

- » **Agrivoltaic systems:**
Simultaneous use of agricultural land for both food production and ground-mounted photovoltaic (PV). Through the co-location of photovoltaic installations with agricultural activities, agrivoltaics reduces the need to convert productive farmland exclusively to energy production while maintaining agricultural use of the land.
- » **Large-scale wind farms:**
Wind farms with installed capacities of at least several megawatts located on land categorised as lower soil quality, may be a higher and stable profit source compared to agricultural production on marginal land.

- » **Individual or hybrid small-scale wind turbines systems:**
Polish law states that micro-installations with capacities of up to 50 kW can generate electricity for on-farm consumption without many of the regulatory requirements associated with large wind farms¹². These can work individually or in tandem with PV installations for additional independence from weather conditions. Unlike photovoltaic systems, wind turbines often achieve their highest electricity production during winter months and periods of reduced solar radiation, making the two technologies highly complementary.

- » **Solar thermal technologies:**
Liquid solar collectors could be employed for hot water production and space heating, whereas air collectors are particularly suitable for drying agricultural products¹³, while the investment necessary is significantly lower than in photovoltaic installations.

- » **Biogas production:**
Biogas, generated through anaerobic digestion of organic materials: agricultural by-products and waste, could be subsequently utilized in combined heat and power systems. Utilizing agricultural waste as feedstocks reduces energy and disposal costs and creates additional income streams. Biogas plants can operate continuously regardless of weather conditions. Additionally anaerobic digestion produces digestate, which retains valuable plant nutrients and can be applied as an organic fertilizer.
- » **Energy storage systems:**
Overproduction of energy in times of favourable weather conditions could be stored for periods of peak demand in battery systems or thermal energy storage units, such as hot water tanks.

¹² Construction Law Act of April 16th 2026 (available here: <https://api.sejm.gov.pl/eli/acts/DU/2026/524/text.pdf>).

¹³ Depending on the application, integrating solar thermal technologies into drying systems can reduce energy consumption by approximately 30% (Innowo (2022): Zamykamy obieg w rolnictwie – zrównoważone wykorzystanie energii w produkcji rolnej i szklarniowej).

Dutch experience in energy-smart agriculture

The Netherlands has developed extensive expertise in the field of sustainable energy for agriculture. This concerns both limiting energy usage thanks to more efficient machinery, heating, cooling and lighting, as well as renewable energy technologies.

Energy sustainability is a cornerstone of Dutch agricultural innovation. This concerns renewable energy sources, with specific technologies that improve their production efficiency and stability, without competing with traditional agricultural use of land.

» **Self-Sufficiency and micro grid energy systems:** Dutch technology can be implemented in farms to enable their operation largely off-grid, achieving self-sufficiency and lowering operating costs¹⁴. Using different energy sources and combining them with energy storage can build resilience in

areas with congested energy systems.

» **Innovative solar systems:** Maximization of solar energy utilization using, for example dual-axis solar tracking mechanism that continuously follows the sun throughout the day or concentrating lenses directing solar radiation onto water-filled collector tubes¹⁵.

» **Integrating complementary energy technologies:** Combining heat and power units with heat pumps, aquifer thermal energy storage, thermal buffer tanks coupled with an integrated energy management system enables highly efficient utilization of renewable and recovered thermal energy throughout the year¹⁶.

» **Agrivoltaics:** Dual land use combining crop cultivation with solar arrays. Panels provide shade to crops while the crops cool the panels,

boosting energy output¹⁷.

The Dutch are international leaders in **anaerobic digestion and biomethane production**, as well as in recovering valuable components such as fibres and lignin from biomass. The key technologies in this area are:

» **Closed-loop anaerobic digesters:**

Converting manure, crop residues, and even food processing waste into biogas.

» **Biomethanol production:**

intermediate product that can often be produced close to the biomass source and subsequently utilized directly as a feedstock for the chemical industry or further processed into advanced biofuels. Gasification-based methanol production offers additional advantages because the same infrastructure can process multiple types of biomass and organic waste.

» **Local biomass**

¹⁴ E.g. <https://www.wenergybess.com/cases/netherlands-agricultural-microgrid-powered-by-stars-series-289kwh-bess-59139.html>

¹⁵ Daylight Greenhouse (DaglichtKas) uses such technologies to reduce the greenhouse's energy demand by approximately 45–50% without adversely affecting crop quality.

¹⁶ One example of such approach is the energy infrastructure of the Ter Laak Orchids facility.

¹⁷ Vaverková, Magdalena Daria & Kousal, Martin & Kosakiewicz, Michał & Krysińska, Karolina & Winkler, Jan, 2026. „Agrivoltaics for sustainable land use: A critical review of synergistic and antagonistic effects,” *Renewable and Sustainable Energy Reviews*, Elsevier, vol. 226(PE).

processing facilities:

Technologies such as torrefaction, fast pyrolysis, hydrothermal liquefaction, and gasification enable local enterprises and agricultural cooperatives to convert low-value biomass into standardized, marketable products suitable for domestic consumption, regional trade, or export to international markets.

Among the most renowned examples of Netherlands farming techniques are **sustainable and climate-optimized greenhouses**. They are at the core of high-quality crop production throughout the whole year. Modern Dutch greenhouses deploy the highest standards in climate optimization, resource management, and integrated sustainability that results in considerable energy savings¹⁸:

» **Energy-efficient glazing:**

High-transparency glass and coatings maximize light while minimizing heat loss and gains¹⁹.

» **Automated shading and variable drives:**

Dynamic light and temperature adjustments respond instantly to weather or crop requirements.

» **CO₂ enrichment:**

Recovered CO₂ from nearby industries is injected to boost photosynthesis—raising yields while lowering net emissions.

» **Heat recovery and geothermal energy:**

Greenhouses use geothermal or residual heat from adjacent industries, dramatically lowering energy consumption.

» **Climate control systems:**

Onboard sensors, integrated software, and AI maintain stable microclimates for crops, ensuring consistently high crop quality and extended growing seasons.

» **Electrification²⁰ and foregoing natural gas**

for heating:

Relying on an all-electric energy system with full LED lighting, electric heating (e.g. heat pumps) and dehumidification, with additional efficiency improvement through recovery of latent heat from the greenhouse environment.

¹⁸ E.g. Het Nieuwe Telen greenhouse represents an integrated crop management strategy using precise climate control through optimized management of temperature, humidity, CO₂ concentration, lighting, ventilation, and thermal screening. These solutions led to a energy demand reduction by up to 30%, without significant capital investment.

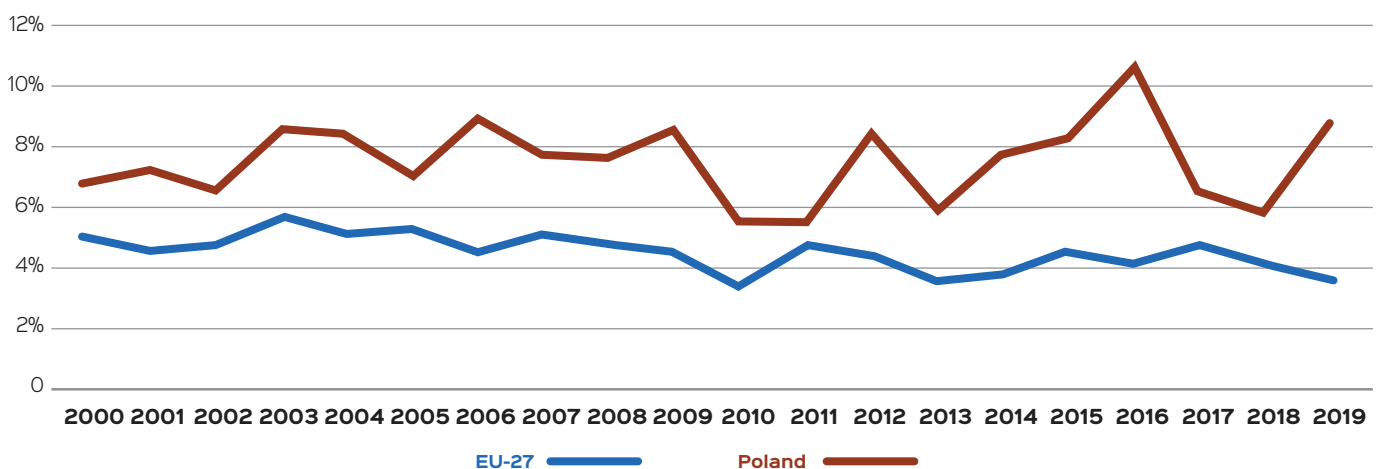
¹⁹ The use of an advanced double-glazed insulated roof (e.g. VenLowEnergyKas), incorporating low-emissivity coatings reduces heat transfer while anti-reflective coatings maintain high levels of solar light transmission.

²⁰ E.g. the Greenhouse2030 concept developed by the Wageningen University, unlike conventional greenhouses, operates entirely without natural gas for heating, relying instead on an all-electric energy system complemented by full LED lighting. Although these technologies require substantial initial investment, they have been shown to reduce energy consumption by approximately 50–70% compared with conventional greenhouse system

Water management and drought resilience

Basic concepts and objectives

Global freshwater is becoming increasingly scarce, due to improper management, indiscriminate use and a changing climate. Water scarcity impacts not only hot climate countries but regions such as Poland, where drought causes greatest economic losses in agriculture among all extreme events²¹. Lack of water resources has considerable impact on crop yields and livestock production as it threatens food security, while simultaneously undermining rural livelihoods and incomes. To ensure sustainable water management for agriculture, there is an urgent need to produce more crop per drop of water used.



Note. The indicator measures total water use as a percentage of renewable freshwater resources available in a given territory and over a given period. It describes the amount of water abstraction and the amount of water returned before or after use to the environment through river basins (e.g. leaks, discharges by economic sectors). The difference between water withdrawal and return is considered as “water use”.

Source: Eurostat database (online data code: sdg_06_60).

²¹ See chapter 5.

Improvements in the handling of water resources must be built on an integrated approach to soil-water-plant-nutrient management. This should include optimizing irrigation, while soil fertility needs to be improved to ensure that crop use of water is not limited by nutrient or physical constraints. Key adaptation measures include soil conservation, efficient irrigation technologies, water harvesting, and the cultivation of drought-tolerant crop varieties, all of which enhance the capacity of agricultural systems to withstand climatic variability.

All of these measures counteract climate variability and growing water scarcity while maximizing water-use efficiency and decreasing water wastage that has been a significant issue in agricultural production for centuries. It takes the form of inefficient water distribution, evaporation, and runoff associated with conventional farming techniques e.g. furrow irrigation. Water losses also contribute to soil erosion, nutrient leaching, and waterlogging, affecting crop yield²². Additionally, water wastage results in energy wastage as conventional water manage-

ment methods often require significant energy inputs for pumping and distribution.

Having all this in mind, it is clear that resilience in agriculture cannot be achieved without tackling water-scarcity issues. Though drought and weather conditions cannot be controlled, adaptation of farming operations and technologies to those events as well as to long-term water-scarcity issues is already possible.

Leading solutions and approaches

Reclaiming used water and collecting it is a crucial part of assuring appropriate water supply for farms. This goal could be attained through different technologies, or most preferably through a combination of solutions in a synergetic system. These technologies can be categorized by their objective:

» **Rainwater Harvesting:**

This involves collecting and storing rainwater runoff from rooftops, land surfaces, etc. for later use in agriculture. This technique utilizes various structures to capture rainwater and channel it to storage tanks and reservoirs.

» **On-farm water storage:**

Ponds, tanks, or reservoirs that are used to store water for irrigation and other agricultural purposes. In addition to supporting crop production, these facilities can supply water for livestock and emergency situations, thereby increasing the resilience of agricultural enterprises to climate variability.

» **Water recycling and reuse:**

Treating and reusing wastewater, drainage water, or other sources for irrigation and agricultural purposes. Using sedimentation, filtration, and disinfection, enables its reuse in agricultural applications.

By improving water use efficiency, reducing energy consumption, and promoting soil conservation, innovative irrigation technologies can contribute to the resilience and sustainability of agricultural systems in the face of growing water scarcity and climate change:

» **Drip irrigation:**

By delivering water directly to the root zone through a network of pipes, emitters, and distribution lines, drip irrigation precisely targets the crop root system, substantially reducing evaporation losses and improving irrigation efficiency. An advanced variation - subsurface drip irrigation, uses irrigation emitters installed below the soil surface to minimize evaporative losses even further while reducing weed development.

» **Precision irrigation and weather-based irrigation scheduling:**

This technology combines sensor networks and data analytics to enable a continuous adaptation of water delivery in response to changing environmental conditions, thereby increasing both water-use efficiency and crop performance.

» **Water system automation:**

Automated valves, pumps and control units (with predefined or sensors-collected parameters) regulate water flow and pressure throughout irrigation networks, ensuring accurate and uniform water distribution across agricultural fields, significantly reducing labour requirements and costs while improving irrigation precision.

Agroecological practices are typically perceived as tools aimed at soil fertility and health. However, they serve a dual goal. Besides improving soil condition they limit water demand of agricultural operations as well as contribute to water-resilience:

» **Drought-resistant crop varieties:**

Selecting varieties that have lower water needs results in more stable yields during times of water-scarcity.

» **Soil moisture conservation practices:**

Practices include mulching, conservation tillage, cover cropping reduces evaporation and runoff while enhancing water retention for plant uptake²³.

» **Soil amendments:**

Organic matter and soil conditioners reduce evaporation, improve water infiltration, and increase the soil's capacity to retain moisture and reduce erosion.

» **Agroforestry:**

Integrating trees and shrubs into agricultural systems provides shade, windbreaks but also reduces evaporation and soil erosion, which contribute to an improved water resilience.

23 (Srinivasarao et al., 2015).

Dutch capability in integrated water management

Water has always been a critical constraint as well as an engineering opportunity in the Netherlands. Sophisticated irrigation systems, canals, dikes, and advanced management are only some of the application used in the country to assure stable and efficient water supply. The Netherlands has established itself as a global leader in the development of innovative technologies for sustainable water management.

» **Wastewater treatment as well as animal manure processing:**

Comprehensive manure treatment technologies that combine anaerobic digestion, biogas production, nitrogen recovery, and advanced purification to produce water suitable for environmental discharge. Treatment commonly combine membrane filtration, ultrafiltration, reverse osmosis, activated carbon, UV disinfection, and advanced oxidation processes to remove pathogens, micropollutants, and excess nutrients. These recovered nutrients can be reused as fertilizers,

supporting circular economy objectives and reducing dependence on mineral fertilizers.

» **Water recycling in greenhouse horticulture:**

The Netherlands is a world leader in closed-loop greenhouse production, where irrigation water is continuously collected, disinfected, and reused. Modern greenhouse systems recover drainage water, monitor nutrient concentrations in real time, and recirculate irrigation water, reducing freshwater consumption by up to 90–95% while minimizing nutrient emissions.

» **Hydroponics:**

Soil-free methods deliver nutrients directly to plant roots, achieving faster growth and considerable water savings while producing vegetables, herbs, and ornamentals in both high-tech greenhouses and controlled-environment agriculture systems.

» **Nature-based water treatment solutions:**

Alongside engineered systems, the Netherlands has extensive expertise in constructed wetlands,

natural filtration systems, and buffer zones that improve water quality while enhancing biodiversity and landscape resilience. Technology based on extensive network of pumps, dikes, and sluices keeps farmland productive despite increasing risks from climate change and saltwater intrusion.

» **Sensors & Satellite Insights:**

Advanced solutions such as real-time water stress monitoring enable farms to detect drought or flooding risks, optimize irrigation timing, and safeguard yields.

» **Irrigation systems:**

Drip and precision irrigation coupled by the use of sensors and data help to optimise water dosage and timing. This is particularly relevant for fruit and vegetable production. Recirculating irrigation systems ensure that water and nutrients not absorbed by the plant are captured, filtered, and reused, minimizing losses, nutrient leaching and pollution.

» **Drainage technology:**

Diverting the excess water into reservoirs

using drainage systems protects fields from flooding. Closed drainage systems allow rainwater to be retained rather than discarded and to decrease salinity and nutrient loss in the process.

» **Freshwater storage:**

Innovative storage tanks, that seamlessly integrate with modern water systems within the agricultural sector, specifically horticulture. They have distinctive advantages, such as better pollution and nutrient management that open reservoirs like ponds.

