



INNOVATIVE APPROACHES IN SUSTAINABLE AGRICULTURE:

CLIMATE-SMART TECHNOLOGIES,
BIOTECHNOLOGY, AND RURAL
DEVELOPMENT MARKETING
STRATEGY

EDITOR
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**INNOVATIVE APPROACHES IN SUSTAINABLE
AGRICULTURE:**
Climate-Smart Technologies, Biotechnology, and Rural Development

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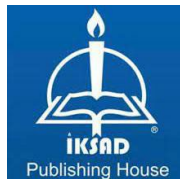
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CONTENTS

PREFACE.....	1
---------------------	----------

CHAPTER 1

THE USE OF ROBOTS IN AGRICULTURE

Assoc. Prof. Dr. Hilal ERDOĞAN

Prof. Dr. Halil ÜNAL.....	3
---------------------------	---

CHAPTER 2

EFFECTS OF TEMPERATURE ON THE PHYSIOLOGICAL CHARACTERISTICS OF ENTOMOPATHOGENIC NEMATODES

Res. Assist. Alperen Kaan BÜTÜNER

Prof. Dr. İsmail Alper SUSURLUK.....	31
--------------------------------------	----

CHAPTER 3

CLIMATE-SMART AGRICULTURAL PRACTICES AND THE LIVELIHOODS OF SMALLHOLDER FARMERS IN NIGERIA

Ozioma Faith ORAZULIKE

Angela Ebere OBETTA.....	41
--------------------------	----

CHAPTER 4

BACTERIA AND NANOMATERIALS PROMOTING PLANT GROWTH in SUSTAINABLE AGRICULTURE

Assoc. Prof. Dr. Çiğdem YAMANER.....	65
--------------------------------------	----

CHAPTER 5

THE DIFFUSION OF DIGITAL AGRICULTURE WITHIN RURAL DEVELOPMENT SUPPORT MECHANISMS IN TÜRKİYE: A POLICY ANALYSIS OF THE KKYDP AND IPARD PROGRAMS

Dr. Ali Emrah ŞAHİN.....	87
--------------------------	----

CHAPTER 6

GOVERNING FRESH PRODUCE VALUE CHAINS FOR MEASURABLE LANDSCAPE OUTCOMES

Gaetano RAGO.....	109
-------------------	-----

CHAPTER 7

CASCADING EFFECTS ON FOOD-SYSTEM STABILITY, NUTRITION AND MARKETS OF POLLINATION AS CRITICAL INFRASTRUCTURE

Assist. Prof. Dr. Duran ÖZKÖK

Assist. Prof. Dr. Nihat YILMAZ

Assist. Prof. Dr. Gülşen YILMAZ

Prof. Dr. Mürsel KARABACAK.....141

CHAPTER 8

DIOXIN-LIKE CONTAMINANTS: SOURCES, EMISSIONS, HEALTH EFFECTS AND REGULATIONS

Dr. Nadjima DEBBOU-IOUKNANE

Chief Engineer Amal OUATAH

Research Support Engineer Abdelkarim AZIB

Dr. Sadia BENFEDALA

Part-time Teacher Samia KHALIFA.....157

Preface

The rapid growth of the global population, the intensifying impacts of climate change, the depletion of natural resources, and the escalating pressure on food security mandate a fundamental paradigm shift in agricultural production systems. As traditional practices fall short of addressing today's complex socio-ecological crises, sustainability has transitioned from a mere environmental preference into a vital cornerstone for the future of global food systems.

Within this framework, *Innovative Approaches in Sustainable Agriculture: Climate-Smart Technologies, Biotechnology, and Rural Development* offers a comprehensive, interdisciplinary synthesis of technological transformations, biotechnological breakthroughs, and policy strategies shaping the future of agriculture. This volume bridges diverse domains-spanning autonomous agricultural robotics, climate-smart agro-ecological practices, beneficial soil microorganisms and nanomaterials that enhance plant stress tolerance, sustainable livestock welfare, and rural policy frameworks (such as IPARD and national support mechanisms).

The research presented in this book demonstrates how agricultural innovation extends beyond laboratory boundaries to directly empower smallholder farmers, enhance rural livelihoods, and fortify fresh produce value chains. Positioned at the intersection of biotechnology, digitalization, and climate resilience, this edited volume serves as an essential reference for academics, researchers, policymakers, and industry stakeholders seeking evidence-based solutions for next-generation agricultural systems.

I express my deepest gratitude to all contributing authors for their valuable scientific insights, to the distinguished peer reviewers for their rigorous evaluations and for ensuring the highest academic standards, and to the publishing team for their dedication throughout the production process. May this volume serve as a valuable reference and inspire future research and interdisciplinary endeavors in sustainable agriculture and rural development.

13.10.2026

Prof. Dr. Ahmet ÇELİK

CHAPTER 1

THE USE OF ROBOTS IN AGRICULTURE*

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1. INTRODUCTION

Various factors necessitate the adoption of agricultural mechanisation. Among the most compelling are reductions in human labour, increases in productivity, improvements in the timing of operations such as sowing and harvesting, and reductions in intensive labour requirements. Agricultural activities are physically demanding, and working conditions are often challenging. Operating a tractor-drawn plow is significantly less physically demanding than manually tilling land with a shovel for an entire day. Compared to manual labor, a tractor-driven plow covers far more acreage in the same timeframe, substantially boosting operational efficiency and productivity. In agricultural systems, operational timeliness is critical; executing key tasks such as planting and harvesting within optimal timeframes directly enhances crop yields and overall profitability. Furthermore, agricultural labor requirements fluctuate seasonally, peaking drastically during planting and harvesting phases compared to intermediate crop growth stages. These surges make labor management particularly challenging. Farm mechanization addresses this issue by mitigating labor spikes during high-demand periods, fostering a more balanced and manageable workforce throughout the year (Lantin, 2016).

Despite fundamental shifts in agricultural practice, core tasks-tilling soil, sowing seeds, tending crops, and conducting harvest and threshing-remain essential to the production cycle. Nevertheless, the methods of executing these operations have undergone a profound historical transformation. Soil tillage originated with basic wooden plows operated by human effort or draft livestock. The advent of steel metallurgy subsequently yielded the mouldboard plow, a landmark innovation that dramatically enhanced weed suppression and soil aeration. Similarly, planting evolved from primitive manual broadcasting to row cropping-initially using simple hand tools and later transitioning to mechanized seed drills. This shift to structured row planting enabled precise control over plant density while streamlining weed management across crop growth cycles (Shuqiet et al., 2019).

Historically, crop harvesting relied on manual labor using scythes or sickles. Once gathered, crops were bound into sheaves and moved to a centralized site for threshing, which involved beating the plants with sticks or treading them with livestock. Separation of grain from chaff and straw was achieved through winnowing in ambient wind; workers repeatedly dropped the

threshed mixture from an elevated position, allowing air currents to disperse lighter debris while heavier grain settled into piles below. The introduction of mechanical reapers with reciprocating blades automated crop cutting, though binding initially remained manual until binder mechanisms integrated both steps. Subsequently, steam power enabled stationary mechanical threshers, replacing natural breeze with powered fans for winnowing. Ultimately, the advent of internal combustion engines consolidated cutting, threshing, and cleaning into a unified field unit, giving rise to the modern "combine harvester" (Brkic et al., 2001, 2004).

Historically, human effort served as the fundamental power source for agricultural tasks, later supplemented by draft animals. The introduction of steam engines in 1858 marked a shift toward mechanical energy as the primary driver of field operations. This was further revolutionized in 1889 with the construction of the first internal-combustion-engine tractor, which offered superior power and a lighter frame than its steam-powered predecessors. By the 1930s, high-compression diesel engines gained widespread adoption in tractor design. Contemporary tractors have evolved into sophisticated systems featuring hydrostatic transmissions, electro-hydraulic servos for precise depth and draft control, and climate-controlled, ergonomic cabs (Fitzgerald, 1991; Goering, 2008).

Furthermore, integrations of Global Positioning Systems (GPS) and Geographic Information Systems (GIS) have laid the foundation for precision farming, enabling onboard computing systems to log field heterogeneity and yield metrics to dynamically regulate agrochemical application rates, including fertilizers, pesticides, and herbicides (Marinoudi et al., 2019; Reina et al., 2017). Nevertheless, manual and animal labor remain dominant in many developing regions, and even highly mechanized economies still rely on hand harvesting for delicate fresh produce. Ultimately, national mechanization levels are determined by industrial development and labor availability (Pedersen et al., 2006).

Agricultural mechanisation has been a significant factor in reducing labour demands in farming and in facilitating the development of other industries. Around 1900, approximately two-thirds of the population in developed countries such as the United States was engaged in farming. Today, only about 3% of the population in developed countries is involved in

production agriculture. Agricultural mechanisation has transformed farming from a subsistence activity into a large-scale industry. Currently, in terms of monetary value, agricultural exports rank second only to arms sales for many countries. However, mechanisation in agriculture requires intensive capital and energy inputs. Energy costs and the financial capacity to purchase machinery largely determine the level of mechanisation within a society. Consequently, production agriculture faces numerous challenges. Rising energy costs, increased competition in global markets, and growing environmental concerns pose new challenges for agricultural engineers to address to maintain agricultural productivity and affordability. The field of agricultural machinery is dynamic and will continue to evolve to meet the changing demands of production agriculture (Fando and Klavdieva, 2021).

The agricultural sector is gradually transitioning towards data-driven farming through the adoption of emerging technologies. Electronics, including microprocessors, have become an integral component of modern agricultural equipment. Mechatronic systems represent one example of such integration. Another example is Site-Specific Crop Management (SSCM), also referred to as precision agriculture (Defterli et al., 2016; Slaughter et al., 2008).

In conventional agriculture, fields are typically treated uniformly. For example, fertiliser application rates remain constant across the entire field, even though the field itself may not be homogeneous. In hilly terrain, soil near the hilltop may retain little rainfall, whereas soil at the base of the hill may retain excess water. Precision agriculture aims to exploit such spatial variability. Due to the uneven land structure, the water-holding capacity varies across different points in the field, which consequently affects fertilisation requirements. Similarly, weed distribution may vary spatially within a field. Applying pesticides uniformly across the entire field may therefore cause unnecessary harm to both the environment and human health. Likewise, pest insect populations may vary across locations, and non-targeted pesticide applications may lead to inefficiencies and increased costs (Kai et al., 2003).

Precision agriculture, often termed smart farming, draws its foundational principles from industrial manufacturing innovations that emerged throughout the 1970s and 1980s. This approach leverages sensing technologies and automated controls to establish robust monitoring and targeted intervention frameworks, ultimately driving operational efficiency. The evolution of

precision farming stems primarily from the imperative to address spatial and temporal field heterogeneities more effectively. By employing intelligent field machinery, the goal is to optimize agrochemical and resource distribution through precise, localized applications. Moreover, the rise of autonomous robotics has facilitated a new paradigm of adaptable field tools centered around compact, smart units. Collectively, these advancements mitigate resource waste, bolster farm profitability, curb ecological degradation, and strengthen long-term food sustainability (Usery et al., 1995).

Robotic technologies have considerable potential to create new opportunities in agriculture, such as operating in wet soils or performing tasks at night. In addition, sensory data collected by robotic platforms in the field can provide valuable information regarding soil conditions, seeds, livestock, crops, operational costs, farm equipment, water usage, and fertiliser applications. Low-cost Internet of Things (IoT) technologies, combined with advanced analytical methods, already assist farmers in analysing data on weather, temperature, humidity, and market prices. These technologies also help farmers make more informed decisions regarding yield optimisation, planning improvements, and resource allocation, while minimising waste and maximising productivity (Fountas et al., 2020; Stone, Benneweis and Van Bergejik, 2008).

Worldwide agricultural operations have developed an extensive reliance on synthetic chemical treatments to manage weeds, insect infestations, and plant pathologies. However, heightened awareness regarding chemical safety and ecological disruption has prompted the phase-out of numerous commercial formulations, narrowing the spectrum of active ingredients accessible to growers. Concurrently, escalating regulatory hurdles and registration expenses have restricted the entry of novel crop protection chemicals into the market. These dynamics underscore an urgent global imperative to establish sustainable cultivation strategies that drastically reduce or eliminate reliance on pesticides. In response, modern weeding robotic platforms leverage vision-guided mechanical hoes, ultra-precise spray systems, or laser systems to reduce herbicide use—a field showing immense potential despite ongoing technological refinement. Furthermore, advanced sensory arrays deployed on field robots facilitate early and pinpoint identification of pathogens and insect threats, enabling spot application of fungicides and insecticides. Such autonomous

systems can also be seamlessly embedded into Integrated Pest Management (IPM) frameworks to achieve targeted, economical distribution of biological control agents (Cowan and Gunby, 1996; Huang et al., 2019; Shoemaker, 1973).

Robotic systems used in agricultural processes can generally be classified into the following categories: 1-Weed control robots, 2-Seeding robots, 3-Disease and insect detection robots, 4-Crop monitoring (plant monitoring and phenotyping) robots, 5-Spraying robots, 6-Harvesting robots, 7-Plant/facility management and biological control robots (Blackmore et al., 2009).

2. ROBOTIC SYSTEMS USED IN AGRICULTURE

2.1. Weed Control Robots

Weed control is one of the most repetitive, tedious, and time-consuming activities in crop production cycles. Particularly on small farms in developing countries, weed management accounts for more than 40% of total labour requirements. In addition to being one of the most difficult tasks, weed management is also among the most expensive operations due to high labour costs, especially in labour-intensive crops. Moreover, weed removal during crop production often requires large amounts of herbicides, which can have negative environmental impacts. For instance, global estimates indicate that weeds account for 46.2–61.5% of potential yield losses in rice, wheat, and maize, while pests account for 27.3 – 33.7% (Oerke, 2006; Utstumo et al., 2018). Traditionally, two main approaches have been used for weed control: Mechanical weed control and chemical weed control.

Mechanical weed control involves removing weeds by uprooting, burning, or cutting them. Various tools exist for each of these mechanical methods. For robotic weed removal to function effectively, the system must first detect crop rows and subsequently cut or uproot the weeds. The row-detection accuracy of mechanical weed removal robots is typically less than 25 mm (Bakker et al., 2006; Naio, 2026). Systems developed for both mechanical and chemical weed control have reported effectiveness rates ranging from 65% to over 90%. However, several commercial mechanical weeding robots have been introduced without clearly defined performance metrics (Kim et al., 2012; Reiser et al., 2019; Vitrover, 2026).

Chemical weed control, on the other hand, involves spraying herbicides that are toxic to weeds. Because it requires relatively little labour, it has become a popular method. Herbicide manufacturers have also developed active ingredients that are selectively toxic to weeds but harmless to crops, allowing full-field spraying. Nevertheless, many chemical substances are currently restricted or expected to be restricted in the European Union, primarily due to environmental and human health concerns. Additionally, weeds have developed resistance to several herbicides, making them increasingly difficult to control. A major proposed solution is selective or spot spraying, where herbicides are applied only to detected weeds rather than across the entire field. However, this approach requires more time for weed detection. Fortunately, recent advances in computer vision technologies enable this detection process to be automated and integrated into advanced spraying or weeding robots (Mengüç and Elibüyük, 2014).

Parallel to mechanical weeders, weed identification accuracy serves as a primary benchmark for evaluating chemical weeding robots. Deploying a Drop-on-Demand (DoD) mechanism that identifies weeds along crop lines and targets herbicide droplets onto foliage, peak operational efficacy reached 100% among chemical robotic platforms (Asterix, 2026; Utstumo et al., 2018). Under optimal field conditions, the EcoRobotix (2022) system achieves an overall weed identification and eradication rate exceeding 85%. Although various commercial chemical weeding units have been introduced, standardized performance metrics remain largely undisclosed across the industry (BlueRiver, 2026; Ibex, 2026). Sensor arrays deployed across these platforms display comparable functional capacities. Optical sensors are universal, predominantly featuring Red-Green-Blue (RGB), infrared (IR), or standard webcams. Furthermore, spatial orientation and relative proximity to targeted weeds are frequently determined through auxiliary sensors, including acoustic rangefinders, gyroscopic devices, and laser distance meters (Van Evert et al., 2006).

Lee, Slaughter, and Giles (1999) conducted a study on weed control detection in tomato fields using a robotic system they developed. They used a color camera as a detection sensor to detect weeds. In their experiments, 24.2% of the weeds were incorrectly identified and treated with pesticides, while 52.4% were not treated.

Bakker et al. (2006) used a color camera for weed detection. They performed mechanical weed control in sugar beet. While the row detection sensitivity they obtained was <25 mm, the weed removal rate on the row reached 90%.

Van Evert et al. (2006) conducted weed control studies on potato and corn crops. Using a system they developed, they detected weeds with a webcam and a solid-state gyroscope. They employed chemical control methods. Their weed detection accuracy was 98% for potatoes and 89% for corn.

Klose, Thiel, Ruckelshausen, and Marquering (2008) used cameras on a robotic system they developed to detect weeds. They used optical and acoustic sensors to determine the spraying distance for chemical control. As a result of their studies, they successfully detected and sprayed the plants, but no performance metrics were recorded.

Kim et al. (2012) studied weed detection in rice plants using a robotic system they developed. Their research utilized sensing sensors such as a laser rangefinder and an inertial measurement unit (IMU). They mechanically combated weeds with the robot, achieving an accuracy of less than 62 mm.

Utstumo et al. (2018) detected weeds in carrot plants using RGB infrared cameras and achieved 100% effectiveness with the DoD method. Weeds are detected on the row by the camera, and spraying is triggered. The required number of droplets is applied based on the weed volume.

Reiser et al. (2019) developed a robotic tilling machine to control weeds in vineyards. They detected vine trunks using electronic and mechanical sonar sensors. The electronic circuit measured the time between the propagation of sound waves from an ultrasonic speaker and their detection by the ultrasonic microphone after hitting and reflecting off an obstacle. This time was then divided by two and multiplied by the speed of sound to calculate the distance between the obstacle and the ultrasonic sensor. Using this method, they achieved mechanical weed control with 82% accuracy.

The robot named “ARA”, developed by EcoRobotics (2026), performs surface spraying precisely only on the target plant. Capable of operating at a maximum speed of 7 km/h, the robot can inspect 96 hectares per day. It can operate day and night. It has an arm with 156 nozzles spaced 4 cm apart.

Three different robots developed by Naio (2026) are commercially used in weed control. The robot sold under the name "OZ" operates completely

autonomously thanks to Real Time Kinematic (RTK) guidance, which provides high positioning performance near a base station for small areas. Another robot, "DINO," navigates autonomously in fields with 2 cm accuracy, thanks to a guidance system that combines RTK-GPS and other sensor data. DINO detects planting rows and positions tools as close to the plants as possible. The robot named "TED," specifically designed for vineyards, is used for precise mechanical weed control.

2.2. Seeding Robots

Planting is a fundamental task in the crop production cycle and accounts for a significant share of labor costs. Seed planting machines have been developed to provide precise seed placement. As recent studies have shown the importance of plant density for high yields, precision planting has gained greater attention in the scientific community, leading to the development of seed-planting robots in recent years (Testa et al., 2016).

When the currently published sources are examined, the main crops targeted for seeding robots are primarily cereals, with wheat, rice, and maize taking precedence (Haibo et al., 2015; Ruangurai et al., 2015). On the other hand, progress has been made in commercial seeding robots, such as those from Fendt (2026), which can be used as part of an intelligent fleet or as standalone units. The most important information for seeding is the depth and location where the seed will be sown. Therefore, force, pressure, and angle sensors are used to combine coding, wheel compasses, and displacement sensors.

Katupitiya (2014) developed a robotic system for wheat planting. They utilized force, displacement, and angle sensors. The path-tracking error is ± 5 cm, and the angle errors are approximately zero.

Haibo et al. (2015) developed a robotic system for wheat planting using signal, angle, pressure, and infrared sensors. Their results showed an accuracy of 93.3%.

Ruangurai et al. (2015) developed a machine capable of automatically navigating a rice paddy field and controlling the number of rice seeds per planting point and the distance between planting points. In a field test, they achieved 92% accuracy for the number of seeds dropped and an error of only about 5 cm at the dropping point.

FarmDroid (2026) has developed a solar panel-driven field robot, the “FarmDroid FD20,” which uses a GPS signal to mark the placement of crops during planting and then performs mechanical weed control both between and on the rows. The precision of planting allows close monitoring of the crop, thereby minimizing or eliminating the need for manual weed control. Four solar panels on the robot generate power for a battery pack.

The robotic planting machines named “XAVER” and “MARS”, developed by Fendt (2026), use small robots working in swarms and a cloud-based solution to plan, monitor, and accurately record precise planting. The location and planting time of each seed are accurately recorded. Knowing exactly where the seed was planted facilitates subsequent agricultural activities.

2.3. Disease and Insect Detection Robots

In modern plant protection, autonomous systems have emerged as a vital alternative to traditional scouting practices, which often fail to identify early-stage infestations and infections. Timely pathogen identification plays a critical role in mitigating severe financial yield losses; however, robotic applications targeting insect pests remain relatively underdeveloped. This disparity stems from the inherent difficulties of entomological monitoring, as insects frequently shelter under foliage, within vegetative buds, or beneath the soil surface.

Because plant pathology identification relies largely on optical cues, vision-based modalities are fundamental to these platforms. Diagnostic accuracy in this context is the proportion of diseased specimens correctly identified among the total infected population. Standard RGB color cameras are widely adopted due to their cost-effectiveness and operational simplicity. Multispectral imaging systems are also utilized, though they incur higher hardware costs and require greater computational resources. While advanced multi- and hyperspectral systems are frequently integrated alongside conventional color sensors, increased hardware complexity does not consistently translate into superior diagnostic performance, leading many streamlined platforms to depend exclusively on RGB image acquisition (Schor et al., 2016, 2017).

Pilli, Nallathambi, George, and Diwanjive (2015) conducted studies on disease detection in cotton and peanuts. They used an RGB camera to detect bacterial blight and magnesium deficiency in cotton, and leaf spot and

anthracnose in peanuts. The disease-detection accuracy they achieved in peanut studies ranged from 83% to 96%. For cotton diseases, they achieved accuracies of 90% or higher.

Schor et al. (2016, 2017) used a color camera to detect powdery mildew (PM) and tomato spotted wilt virus (TSWV) in greenhouse pepper plants. This method showed high accuracy (90%). Using a multispectral camera, they achieved 80% and 61% accuracy for these two diseases, respectively.

Liu, Hu, Zhao, Bai, and Wangve (2019) designed a machine using an RGB camera for detecting *Pyralidae* insects on tomato and rice plants. Their experimental results showed that the robotic vehicle could automatically capture pest images and achieve 94.3% recognition accuracy in the field.

Rey, Aleixos, Cubero, and Blascove (2019) developed a different approach combining a series of sensors to detect *Xylella fastidiosa* in olive trees. They used a digital single-lens reflex (DSLR) camera, a hyperspectral system in the near-infrared (NIR) range, a light detection and ranging sensor (LiDAR), and a thermal camera in the Blue Normalized Difference Vegetation Index (BNDVI) mode. No information on the sensitivity of disease detection was provided.

Sultan Mahmud, Zaman, Esau, Price, and Prithiviraj (2019) detected powdery mildew leaf disease in strawberry plants using a machine vision system under both natural and artificial lighting conditions. According to their research findings, they achieved accuracy rates of 72% and 95% under the two different lighting conditions, respectively.

2.4. Crop Monitoring Robots

Crop surveillance is a foundational agricultural strategy critical to safeguarding yield potential and product quality. Historically, physiological stress has been identified by visible indicators, including foliar lesions, wilting, chlorosis, and other morphological anomalies. Modern developments in remote sensing have expanded these diagnostic capabilities, allowing early detection of sub-clinical plant stress factors before visual symptoms manifest. Thermal imaging units and infrared pyrometers are deployed to map canopy temperature dynamics (Bayati and Fotouhi, 2018). Furthermore, multi-spectral data integration enables the calculation of spectral vegetation indices – such as the Normalized Difference Vegetation Index (NDVI) and Ratio Vegetation Index

(RVI) – to evaluate photosynthetic performance and overall plant vigor (Wang et al., 2018; Xue and Su, 2017). Despite substantial sensor acquisition costs, specialized autonomous platforms are increasingly deployed, primarily targeting perennial crop systems such as orchards and vineyards, though standardized performance benchmarks remain limited (Grape, 2026; Vinescout, 2026).

CO₂ concentration levels can significantly impact crop development. In this context, Iida, Kang, Taniwaki and Umeda (2008) developed the “Hexapod” robot to collect agricultural information, such as soil nutrients and plant growth, and to monitor CO₂ levels up to 2500 ppm.

To evaluate canopy volume, vegetative density, and overall plant physiological status, autonomous agricultural platforms integrate diverse optical sensors – including RGB, multispectral, and hyperspectral cameras – alongside spatial profiling technologies like LiDAR. However, navigating complex viticultural environments presents significant operational hurdles, as vineyards are frequently cultivated on steep, uneven, or mountainous topographies (Dos Santos et al., 2015).

Bietresato, Carabin, Vidoni, Gasparetto, and Mazzetto (2016) and Vidoni et al. (2017) conducted experimental evaluations in laboratory and semi-structured environments, developing a crop monitoring robot to estimate orchard canopy volume and vitality using a series of sensors and arguing that it is highly reliable.

Bayati and Fotouhi (2018) developed a crop-tracking robot with a measurement error of up to 2.5% for canola using cameras and sensors. For special cases, the platform is mounted on a cover to reduce the error.

Vaeljaots, Lehiste, Kiik and Leemet (2018) developed a general-purpose crop-monitoring robot and performed agricultural operations, including soil sampling.

Earthsense (2022) has developed a robot called “TERRASENTIA” suitable for crops such as corn, soybeans, and wheat.

In tandem with crop surveillance technology, autonomous phenotyping platforms are advancing rapidly. While crop monitoring and high-throughput phenotyping share considerable functional overlap through their mutual reliance on vision systems to gather comprehensive physiological data, their primary analytical objectives diverge. Phenotyping systems focus on structural

morphology, developmental trajectories, and agronomic traits associated with crop performance. Conversely, monitoring platforms prioritize evaluating immediate physiological health, stress conditions, and biochemical status (Deery et al., 2014). Demonstrating this phenotypic capability, Mueller-Sim et al. (2017) deployed a fully autonomous platform in sorghum trials, achieving a stem-detection accuracy of up to 96% while simultaneously assessing light interception, leaf-angle dynamics, foliar necrosis, and the Green-Red Vegetation Index (GRVI).

2.5. Spraying Robots

Robotic application platforms serve diverse field tasks, including targeted herbicide distribution for weed suppression, pesticide spraying for pathogen and insect management, and liquid fertilizer application. Despite conventional safety protocols, agricultural workers face significant occupational exposure to hazardous active ingredients; autonomous sprayers effectively mitigate these critical health risks. Driven by rapid innovations in artificial intelligence and computer vision, modern spraying robots are replacing blanket agrochemical applications with intelligent, highly selective spot-treatment systems. Deploying these advanced modalities enables farms to curb ecological degradation, limit dietary pesticide residues for consumers, and suppress the onset of chemical resistance in target pest populations (Fountas et al., 2020).

Sammons, Furukawa, and Bulgin (2005) tested the system they developed using cucumber plants. They conducted their tests using pulse, infrared sensors, and inductive sensors. They determined that the upper leaf cover was 95%, the lower leaf cover was 80%, and the overspray rate was 20%. They determined the system's success rate to be 95%.

Singh, Burks, and Lee (2005) developed a prototype vehicle platform with six-wheel differential steering for greenhouse spraying. Power was transmitted from two independent drives to the wheels via a chain and a sprocket. Using range information from ultrasonic sensors, they developed a "Fuzzy Logic Based Proportional Derivative" controller to navigate the vehicle through simulated greenhouse corridors.

Ogawa, Kondo, Monta, and Shibusawa (2006) developed and tested a robot capable of spraying chemicals under vine leaves using an ultrasonic

sensor and camera. Experimental results showed that the robot system enabled precise spraying and accurate operation recording.

Søgaard and Lund (2007) tested the robotic system they developed under controlled indoor conditions. They found that the spraying process could be applied with an accuracy of less than 1 cm and that the application speed could be twice that of traditional methods.

Sanchez-Hermosilla, Rodriguez, Gonzalez, Luis, and Berenguel (2010) conducted experiments in a greenhouse with the robotic system they developed and found that longitudinal, lateral, and orientation errors, including slip variation, were close to zero in navigation tests. They used medium and short-range sonar devices. They tested the spraying system along different operating points.

Oberti et al. (2013) conducted studies on grapevines grown in pots in a greenhouse environment. They used an RGB camera to identify diseased areas and apply pesticides. They determined the sensitivity of robotic selective spraying to be 85%, but found that 8% of the total healthy area was unnecessarily treated.

Underwood et al. (2015) designed a system for precisely spraying individual plants in a vegetable field using a fine-spray nozzle attached to a manipulator arm mounted on a mobile robot. In this system, which they named “Ladybird,” they used a hyperspectral camera, stereo vision, thermal, and monocular cameras.

Mahmud, Abidin, Mohamed, Rahman, and Iida (2019) conducted experiments with cantaloupe, a type of melon. They developed and implemented algorithms to enable the mobile robot to determine optimal routes. They confirmed that the Non-dominated Sorting Genetic Algorithm III (NSGA-III) yielded better-quality results than NSGA-II.

2.6. Harvesting Robots

Although harvesting remains an indispensable stage across all agricultural production cycles, it constitutes one of the most physically demanding and repetitive operations. To automate this phase, numerous commercial enterprises and academic research institutions have engineered specialized robotic platforms. Robotic harvesting architecture generally falls into two distinct categories: non-selective bulk harvesting, where entire crop

yields are collected indiscriminately, and selective harvesting, which targets exclusively mature, harvest-ready produce. Key operational benchmarks for evaluating selective systems focus on harvesting velocity and the picking success rate – defined as the proportion of undamaged, successfully harvested fruit relative to the total ripe population (Hayashi et al., 2014). Furthermore, harvesting operations must occur within a constrained temporal window upon crop maturity, requiring maximum yield recovery while preventing mechanical damage to both the produce and host plant. Consequently, technological development has largely focused on high-value specialty crops such as strawberries, where intensive labor demands drive up overall production costs (Feng et al., 2012).

Ceres, Pons, Jiménez, Martín and Calderón (1998) determined that the time required to grasp and detach a fruit in their developed system was 2 seconds per fruit. For this purpose, they utilized a pressure sensor, an infrared (IR) detection sensor, and a camera.

Umeda, Kubota and Iida (1999) developed a system for watermelon harvesting and reported a maximum picking rate of 66.7%. They utilized a CCD (Charge-Coupled Device) camera and a vacuum sensor.

Edan, Rogozin, Flash and Miles (2000) developed a robot for melon harvesting using two black-and-white CCD cameras, a proximity sensor, and far- and near-vision sensors. Their system could harvest one fruit every 15 seconds, achieving a maximum picking rate of 85.67%.

Hayashi, Ganno, Ishii and Tanaka (2002) successfully harvested eggplants in 64.1 seconds using their developed system. They employed a CCD camera and a photoelectric sensor, achieving a maximum picking rate of 62.5%.

Pilarski et al. (2002) engineered an automated mowing platform utilizing dual video cameras integrated with a global positioning sensor for field navigation. The system autonomously formulates comprehensive field-level harvesting schedules and executes operations by systematically mowing crop rows (specifically alfalfa), executing end-of-row turns to engage consecutive passes, maneuvering dynamically across the plot, and identifying real-time obstacles.

Silwal et al. (2016) utilized a color camera and a time-of-flight-based three-dimensional camera in their robotic system developed for apple

harvesting. They achieved a maximum harvesting rate of 84% and harvested one apple in 7.5 seconds.

Yaguchi, Nagahama, Hasegawa and Inaba (2016) developed a robotic system for tomato harvesting, achieving a harvesting time of 23 seconds per fruit and a maximum harvesting rate of 60%. They used stereo and PlayStation cameras. Their system harvests the tomato by first grasping it (1), then rotating it (2), and finally detaching it (3).

Feng, Zou, Fan, Zhang, and Wang (2018) utilized a camera and laser sensor for cherry tomato harvesting. However, since cherry tomatoes grow in clusters, they are harvested by cutting the clusters. By cutting a cluster of cherry tomatoes in 8 seconds, they achieved an 83% harvest rate.

Xiong, Peng, Grimstad, From and Isler (2019) harvested strawberries in 10.6 seconds, achieving a harvesting rate of 53.6%. After detecting the strawberry, they used a cutting method involving one passive arm and one active arm. RGB cameras and infrared sensors were utilized.

A wide variety of commercially developed harvesting robots are currently available. These systems are generally focused on crops such as strawberries (Agrobot, 2026; Dogtooth, 2026; Harvest Croo Robotics, 2026; Octinion, 2026), apples (Abundant Robots, 2026; FF Robotics, 2026), tomatoes (Metomotion, 2026; Root-AI, 2026), citrus fruits (Energid, 2026), bell peppers (Sweeper, 2026), and asparagus (Cerescon, 2026). These robotic systems are already available on the market and perform harvesting operations using cutting, detaching, and vacuum-based methods.

2.7. Plant/Facility Management Robots

In addition to primary field operations, there are robots focused on plant architecture. More specifically, these systems focus on material handling, pruning/thinning, and string tying. Although material handling is not a critical task within the production cycle, it is highly important in cultivation operations such as plant nurseries (Harvest Automation, 2026; Vision Robotics, 2026).

During hop plant growth, string tying is used to support plant climbing. This process requires intensive labor and incurs high costs. He, Zhou, Zhang and Charvet (2016) developed a string-tying robot achieving a success rate of up to 97% at a speed of 0.19 m/s. Botterill et al. (2017) and Zahid et al. (2020) developed robotic systems designed for pruning vines and apple trees. These

systems are structured to move along rows in a cabin-like configuration that shades sunlight. Pruning operations are carried out using a six-degree-of-freedom robotic arm equipped with cutting tools, cameras, and LED lighting systems.

2.8. Biological Control Robots

Biological control refers to practices aimed at keeping pest populations below the economic damage threshold by using living organisms rather than chemical substances. Although some precision agriculture techniques for biological control exist, they remain limited. For example, Parabug (2022) uses beneficial insects delivered by unmanned aerial vehicles, particularly in regions such as the United States and Australia, to combat pests in the field. Applications have been carried out across a wide range of scales, from strawberries to large hazelnut orchards, and from small plots to large agricultural fields.

Koppert (2026) has developed a system for the application of beneficial insects. In this system, beneficial insects are placed into a drum mechanism capable of carrying up to 30 L of material, where they are mixed and subsequently applied over crop rows via airflow. This system is called Natutec Drive. Similarly, another product developed by the company, Natutec Drone, uses a drone platform to apply beneficial insects.

Entomopathogenic nematodes (EPNs) are biological control agents used against soil-dwelling pest larvae. Since EPNs are living organisms, their application is relatively challenging. Erdoğan, Ünal and Lewis (2021) developed a patented prototype robotic system (NEMABOT) for the precise application of EPNs. The robot is constructed from 2 mm aluminum material. Using this robotic system, EPNs can be applied to a desired location, within a specified suspension volume, and in a controlled quantity. The robot operates in the X–Y–Z axes using stepper motors, which are controlled via a CNC control board. The robot executes movements through G-code instructions defined on the CNC controller. During application, the system activates a micro-switch, which sends a signal to an Arduino, which in turn controls a peristaltic pump. In this way, the robot determines the plant position and adjusts the pump operation according to the required application volume. It is therefore possible to apply either a uniform dose across all points or variable doses

depending on specific requirements. The software implemented on the Arduino provides flexibility in this regard. Furthermore, with NEMABOT, studies have been conducted in which EPN dosing is based on thrips damage levels using computer vision, in which image data acquired from a camera is analyzed to determine the appropriate dosage (Erdoğan et al., 2023; 2026).

REFERENCES

- Abundant Robots. (2026). Available at: <https://waxinvest.com/projects/abundant-robots/>
- Agrobot. (2026). Available at: <https://www.agrobot.com/>
- Asterix. (2026). Available at: https://www.adigo.no/portfolio/precision_spraying_robot/?lang=en
- Bakker, T., Van Asselt, K., Bontsema, J., Müller, J., Van Straten, G. (2006). An autonomous weeding robot for organic farming. In *Field and Service Robotics* (ss. 579-590). Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-540-33453-8_48
- Bayati, M., Fotouhi, R. (2018). A mobile robotic platform for crop monitoring. *Advances in Robotics and Automation*, 7(1), 1000186. <https://doi.org/10.4172/2168-9695.1000186>
- Bietresato, M., Carabin, G., Vidoni, R., Gasparetto, A., Mazzetto, F. (2016). Evaluation of a LiDAR-based 3D-stereoscopic vision system for crop-monitoring applications. *Computers and Electronics in Agriculture*, 124, 1-13. <https://doi.org/10.1016/j.compag.2016.03.017>
- Blackmore, B. S., Fountas, S., Gemtos, T. A., Griepentrog, H. W. (2009). A specification for an autonomous crop production mechanization system. *Acta Horti*, 824, 201-216. <https://doi.org/10.17660/ActaHortic.2009.824.23>
- Brkic, D., Sumanovac, L., Juric, T., Knezevic, D. (2001). Development tendencies of universal combine harvesters. *Strojarstvo*, 43, 41-48.
- Brkic, D., Sumanovac, L., Juric, T., Knezevic, D. (2004). Modern controlling and guiding of combine harvesters. *Strojarstvo*, 46, 161-169.
- Ceres, R., Pons, J. L., Jiménez, A. R., Martín, J. M., Calderón, L. (1998). Design and implementation of an aided fruit-harvesting robot (Agribot). *Industrial Robot*, 25, 337-346. <https://doi.org/10.1108/01439919810232440>
- Cerescon. (2026). Available at: <https://www.cerescon.com/EN/sparter>
- Cowan, R., Gunby, P. (1996). Sprayed to death: Path dependence, lock-in and pest control strategies. *The Economic Journal*, 106, 521-542. <https://doi.org/10.2307/2235561>

- Deery, D., Jimenez-Berni, J., Jones, H., Sirault, X., Furbank, R. (2014). Proximal remote sensing buggies and potential applications for field-based phenotyping. *Agronomy*, 4(3), 349-379. <https://doi.org/10.3390/agronomy4030349>
- Defterli, S. G., Shi, Y., Xu, Y., Ehsani, R. (2016). Review of robotic technology for strawberry production. *Applied Engineering in Agriculture*, 32, 301-318. <https://doi.org/10.13031/aea.32.11318>
- Dogtooth. (2026). Available at: <https://dogtooth.tech/>
- Dos Santos, F. N., Sobreira, H., Campos, D., Morais, R., Moreira, A. P., Contente, O. (2015, April). Towards a reliable monitoring robot for mountain vineyards. In *Proceedings of the 2015 IEEE International Conference on Autonomous Robot Systems and Competitions*, pp. 37-43. <https://doi.org/10.1109/ICARSC.2015.21>
- Earthsense. (2026). Available at: <https://www.earthsense.co/>
- EcoRobotix. (2026). Available at: <https://ecorobotix.com/en/>
- Edan, Y., Rogozin, D., Flash, T., Miles, G. E. (2000). Robotic melon harvesting. *IEEE Transactions on Robotics Automation*, 16, 831-835. <https://doi.org/10.1109/70.897793>
- Energid. (2026). Available at: <https://www.energid.com/industries/agricultural-robotics>
- Erdoğan, H., Erdinç, A., Bütüner, A. K., Ulu, T. C., Alper Susurluk, İ., Lewis, E. E., Ünal, H. (2026). Part I—Modernizing Nemabot: AI-Supported Identification of *Frankliniella occidentalis* Damage for Enhanced Biological Control Efficiency. *Journal of Field Robotics*, 43(2), 761-778. <https://doi.org/10.1002/rob.70068>
- Erdoğan, H., Ünal, H., Susurluk, İ. A., Lewis, E. E. (2023). Precision application of the entomopathogenic nematode *Heterorhabditis bacteriophora* as a biological control agent through the Nemabot. *Crop Protection*, 174, 106429. <https://doi.org/10.1016/j.cropro.2023.106429>
- Fando, R. A., Klavdieva, M. M. (2021). N.A. Borodin's first hand study of the USA power farming experience: The lessons from history. *AMA-Agricultural Mechanization in Asia Africa and Latin America*, 51, 82-86.
- FarmDroid. (2026). Available at: <https://farmdroid.dk/en/welcome/>
- Fendt. (2026). Available at: <https://www.fendt.com/int/xaver>

- Feng, Q., Zheng, W., Qiu, Q., Jiang, K., Guo, R. (2012, May). Study on strawberry robotic harvesting system. In Proceedings of the CAAE 2012 IEEE International Conference on Computer Science and Automation Engineering, (Vol. 1, pp. 320-324). <https://doi.org/10.1109/CAA.2012.6272606>
- Feng, Q., Zou, W., Fan, P., Zhang, C., Wang, X. (2018). Design and test of robotic harvesting system for cherry tomato. *International Journal of Agricultural and Biological Engineering*, 11, 96-100. <https://doi.org/10.25165/j.ijabe.20181101.2853>
- FF Robotics. (2026). Available at: <https://www.ffrobotics.com/>
- Fitzgerald, D. (1991). Beyond tractors—The history of technology in american agriculture. *Technology and Culture*, 32, 114-126. <https://doi.org/10.2307/3106015>
- Fountas, S., Mylonas, N., Malounas, I., Rodias, E., Santos, C. H., Pekkeriet, E. (2020). Agricultural robotics for field operations. *Sensors*, 20, 2672. <https://doi.org/10.3390/s20092672>
- Goering, C. E. (2008). A century of tractor development: 1907-2007. *Transactions of The ASABE*, 51, 379-383. <https://doi.org/10.13031/2013.24376>
- Grape. (2026). Available at: <https://www.grape-project.eu/home/>
- Haibo, L., Shuliang, D., Zunmin, L., Chuijie, Y. (2015). Study and experiment on a wheat precision seeding robot. *Journal of Robotics*, 696301. <https://doi.org/10.1155/2015/696301>
- Harvest Automation. (2026). Available at: <https://www.public.harvestai.com/>
- Harvest Croo Robotics. (2026). Available at: <https://www.harvestcroorobotics.com/>
- Hayashi, S., Ganno, K., Ishii, Y., Tanaka, I. (2002). Robotic harvesting system for eggplants. *Japan Agricultural Research Quarterly*, 36, 163-168. <https://doi.org/10.6090/jarq.36.163>
- Hayashi, S., Yamamoto, S., Tsubota, S., Ochiai, Y., Kobayashi, K., Kamata, J., ... Peter, R. (2014). Automation technologies for strawberry harvesting and packing operations in Japan. *Journal of Berry Research*, 4, 19-27. <https://doi.org/10.3233/JBR-140065>

- Huang, L., Chen, X., Tan, X., Chen, X., Liu X. (2019). A stochastic predator-prey model for integrated pest management. *Advances in Difference Equations*, 2019(1), 1-10. <https://doi.org/10.1186/s13662-019-2291-1>
- Iida, M., Kang, D., Taniwaki, M., Tanaka, M., Umeda, M. (2008). Localization of CO₂ source by a hexapod robot equipped with an anemoscope and a gas sensor. *Computers and Electronics in Agriculture*, 63, 73-80. <https://doi.org/10.1016/j.compag.2008.01.016>
- Kai, A., Gao-di, X. I. E., Yun-fa, L., Yu, X. (2003). Design of farmland GIS for precision agriculture. *Chinese Geographical Science*, 13, 20-24. <https://doi.org/10.1007/s11769-003-0079-3>
- Katupitiya, J. (2014). An autonomous seeder for broad acre crops. In *Proceedings of the American Society of Agricultural and Biological Engineers Annual International Meeting*, ss. 169-176. <https://doi.org/10.13031/aim.20141883199>
- Kim, G. H., Kim, S. C., Hong, Y. K., Han, K. S., Lee, S. G. (2012). A robot platform for unmanned weeding in a paddy field using sensor fusion. In *Proceedings of the IEEE International Conference on Automation Science and Engineering (CASE)*, ss. 904-907. <https://doi.org/10.1109/CoASE.2012.6386466>
- Klose, R., Thiel, M., Ruckelshausen, A., Marquering, J. (2008). Weedy-a sensor fusion based autonomous field robot for selective weed control. In *Proceedings of the Conference: Agricultural Engineering—Land-Technik*, ss. 167-172.
- Lantin, R. M. (2016). Agricultural mechanization in the Philippines, Part 1: Brief history. *AMA-Agricultural Mechanization in Asia Africa and Latin America*, 47(2), 80-86.
- Lee, W. S., Slaughter, D. C., Giles, D. K. (1999). Robotic weed control system for tomatoes. *Precision Agriculture*, 1(1), 95-113. <https://doi.org/10.1023/A:1009977903204>
- Liu, B., Hu, Z., Zhao, Y., Bai, Y., Wang, Y. (2019). Recognition of pyralidae insects using intelligent monitoring autonomous robot vehicle in natural farm scene. *arXiv:physics*, 1903, 10827. <https://doi.org/10.48550/arXiv.1903.10827>
- Mahmud, M. S. A., Abidin, M. S. Z., Mohamed, Z., Rahman, M. K. I. A., Iida, M. (2019). Multi-objective path planner for an agricultural mobile robot

- in a virtual greenhouse environment. *Computers and Electronics in Agriculture*, 157, 488-499. <https://doi.org/10.1016/j.compag.2019.01.016>
- Marinoudi, V., Sørensen, C. G., Pearson, S., Bochtis, D. (2019). Robotics and labour in agriculture. A context consideration. *Biosystems Engineering*, 184, 111-121. <https://doi.org/10.1016/j.biosystemseng.2019.06.013>
- Mengüç, Ç., Elibüyük, İ. Ö. (2014). Yabancı otlarda herbisitlere dayanıklılık ve yönetimi. *Türk Bilimsel Derlemeler Dergisi*, 7(2), 19-22.
- Metomotion. (2026). Available at: <https://www.metomotion.com/>
- Mueller-Sim, T., Jenkins, M., Abel, J., Kantor, G. (2017, Mayıs). The Robotanist: A ground-based agricultural robot for high-throughput crop phenotyping. In *Proceedings of the IEEE International Conference on Robotics and Automation*, ss. 3634-3639. <https://doi.org/10.1109/ICRA.2017.7989418>
- Naio. (2026). Available at: <https://www.naio-technologies.com/en/oz/>
- Oberti, R., Marchi, M., Tirelli, P., Calcante, A., Iriti, M., Hocevar, M., ... Ulbrich, H. (2013). Selective spraying of grapevine's diseases by a modular agricultural robot. *Journal of Agricultural Engineering*, 44, 149-153. <https://doi.org/10.4081/jae.2013.271>
- Octinion. (2026). Available at: <http://octinion.com/products/agricultural-robotics/rubion>
- Oerke, E. C. (2006). Crop losses to pests. *The Journal of Agricultural Science*, 144(1), 31-43. <https://doi.org/10.1017/S0021859605005708>
- Ogawa, Y., Kondo, N., Monta, M., Shibusawa, S. (2006). Spraying robot for grape production. *Springer Tracts in Advanced Robotics*, 24, 539-548. https://doi.org/10.1007/10991459_52
- Pedersen, S. M., Fountas, S., Have, H., Blackmore, B. S. (2006). Agricultural robots-system analysis and economic feasibility. *Precision Agriculture*, 7, 295-308. <https://doi.org/10.1007/s11119-006-9014-9>
- Pilarski, T., Happold, M., Pangels, H., Ollis, M., Fitzpatrick, K., Stentz, A. (2002). The demeter system for automated harvesting. *Autonomous Robots*, 13, 9-20. <https://doi.org/10.1023/A:1015622020131>
- Reina, G., Milella, A., Galati, R. (2017). Terrain assesment for precision agriculture using vehicle dynamic modelling. *Biosystems Engineering*, 162, 124-139. <https://doi.org/10.1016/j.biosystemseng.2017.06.025>

- Reiser, D., Sehsah, E. S., Bumann, O., Morhard, J., Griepentrog, H. W. (2019). Development of an autonomous electric robot implement for intra-row weeding in vineyards. *Agriculture*, 9(1), 18. <https://doi.org/10.3390/agriculture9010018>
- Rey, B., Aleixos, N., Cubero, S., Blasco, J. (2019). XF-ROVIM. A field robot to detect olive trees infected by *Xylella fastidiosa* using proximal sensing. *Remote Sensing*, 11(3), 221. <https://doi.org/10.3390/rs11030221>
- Root–AI. (2026). Available at: <https://root-ai.com/>
- Ruangurai, P., Ekpanyapong, M., Pruetong, C., Watwai, T. (2015). Automated three-wheel rice seeding robot operating in dry paddy fields. *Maejo International Journal of Science and technology*, 9(3), 403-412. <https://doi.org/10.14456/mijst.2015.31>
- Sammons, P. J., Furukawa, T., Bulgin, A. (2005, Aralık). Autonomous pesticide spraying robot for use in a greenhouse. In *Proceedings Australasian Conference on Robotics and Automation* (Vol. 1, No.9). Canberra, Australia, Commonwealth Scientific and Industrial Research Organisation.
- Sanchez-Hermosilla, J., Rodriguez, F., Gonzalez, R., Luis, J., Berenguel, M. (2010). A mechatronic description of an autonomous mobile robot for agricultural tasks in greenhouses. In *Mobile Robots Navigation*, IntechOpen.
- Schor, N., Bechar, A., Ignat, T., Dombrovsky, A., Elad, Y., Berman, S. (2016). Robotic disease detection in greenhouses: Combined detection of powdery mildew and tomato spotted wilt virus. *IEEE Robotics and Automation Letters*, 1(1), 354-360. <https://doi.org/10.1109/LRA.2016.2518214>.
- Schor, N., Berman, S., Dombrovsky, A., Elad, Y., Ignat, T., Bechar, A. (2017). Development of a robotic detection system for greenhouse pepper plant diseases. *Precision Agriculture*, 18(3), 394-409. <https://doi.org/10.1007/s11119-017-9503-z>
- Shoemaker, C. (1973). Optimization of agricultural pest management II: Formulation of a control model. *Mathematical Biosciences*, 17, 357-365. [https://doi.org/10.1016/0025-5564\(73\)90076-X](https://doi.org/10.1016/0025-5564(73)90076-X)

- Shuqi, S., Jiasheng, W., Dongwei, W. (2019). Development of agricultural mechanization in China and its current strategic focus. *Agricultural and Machinery Technologies*, 13, 4-7. <https://doi.org/10.22314/2073-7599-2019-13-3-4-7>
- Silwal, A., Davidson, J., Karkee, M., Mo, C., Zhang, Q., Lewis, K. (2016). Effort towards robotic apple harvesting in Washington State. In *Proceedings of the 2016 American Society of Agricultural and Biological Engineers Annual International Meeting*, American Society of Agricultural and Biological Engineers. <https://doi.org/10.13031/aim.20162460869>
- Singh, S., Burks, T. F., Lee, W. S. (2005). Autonomous robotic vehicle development for greenhouse spraying. *Transactions of the American Society of Agricultural and Biological Engineers*, 48(6), 2355-2361. <https://doi.org/10.13031/2013.20074>
- Slaughter, D. C., Giles, D. K., Downey, D. (2008). Autonomous robotic weed control systems: A review. *Computers and Electronics in Agriculture*, 61, 63-78. <https://doi.org/10.1016/j.compag.2007.05.008>
- Søgaard, H. T., Lund, I. (2007). Application accuracy of a machine vision-controlled robotic micro-dosing system. *Biosystems Engineering*, 96, 315-322. <https://doi.org/10.1016/j.biosystemseng.2006.11.009>
- Stone, M. L., Benneweis, R. K., Van Bergejik, J. (2008). Evolution of electronics for mobile agricultural equipment. *Transactions of The ASABE*, 51(2), 385-390. <https://doi.org/10.13031/2013.24374>
- Sultan Mahmud, M., Zaman, Q. U., Esau, T. J., Price, G.W., Prithiviraj, B. (2019). Development of an artificial cloud lighting condition system using machine vision for strawberry powdery mildew disease detection. *Computers and Electronics in Agriculture*, 158, 219-225. <https://doi.org/10.1016/j.compag.2019.02.007>
- Sweeper. (2026). Available at: <http://www.sweeper-robot.eu/>
- Testa, G., Reyneri, A., Blandino, M. (2016). Maize grain yield enhancement through high plant density cultivation with different inter-row and intra-row spacings. *European Journal of Agronomy*, 72, 28-37. <https://doi.org/10.1016/j.eja.2015.09.006>

- Umeda, M., Kubota, S., Iida, M. (1999). Development of “STORK”, a watermelon-harvesting robot. *Artificial Life and Robotics*, 3, 143-147. <https://doi.org/10.1007/BF02481130>
- Underwood, J.P., Calleija, M., Taylor, Z., Hung, C., Nieto, J., Fitch, R., Sukkarieh, S. (2015, May). Real-time target detection and steerable spray for vegetable crops. In *Proceedings of the International Conference on Robotics and Automation: Robotics in Agriculture Workshop*, Seattle, WA, USA, pp. 26-30.
- Usery, E. L., Pocknee, S., Boydell, B. (1995). Precision farming data management using geographic information sytems. *Photogrammetric Engineering and Remote Sensing*, 61(11), 1383-1391.
- Utstumo, T., Urdal, F., Brevik, A., Dørum, J., Netland, J., Overskeid, Ø., Berge, T.W., Gravdahl, J. T. (2018). Robotic in-row weed control in vegetables. *Computers and Electronics in Agriculture*, 154, 36-45. <https://doi.org/10.1016/j.compag.2018.08.043>
- Vaeljaots, E., Lehiste, H., Kiik, M., Leemet, T. (2018). Soil sampling automation case-study using unmanned ground vehicle. *Engineering for Rural Development*, 17, 982-987. <https://doi.org/10.22616/ERDev2018.17.N503>
- Van Evert, F. K., Van Der Heijden, G. W. A. M., Lotz, L. A. P., Polder, G., Lamaker, A., De Jong, A., ... Van Der Zalm, T. (2006). A mobile field robot with vision-based detection of volunteer potato plants in a corn crop. *Weed Technology*, 20(4), 853-861. <https://doi.org/10.1614/WT-05-132.1>
- Vidoni, R., Gallo, R., Ristorto, G., Carabin, G., Mazzetto, F., Scalera, L. ve Gasparetto, A. (2017, November). Byelab: An agricultural mobile robot prototype for proximal sensing and precision farming. In *Proceedings of the ASME International Mechanical Engineering Congress and Exposition (Vol. 58370)*, American Society o Mechanical Engineers. <https://doi.org/10.1115/IMECE2017-71216>
- Vinescout. (2026). Available at: <http://vinescout.eu/web/>
- Vision Robotics. (2026). Available at: <https://www.visionrobotics.com/vr-grapevine-pruner>
- Vitirover. (2026). Available at: <https://www.vitirover.fr/en-home>

- Wang, Y., Hu, X., Hou, Z., Ning, J., Zhang, Z. (2018). Discrimination of nitrogen fertilizer levels of tea plant (*Camellia sinensis*) based on hyperspectral imaging. *Journal of Science Food and Agriculture*, 98(12), 4659-4664. <https://doi.org/10.1002/jsfa.8996>
- Xiong, Y., Peng, C., Grimstad, L., From, P. J. Isler, V. (2019). Development and field evaluation of a strawberry harvesting robot with a cable-driven gripper. *Computers and Electronics in Agriculture*, 157, 392-402. <https://doi.org/10.1016/j.compag.2019.01.009>
- Yaguchi, H., Nagahama, K., Hasegawa, T., Inaba, M. (2016). Development of an autonomous tomato harvesting robot with rotational plucking gripper. In *Proceedings of the IEEE International Conference on Intelligent Robots and Systems*, ss. 652-657. <https://doi.org/10.1109/IROS.2016.7759122>

CHAPTER 2

EFFECTS OF TEMPERATURE ON THE PHYSIOLOGICAL CHARACTERISTICS OF ENTOMOPATHOGENIC NEMATODES

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1. INTRODUCTION

Entomopathogenic nematodes (EPNs) belonging to the families Steinernematidae and Heterorhabditidae are recognised as some of the most effective biological control agents used against a wide range of agricultural pests (Stock et al., 1999; Burnell and Stock, 2000; Kary et al., 2009). These organisms are barely visible to the naked eye and spend the majority of their life cycle in the soil, where they encounter and infect susceptible hosts. Upon locating a suitable host, infective juveniles (IJs) enter the insect through natural body openings and release their symbiotic gram-negative bacteria belonging to the family Enterobacteriaceae into the host haemocoel. These bacteria rapidly reproduce within the insect, causing septicaemia and ultimately leading to host death within 24–48 hours (Boemare et al., 1996; Stock et al., 1999; Mahar et al., 2005).

The ability of EPNs to actively search for hosts, together with their sustainability and environmentally friendly characteristics, has established them as important components of Integrated Pest Management (IPM) programmes (Georgis, 1992; Askary and Abd-Elgawad, 2021; Erdoğan and Ulu, 2024). Unlike synthetic pesticides, EPNs pose minimal risks to humans, non-target organisms and the environment. Furthermore, increasing awareness of the adverse effects of chemical pesticides on non-target organisms and ecosystems has enhanced the commercial importance of EPNs and stimulated growing interest in their application as biological control agents (Boemare et al., 1996; Cruz-Martínez et al., 2017; Bütüner and Susurluk, 2023; Yaraşır et al., 2024).

The physiological performance of EPNs is strongly influenced by various abiotic factors; among these, temperature is considered one of the most critical. Temperature can significantly affect numerous biological characteristics, including survival, infectivity, reproductive capacity, mobility and persistence in the environment (Brown and Gaugler, 1997; Gouge et al., 1999; Chen et al., 2003). As EPNs spend a substantial proportion of their life cycle in soil habitats, fluctuations in temperature directly influence their physiological processes and consequently their efficacy as biological control agents. Both low and high temperatures can alter metabolic activity, energy reserves, host-seeking behaviour and tolerance to environmental stress. Numerous studies have demonstrated considerable variation among EPN

species and isolates in their responses to temperature, indicating differences in thermal tolerance and adaptive capacity (Pervez et al., 2016; El Khoury et al., 2018; Bütüner and Susurluk, 2023; Matuska-Łyżwa et al., 2024; Susurluk and Bütüner, 2024).

In recent years, the increasing impact of climate change on agricultural production systems has intensified interest in understanding the responses of EPNs to environmental stressors. In particular, temperature fluctuations have the potential to directly affect the survival, distribution and biological control performance of EPN populations (Griffin, 1993; Chen et al., 2003; Stuart et al., 2015). Consequently, the identification of temperature-tolerant isolates and the elucidation of physiological adaptation mechanisms associated with thermal stress have become important areas of research for the sustainable utilisation of EPNs in biological control programmes (Bütüner and Susurluk, 2023; Matuska-Łyżwa et al., 2024; Susurluk and Bütüner, 2024).

The aim of this review is to summarise current knowledge regarding the effects of temperature on the physiological characteristics of EPNs, with particular emphasis on survival, infectivity, reproductive capacity and adaptive responses to thermal stress. Furthermore, the implications of temperature-induced physiological changes for biological control applications and future research directions are discussed.

2. Temperature Effects on Entomopathogenic Nematode Biological Activity

Temperature is one of the most important abiotic factors influencing the biological activity, survival, infectivity and reproduction of EPNs. As soil-dwelling organisms, EPNs are continuously exposed to temperature fluctuations that directly affect their physiological processes and biocontrol performance. Environmental temperatures outside the optimal range may impair nematode movement, host-finding ability, penetration success, reproductive potential and long-term persistence in the soil (Hussaini, 2017; Bütüner et al., 2023; Fatimah et al., 2025). Consequently, temperature is considered a key determinant of the efficacy of EPNs in biological control programs. The influence of temperature on EPN activity begins with host-seeking behaviour and mobility. Chen et al. (2003) demonstrated that temperature significantly affected the host-searching ability of several

Steinernema and *Heterorhabditis* species. Reduced mobility was observed at lower temperatures, resulting in delayed host location and penetration. The same study revealed substantial interspecific variation in thermal tolerance, with *Steinernema feltiae* (Rhabditida: Steinernematidae) maintaining infectivity at 10°C, whereas *Heterorhabditis bacteriophora* (Rhabditida: Heterorhabditidae) was only effective at 20°C. Furthermore, penetration into host larvae occurred more rapidly as temperature increased, indicating that thermal conditions strongly regulate the infection process. Temperature also plays a crucial role in determining infectivity and virulence. Gouge et al. (1999) reported that the number of IJs invading insect hosts varied significantly according to temperature, nematode species and host species. Importantly, the temperature supporting maximum infection differed among host insects, suggesting that optimal temperatures for biological control are host-dependent rather than species-specific alone.

Similarly, El Khoury et al. (2018) observed that the highest mortality rates of *Galleria mellonella* (Lepidoptera: Pyralidae) larvae occurred between 15 and 20°C, whereas infectivity declined substantially at lower temperatures. However, some isolates of *S. ichnusae* (Rhabditida: Steinernematidae) and *H. bacteriophora* retained infective capacity even at 35°C, highlighting considerable isolate-dependent variation in thermal adaptation. The interaction between temperature and other environmental factors may further influence EPN performance.

Radová and Trnková (2010) demonstrated that both temperature and soil moisture significantly affected the virulence of *S. carpocapsae* (Rhabditida: Steinernematidae) and *S. feltiae*. While *S. carpocapsae* performed better at 25°C, *S. feltiae* exhibited greater efficacy at lower temperatures and under drier conditions. The authors also reported that reduced soil moisture substantially decreased insect mortality, emphasizing that temperature responses cannot be evaluated independently of other environmental variables. Such findings indicate that successful field applications require consideration of both thermal and moisture conditions. In addition to infectivity, temperature strongly influences nematode development and reproduction.

Pervez et al. (2016) found that attachment, penetration, pathogenicity and multiplication of several EPN isolates were significantly affected by temperature. Maximum larval mortality and IJ production were recorded at

30°C, whereas both parameters declined at 20°C and 35°C. These findings suggest that moderate temperatures promote both successful infection and subsequent reproduction, while thermal stress may limit population development.

Similar observations were reported by Bütüner and Susurluk (2023), who demonstrated that storage temperature and duration significantly affected the morphological and reproductive characteristics of *H. bacteriophora* HBH hybrid strain. IJs stored at 15°C for seven days produced the longest hermaphrodite individuals, the largest egg diameters and the highest reproductive capacity, indicating that storage conditions can substantially influence biological quality. Recent studies have further demonstrated that temperature-induced responses occur not only at behavioural and reproductive levels but also at the molecular level. Using quantitative proteomics, Lillis et al. (2022) showed that storage temperature significantly altered protein expression profiles in *S. carpocapsae* and *H. megidis* (Rhabditida: Heterorhabditidae) IJs. Low-temperature storage promoted the accumulation of chaperone and stress-related proteins, whereas proteins associated with metabolism, cell signalling and oxidative stress responses were differentially regulated depending on species and storage conditions. These findings suggest that EPNs activate complex physiological and molecular mechanisms to cope with thermal stress and maintain survival during prolonged storage.

3. Conclusion

Overall, current evidence indicates that temperature influences nearly every aspect of EPN biology, including movement, host-seeking behaviour, penetration efficiency, infectivity, reproduction and physiological adaptation. However, temperature responses vary considerably among species, isolates and environmental conditions. Therefore, understanding species-specific thermal requirements and adaptive mechanisms is essential for maximizing the effectiveness of EPN-based biological control programs under both current and future climatic conditions

KAYNAKÇA

- Askary, T. H., & Abd-Elgawad, M. M. (2021). Opportunities and challenges of entomopathogenic nematodes as biocontrol agents in their tripartite interactions. *Egyptian Journal of Biological Pest Control*, 31(1), 42.
- Boemare, N., Laumond, C., & Mauleon, H. (1996). The entomopathogenic nematode-bacterium complex: biology, life cycle and vertebrate safety. *Biocontrol Science and Technology*, 6(3), 333-346.
- Brown, I. M., & Gaugler, R. (1997). Temperature and humidity influence emergence and survival of entomopathogenic nematodes. *Nematologica*, 43(5), 363-376.
- Burnell, A., & Stock, S. P. (2000). *Heterorhabditis*, *Steinernema* and their bacterial symbionts—lethal pathogens of insects. *Nematology*, 2(1), 31-42.
- Bütüner, A. K., & Susurluk, A. (2023). Efficiency of temperature and storage duration on some morphological measurements and reproductive capacity of the entomopathogenic nematode *Heterorhabditis bacteriophora* Poinar, 1976 (Rhabditida: Heterorhabditidae)'s Turkish HBH hybrid strain. *Turkish Journal of Entomology*, 47(4), 469-476.
- Bütüner, A. K., & Susurluk, İ. A. (2023). Pathogenicity of Turkish entomopathogenic nematodes, *Steinernema feltiae* and *Steinernema carpocapsae* (Rhabditida: Steinernematidae) on the rice weevil: *Sitophilus oryzae* (Coleoptera: Curculionidae). *Türk Tarım ve Doğa Bilimleri Dergisi*, 10(3), 541-547.
- Bütüner, A. K., İlktan, M., & Susurluk, A. (2023). Effects of storage temperature on viability and virulence of entomopathogenic nematodes *Heterorhabditis bacteriophora* Poinar, 1976 (Rhabditida: Heterorhabditidae), *Steinernema carpocapsae* Weiser, 1955 and *Steinernema feltiae* Filipjev, 1934 (Rhabditida: Steinernematidae). *Turkish Journal of Entomology*, 47(3), 247-257.

- Chen, S., Li, J., Han, X., & Moens, M. (2003). Effect of temperature on the pathogenicity of entomopathogenic nematodes (*Steinernema* and *Heterorhabditis* spp.) to *Delia radicum*. *BioControl*, 48(6), 713-724.
- Cruz-Martínez, H., Ruiz-Vega, J., Matadamas-Ortíz, P. T., Cortés-Martínez, C. I., & Rosas-Díaz, J. (2017). Formulation of entomopathogenic nematodes for crop pest control—a review. *Plant Protection Science*, 53(1), 15.
- El Khoury, Y. A. R. A., Oreste, M., Noujeim, E., Nemer, N., & Tarasco, E. (2018). Effect of temperature on the pathogenicity of Mediterranean native entomopathogenic nematodes (Steinernematidae and Heterorhabditidae) from natural ecosystems. *Redia*, 101, 123-127.
- Erdoğan, H., & Ulu, T. C. (2024). Evaluating a portable method and two irrigation drippers for field application of entomopathogenic nematodes. *Yuzuncu Yıl University Journal of Agricultural Sciences*, 34(1), 138-150.
- Fatimah, N., Askary, T. H., & Abd-Elgawad, M. M. (2025). Factors influencing the performance of entomopathogenic nematodes: from laboratory to field conditions. *Egyptian Journal of Biological Pest Control*, 35(1), 29.
- Georgis, R. (1992). Present and future prospects for entomopathogenic nematode products. *Biocontrol Science and Technology*, 2(2), 83-99.
- Gouge, D. H., Lee, L. L., & Henneberry, T. J. (1999). Effect of temperature and lepidopteran host species on entomopathogenic nematode (Nematoda: Steinernematidae, Heterorhabditidae) infection. *Environmental Entomology*, 28(5), 876-883.
- Griffin, C. T. (1993). Temperature responses of entomopathogenic nematodes: Implications for the success of biological control programmes. *Nematodes and the biological control of insect pests*, 115-126.

- Hussaini, S. S. (2017). Entomopathogenic nematodes: ecology, diversity and geographical distribution. In Biocontrol agents: entomopathogenic and slug parasitic nematodes (pp. 88-142). Wallingford UK: CABI.
- Kary, N. E., Niknam, G., Griffin, C. T., Mohammadi, S. A., & Moghaddam, M. (2009). A survey of entomopathogenic nematodes of the families Steinernematidae and Heterorhabditidae (Nematoda: Rhabditida) in the north-west of Iran. *Nematology*, 11(1), 107-116.
- Lillis, P. E., Griffin, C. T., & Carolan, J. C. (2022). The effect of temperature conditioning (9 C and 20 C) on the proteome of entomopathogenic nematode infective juveniles. *PloS one*, 17(4), e0266164.
- Mahar, A. N., Munir, M., Elawad, S., Gowen, S. R., & Hague, N. G. M. (2005). Pathogenicity of bacterium, *Xenorhabdus nematophila* isolated from entomopathogenic nematode (*Steinernema carpocapsae*) and its secretion against *Galleria mellonella* larvae. *Journal of Zhejiang University-SCIENCE B*, 6(6), 457-463.
- Matuska-Lyżwa, J., Duda, S., Nowak, D., & Kaca, W. (2024). Impact of abiotic and biotic environmental conditions on the development and infectivity of entomopathogenic nematodes in agricultural soils. *Insects*, 15(6), 421.
- Pervez, R., Eapen, S. J., Devasahayam, S., & Jacob, T. K. (2016). Effect of temperature on the infectivity of entomopathogenic nematodes against shoot borer (*Conogethes punctiferalis* Guen.) infesting ginger (*Zingiber officinale* Rosc.). *Journal of Biological Control*, 29(4): 187-193.
- Radová, S., & Trnková, Z. (2010). Effect of soil temperature and moisture on the pathogenicity of two species of entomopathogenic nematodes (Rhabditida: Steinernematidae). *Journal of Agrobiology*, 27(1), 1.
- Stock, S. P., Pryor, B. M., & Kaya, H. K. (1999). Distribution of entomopathogenic nematodes (Steinernematidae and Heterorhabditidae) in natural habitats in California, USA. *Biodiversity & Conservation*, 8(4), 535-549.

- Stuart, R. J., Barbercheck, M. E., & Grewal, P. S. (2015). Entomopathogenic nematodes in the soil environment: distributions, interactions and the influence of biotic and abiotic factors. *Nematode Pathogenesis of Insects and Other Pests: Ecology and Applied Technologies for Sustainable Plant and Crop Protection*, 97-137.
- Susurluk, A., & Bütüner, A. K. (2024). The role of drought in the efficacy of some entomopathogenic nematodes. *Turkish Journal of Entomology*, 48(1), 103-110.
- Yaraşır, O. N., Ergene, E., Bütüner, A. K., Susurluk, H., & Susurluk, A. (2024). Pathogenicity of the *Steinernema feltiae* TUR-S3 (Rhabditida: Steinernematidae) isolate on *Oryzaephilus surinamensis* (Coleoptera: Silvanidae) and *Tribolium confusum* (Coleoptera: Tenebrionidae). *Turkish Journal of Agricultural and Natural Sciences*, 11(2), 409-416.

CHAPTER 3

CLIMATE-SMART AGRICULTURAL PRACTICES AND THE LIVELIHOODS OF SMALLHOLDER FARMERS IN NIGERIA

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1. INTRODUCTION

Agriculture remains a major foundation of Nigeria's economy and an important source of livelihood for rural families. Small-scale producers account for a substantial proportion of agricultural activity and supply food crops, livestock and other farm products to local and national markets. Yet many of these households operate with limited productive assets, inadequate infrastructure, weak agricultural advisory systems, imperfect markets, low levels of mechanization and restricted access to finance. The growing instability of the climate has added another layer of difficulty, making farm planning and household livelihood management increasingly uncertain.

Because farming depends strongly on environmental conditions, changes in temperature, rainfall, water availability and the frequency or intensity of extreme events can affect agricultural performance through several channels. Nigerian farmers increasingly contend with late or poorly distributed rainfall, prolonged dry spells, flooding, intense precipitation, rising temperatures, drought, wind damage and changing pest and disease pressures. Such events can reduce yields, increase production risk, damage farm assets, interrupt the movement of produce and weaken household income and food security.

The burden of climate change is not evenly distributed. Smallholder households are particularly exposed because many depend on rain-fed production and possess limited financial and institutional capacity to withstand shocks. Their vulnerability may be heightened by low incomes, small or fragmented holdings, inadequate irrigation, weak insurance coverage, uncertain land rights, poor access to climate information and weak connections to markets. Consequently, a climate shock may affect much more than farm output; it can also influence household consumption, nutrition, schooling, health, asset ownership and the ability to maintain alternative sources of income.

Climate-smart agriculture (CSA) has developed as an approach for responding to these interconnected problems. The Food and Agriculture Organization of the United Nations defines CSA as an approach intended to transform agricultural systems so that they can sustain development and food security under changing climatic conditions. Its three principal aims are to improve agricultural productivity and incomes sustainably, strengthen

adaptation and resilience, and reduce or remove greenhouse-gas emissions where this is practicable (FAO, 2013).

For Nigeria, CSA is especially relevant because a large smallholder population is exposed to substantial climate risks. The approach includes practices such as the use of improved and climate-resilient varieties, diversification, intercropping, crop rotation, conservation agriculture, agroforestry, better soil and water management, modification of planting periods, crop-livestock integration, irrigation, water harvesting, efficient fertilizer use and improved livestock management.

However, the existence of suitable technologies does not automatically result in their use. Adoption decisions are shaped by the cost of improved inputs and equipment, availability of credit, extension contact, access to climate information, land tenure arrangements, household labour, perceived profitability and uncertainty about the performance of unfamiliar technologies. Thus, the success of CSA depends not only on the technical quality of a practice but also on the economic, social, institutional and environmental setting in which farmers make decisions.

This chapter therefore explores the link between climate-smart agricultural practices and the livelihoods of Nigerian smallholders. It considers the effects of climate change on agriculture, the vulnerability of smallholder households, the meaning and scope of CSA, major adaptation practices, barriers to adoption and the implications of CSA for productivity, income, food security and rural welfare. Attention is also given to gender and socioeconomic differences, followed by policy directions for strengthening climate resilience and improving rural livelihoods.

2. CLIMATE CHANGE AND NIGERIAN AGRICULTURE

Climate change is increasingly regarded as a serious constraint to agricultural development in Nigeria. The country contains several agroecological environments, and the risks faced by farmers vary across locations. Northern farming areas are particularly exposed to heat, drought, desertification and irregular rainfall, whereas many southern communities face heavy rainfall, flooding, erosion and other water-related hazards. Different hazards can also occur within the same agricultural season, creating cumulative pressure on farm households.

Nigeria's dependence on rainfall makes agricultural production highly responsive to changes in the timing and distribution of precipitation. A delayed onset of rain may force farmers to postpone planting, while unusually heavy rain soon after planting can produce waterlogging, soil erosion, nutrient losses and crop damage. Changes in the length of the growing season may also influence farmers' choice of crops, timing of farm operations and eventual harvests.

Temperature is another important pathway through which climate variability affects farming. Higher temperatures can increase evapotranspiration and crop water requirements and may accelerate crop development in some circumstances. When heat occurs during sensitive growth stages, however, yield losses can result. Livestock are also affected through heat stress, increased demand for drinking water, reduced feed availability and greater susceptibility to some diseases and parasites.

Climate conditions can further influence the occurrence and geographical spread of agricultural pests and pathogens. Changes in temperature and humidity may create more suitable environments for particular organisms, forcing farmers to spend more on crop protection while potentially experiencing lower output. Resource-poor producers may be unable to respond adequately to these new pressures and can therefore suffer larger losses.

Flooding constitutes another major risk. Excess water can destroy crops, remove topsoil, damage farm structures, contaminate water sources and interfere with roads and agricultural marketing. The effects may continue after floodwaters recede because farmers can lose seed, livestock, tools and other assets needed to restart production in the next season.

The consequences of climate change extend beyond the farm. Agriculture supports rural employment, household earnings, local food supplies and market activity. When production falls, farm income may decline at the same time that food prices rise. Households that both produce and purchase food can consequently experience a double pressure: less income with which to buy food and higher expenditure on the food they must purchase.

Climate exposure is also intensified by pre-existing weaknesses in the agricultural economy. Many producers have inadequate access to irrigation,

insurance, affordable loans, improved planting materials, machinery, storage and dependable market infrastructure. Climate change therefore interacts with existing development constraints rather than operating as an isolated problem.

Research on agricultural vulnerability in Nigeria has emphasized the importance of considering climate hazards alongside farmers' adaptive capacity. Adebisi et al. (2020), for example, stressed the relevance of climatic trends and socioeconomic conditions in understanding agricultural vulnerability. The dominance of rain-dependent and diverse smallholder production systems makes climate variability especially consequential.

Accordingly, agricultural policy should not focus only on maximizing production under favourable weather. Greater attention is required for resilience—the capacity of farm households to anticipate shocks, withstand their immediate effects, recover afterwards and adjust production and livelihood strategies while maintaining or improving welfare.

3. VULNERABILITY OF SMALLHOLDER FARMERS TO CLIMATE CHANGE

Climate vulnerability can be examined through three related concepts: exposure, sensitivity and adaptive capacity. Exposure concerns the extent to which a person or livelihood system encounters climate hazards. Sensitivity refers to the degree to which that system is affected when a hazard occurs. Adaptive capacity describes the resources and ability available to adjust to impacts, make use of opportunities or manage adverse consequences.

Nigerian smallholders can face substantial vulnerability in each of these dimensions. Their exposure is high where production depends on rainfall and local environmental conditions. Producers without irrigation or alternative water sources are particularly vulnerable to drought and irregular precipitation, while households located in flood-prone environments may face recurrent losses from excessive rainfall.

Sensitivity is also high because agriculture frequently provides both food and cash income. A failed harvest can therefore reduce food availability and earnings simultaneously. Families with little savings and few alternative livelihood options may respond by selling productive assets, reducing food consumption, interrupting children's schooling or borrowing under unfavourable conditions.

Adaptive capacity is constrained by limited resources and insufficient institutional support. Better-resourced households may be able to purchase improved seed, invest in irrigation or machinery, diversify into non-farm activities and alter production locations when conditions change. Poorer households often cannot finance such adjustments.

Farm size matters as well. Very small holdings may restrict experimentation with unfamiliar practices or the allocation of land to risk-reducing activities. Fragmented plots can additionally make mechanization and efficient water management more difficult.

Information is an important component of adaptive capacity. Farmers need timely and locally relevant information concerning rainfall expectations, drought, pest outbreaks, planting periods and available adaptation options. Traditional extension services may not reach remote communities effectively. Mobile phones and digital communication can widen access to information, although unequal digital access may itself become a source of exclusion.

Financial conditions further shape vulnerability. A climate shock can reduce household income at precisely the time when money is needed for recovery. In the absence of affordable credit, insurance or emergency assistance, repeated shocks can produce a cycle of low investment and persistent losses.

Vulnerability should therefore be understood as multidimensional rather than as a simple reflection of the intensity of a climatic event. Two farmers may encounter the same drought yet experience very different consequences because one has irrigation, savings, credit, improved seed, extension support, social networks or non-farm opportunities while the other lacks these resources.

This distinction is central to climate-smart agricultural policy. Even a technically sound CSA technology may have little effect on resilience when farmers cannot afford it, lack the knowledge required for proper use, have no access to complementary inputs or operate in markets that provide inadequate returns.

4. CLIMATE-SMART AGRICULTURE

Climate-smart agriculture represents an agricultural development approach that brings food security and climate concerns into the same policy

and production framework. The concept emphasizes the need for farming systems that can raise productivity, strengthen resilience and, where technically and economically feasible, contribute to lower greenhouse-gas emissions (FAO, 2013).

The three broad pillars of CSA are: sustainably improving agricultural productivity and income; strengthening adaptation and resilience to climate change; and reducing or removing greenhouse-gas emissions where possible.

These objectives are related but should not be assumed to occur together automatically. A technology that raises yields may have little mitigation benefit, while a practice designed to reduce emissions may involve substantial initial expenditure. CSA should therefore be treated as a context-dependent framework rather than as a universal package of technologies.

In Nigeria, the approach is relevant because agricultural development must occur alongside increasing climate uncertainty and pressure on natural resources. Climate-smart practices can improve soil condition, conserve water, diversify production and reduce dependence on a single crop or production activity, thereby helping farmers manage climatic variability.

Knowledge and innovation are also central to CSA. Farmers possess indigenous knowledge developed through long experience of local environmental conditions. Such knowledge may guide decisions about rainfall, planting periods, crop selection and responses to environmental changes. Combining local experience with scientific weather and agronomic information can make climate interventions more practical and locally appropriate.

CSA should also extend beyond primary production. Farm-level resilience can be undermined by post-harvest losses, inadequate storage, poor transport and unstable markets. A genuine climate-smart transformation therefore needs to consider processing, storage, marketing and value addition alongside production.

Evidence from Southeast Nigeria illustrates this growing interest. A 2024 study of crop farmers in the region examined awareness, adoption and intensity of CSA practices, underscoring the need to distinguish between the decision to adopt and the degree to which practices are implemented (Climate smart agriculture practices by crop farmers, 2024). Research elsewhere in

Nigeria has likewise identified socioeconomic and institutional characteristics as important influences on adoption.

CSA is consequently relevant to Nigeria because it provides a framework through which productivity improvement, climate adaptation, natural-resource management and rural development can be considered together.

5. CLIMATE-SMART AGRICULTURAL ADAPTATION PRACTICES

Smallholder households generally combine traditional responses with newer agricultural technologies when managing climate-related risks. The mix of practices varies according to local ecology, crops cultivated, household resources, information, labour availability and institutional support.

5.1. Crop Diversification

Crop diversification means allocating land or production resources to more than one crop instead of relying on a single crop. The strategy spreads production risk because crops do not necessarily respond identically to drought, excess rainfall or other climatic stresses. When one crop performs poorly, another may still generate food or income.

Beyond risk reduction, diversification can support dietary variety and create additional market opportunities. Its usefulness nevertheless depends on access to suitable seed, knowledge and functioning markets.

5.2. Intercropping and Mixed Cropping

Intercropping involves cultivating at least two crops simultaneously on the same piece of land. Properly designed combinations can improve the use of available land, sunlight, water and nutrients and may reduce the consequences of losing a single crop. Maize-legume combinations are common in several Nigerian production systems.

Legumes can improve soil fertility through biological nitrogen fixation while supplying additional food and income. However, poorly managed mixtures may intensify competition among crops for water, nutrients and light, reducing the performance of individual components.

5.3. Improved and Climate-Resilient Varieties

Farmers can respond to climatic stress through varieties with characteristics such as drought tolerance, early maturity, flood tolerance and resistance to pests and diseases. Early-maturing cultivars, for instance, can enable farmers to harvest before severe moisture shortages become critical.

The benefits of improved varieties depend on reliable seed systems. Farmers need affordable and quality-assured seed, information on suitable varieties and dependable access to planting materials. Without these conditions, awareness alone may not result in adoption.

5.4. Adjusting Planting Dates

Changing the timing of planting is a relatively direct way of responding to shifts in rainfall. Depending on expected weather conditions, farmers may plant earlier or later than their customary date. The success of this strategy depends greatly on the accuracy and availability of seasonal forecasts.

Climate information services are therefore important because planting-date decisions are more effective when farmers receive forecasts that are timely, understandable and relevant to their location.

5.5. Soil and Water Conservation

Examples of soil and water conservation include mulching, reduced or conservation tillage, contour cultivation, terracing, cover crops and the addition of organic materials. Such measures can improve soil structure, reduce erosion, increase infiltration and help soils retain moisture. They may also support longer-term soil fertility.

Adoption can nevertheless be difficult when practices require considerable labour, equipment or cash. Households with limited family labour or financial resources may be unable to use them consistently.

5.6. Agroforestry

Agroforestry combines trees with crops and/or livestock. Trees can supply fruits, fodder, fuelwood, timber and shade while helping protect soil and store carbon. Tree-based systems can also diversify household earnings and reduce dependence on annual crops.

Farmers may, however, hesitate to make such long-term investments when land tenure is uncertain or when returns are delayed for several years.

5.7. Irrigation and Water Harvesting

Irrigation reduces dependence on unpredictable rainfall and can help farmers maintain production during dry periods. Small-scale irrigation, farm ponds, water harvesting and efficient water-use technologies can strengthen resilience where water resources are available.

Adoption is constrained by the price of equipment and energy, limited water access, inadequate infrastructure and insufficient technical skills. Affordable farmer-managed irrigation could therefore be particularly useful in areas experiencing greater rainfall variability.

5.8. Integrated Crop-Livestock Systems

Combining crops and livestock can improve resource use within the farm. Crop residues can serve as animal feed, while manure can be returned to the soil as organic fertilizer. Livestock also provides another income source, reducing dependence on crop sales alone.

Such systems require effective management and can still face problems involving animal disease, feed shortages and competition for land and water.

5.9. Improved Livestock Management

Climate-smart livestock management may include better breeds, improved feeding, appropriate housing, disease prevention, adequate water supply and measures for reducing heat stress. Diversified livestock enterprises can act as a financial buffer when crop production is disrupted.

Small ruminants and poultry may be especially useful to rural families because they can provide food and relatively accessible sources of cash income.

5.10. Weather and Climate Information Services

Climate information supports decisions about planting, crop choice, input application and harvesting. Extension personnel, radio, mobile phones, farmer associations and digital platforms can all be used to distribute such information.

Forecasts are most useful when farmers receive them early enough to act, understand their meaning, regard them as trustworthy and consider them relevant to local conditions. Information availability by itself therefore does not ensure effective adaptation.

6. CONSTRAINTS TO THE ADOPTION OF CLIMATE-SMART AGRICULTURAL PRACTICES

Although CSA offers important opportunities, uptake among Nigerian smallholders remains uneven because adoption is affected by several interconnected barriers.

6.1. Financial Constraints

Many CSA options require substantial expenditure before benefits are realized. Improved seed, irrigation facilities, machinery, soil amendments, water-harvesting systems and tree-based investments can be beyond the reach of low-resource households.

Limited access to reasonably priced agricultural credit is therefore a major obstacle. Farmers excluded from formal financial institutions may turn to informal lenders whose borrowing conditions can be expensive.

6.2. Limited Access to Extension Services

Extension systems help farmers learn about technologies and acquire practical knowledge. However, insufficient personnel, inadequate operating resources and weak links between extension providers and farmers can restrict coverage.

Extension programmes should increasingly integrate climate-risk management, interpretation of climate information and hands-on CSA training.

6.3. Inadequate Climate Information

Farmers need dependable information about rainfall onset, dry spells, flooding and other extreme events. Where such information is unavailable or arrives too late, households may be unable to modify farm operations in time.

Communication is also important: climate messages must be presented in ways that farmers can understand and trust.

6.4. Land Tenure Insecurity

Practices such as agroforestry and soil improvement often produce benefits over a long period. Farmers who are uncertain about continued access to land have less incentive to make investments whose returns may occur after several seasons.

6.5. High Labor Requirements

Some adaptation measures require substantial labour, including mulching, conservation agriculture, manual water management and organic soil improvement. Families with insufficient labour may therefore need machinery or hired workers to adopt such practices.

6.6. Limited Access to Inputs

Awareness of CSA technologies does not overcome shortages of quality seed, fertilizer, machinery, irrigation equipment and other complementary inputs. Stronger input distribution systems are consequently necessary if promotion efforts are to translate into sustained adoption.

6.7. Market Constraints

Farmers have stronger incentives to adopt productivity-enhancing technologies when they can sell output reliably at remunerative prices. Poor roads, inadequate storage, weak value chains and unstable prices can reduce expected returns and discourage investment.

6.8. Risk and Uncertainty

New technologies may be perceived as risky when farmers are uncertain about their performance under local conditions. Risk-averse households may continue using familiar methods even where new alternatives could provide better results.

Demonstration farms, farmer field schools, cooperative activities and pilot projects can reduce uncertainty by giving farmers opportunities to observe technologies under comparable conditions.

7. EFFECTS OF CLIMATE-SMART AGRICULTURAL PRACTICES ON AGRICULTURAL PRODUCTIVITY

Improving agricultural productivity is one of the main outcomes expected from CSA. Several pathways can generate such gains. Improved varieties may produce higher yields under drought, pest, disease or moisture stress. Soil-management practices can improve fertility and moisture retention, while diversification may reduce the risk associated with dependence on one crop.

Intercropping can improve the efficiency with which land and other resources are used when component crops have complementary requirements. Agroforestry may improve soil conditions and local microclimates, although results depend on tree species, density and management.

Irrigation can raise output by reducing dependence on rainfall and making dry-season production possible. Where resources permit, it can also allow additional cropping cycles and increase annual land productivity.

Productivity improvements should not always be expected immediately. Tree establishment and soil rehabilitation, for example, may require several seasons before measurable benefits emerge. The timing of benefits is therefore important when evaluating CSA adoption.

Effects may also vary among households. Farmers with greater resources may achieve larger gains because they can combine CSA practices with improved inputs, machinery, finance and market access.

Evidence from Southeast Nigeria suggests that farmers use combinations of CSA practices involving soil and water management, crop diversification and changes in production decisions (Climate smart agriculture practices by crop farmers, 2024). Such combinations are important because resilience often depends on complementary measures rather than on one isolated intervention.

Productivity assessment should consequently go beyond average crop yield. Useful measures may include total farm output, output per unit of land or labour, production risk, input-use efficiency and stability of output across seasons.

CSA can improve productivity not only by raising average yields but also by reducing fluctuations in output. For smallholder households, greater stability may be highly valuable because it lowers the probability of severe income losses.

8. EFFECTS ON INCOME AND RURAL LIVELIHOODS

The livelihood implications of CSA extend beyond physical production. Higher productivity can increase farm earnings through greater marketable surplus, while diversification can provide several income streams.

For example, a household cultivating drought-tolerant crops may experience fewer crop failures and therefore more stable earnings. More

stable production can also reduce pressure to sell livestock or other productive assets after a climate shock.

Crop-livestock integration offers another route to income diversification. When crop revenue is weak, livestock sales can help households meet food, education or other essential expenses.

CSA may also reduce production expenditure over time. Better soil fertility management can decrease dependence on purchased inputs in some settings, while efficient water-management systems can lower the cost of irrigation when appropriately designed.

Potential livelihood gains include higher farm earnings, less income instability, greater diversification of livelihood activities, accumulation of productive assets, fewer distress sales, stronger household resilience, additional employment and deeper participation in agricultural value chains.

The relationship between CSA and income is nevertheless not always immediate or linear. Some practices involve high start-up costs and may reduce short-term returns before producing longer-term benefits. Market conditions are also decisive: an increase in physical production does not necessarily result in higher income when farm-gate prices are depressed or transportation and marketing costs are high.

CSA is therefore likely to generate stronger livelihood gains when technological adoption is supported by market access, storage, processing, finance and value addition.

From the sustainable-livelihoods perspective, CSA can strengthen several categories of household capital. Soil and water conservation may protect natural capital; training can develop human capital; more stable earnings can strengthen financial capital; farmer groups can build social capital; and investment in productive equipment can expand physical capital.

This broader perspective is important because rural welfare cannot be adequately captured by agricultural income alone.

9. FOOD SECURITY IMPLICATIONS

Climate-smart agriculture has important implications for food security in Nigeria. Food security is achieved when people consistently have physical and economic access to adequate, safe and nutritious food that satisfies dietary requirements and preferences for an active and healthy life (FAO et al., 2023).

Climate change can threaten each of the four conventional dimensions of food security: availability, access, utilization and stability. At the production level, climate-related losses can reduce the supply of food. At the household level, lower farm income can weaken purchasing power, while poor harvests may force households to rely more heavily on markets when food prices are rising.

CSA can support food security by raising and stabilizing production. Diversification can improve the variety of foods available to households, while improved livestock management can increase access to animal-source foods.

Climate-resilient varieties can reduce the probability of complete crop failure, and irrigation can make production less dependent on the main rainy season. These measures can contribute to a more stable food supply.

Food-security effects, however, depend on how agricultural output is distributed and used. Farmers who produce more but lack reliable markets may obtain limited income gains. Conversely, increased commercialization can raise household earnings while potentially reducing the amount of food retained for direct consumption. CSA and food security should therefore be examined at both household and community levels.

At household level, relevant indicators include food consumption, dietary diversity, food expenditure and experiences of food insecurity. At community level, agricultural supply, productivity, market availability and food-price movements can provide useful information.

Climate-resilient production may also help reduce food-price instability by lowering the likelihood of severe supply disruptions. Nevertheless, CSA cannot replace wider food-system reforms. Food security also depends on infrastructure, functioning markets, social protection, conflict reduction, income opportunities and effective governance.

10. GENDER AND SOCIOECONOMIC DIMENSIONS OF CLIMATE-SMART AGRICULTURE

Climate change and CSA have important gender and socioeconomic implications because men and women may have different responsibilities, access to resources and influence over household decisions.

Women make major contributions to agricultural production and household food provisioning in many rural communities but may have less access to land, credit, extension, improved inputs, technology and climate information. These disadvantages can restrict their capacity to adopt CSA.

For instance, awareness of an improved variety does not lead to adoption if a woman farmer lacks the money to purchase seed. Likewise, insecure rights over land can discourage investment in long-term measures such as agroforestry or soil conservation.

Climate shocks may also affect men and women differently. Women can experience particular pressure when food availability declines because they often carry substantial responsibilities for food preparation and care work.

CSA programmes should therefore avoid treating farm households as uniform units. Interventions need to identify gender-specific barriers and create direct opportunities for women to obtain productive resources and participate in decisions.

Other socioeconomic characteristics also shape adoption. Age, education, household size, farm size, income, wealth, access to credit, cooperative membership and extension contact can influence whether farmers adopt particular technologies.

Education can improve the ability to understand technical information and assess unfamiliar technologies. Farm size may influence the capacity to experiment, while wealth affects the ability to finance initial investments. Younger farmers may be more receptive to some new technologies, whereas older producers may possess valuable accumulated experience and indigenous knowledge. Effective programmes should combine these knowledge sources instead of assuming that modern techniques must replace local practices.

Social networks and farmer organizations can also facilitate adoption. Cooperatives may improve access to credit, inputs, information, machinery and markets while lowering transaction costs and strengthening bargaining power.

These socioeconomic differences underline the importance of inclusive agricultural transformation. If climate-smart interventions are accessible mainly to relatively wealthy producers, they could unintentionally widen inequality. Policies should therefore pay particular attention to women, young

farmers, poorer households and producers with limited land or institutional access.

11. POLICY RECOMMENDATIONS

11.1 Strengthen Climate Information and Early Warning Systems

Nigeria should improve the production and dissemination of timely, reliable and geographically relevant climate information. Forecasts need to be translated into practical recommendations concerning planting periods, crop selection, irrigation, fertilizer use, pest control and harvesting.

Information should reach farmers through several channels, including extension personnel, radio, mobile phones, farmer associations and digital platforms.

11.2. Improve Agricultural Extension Services

Extension institutions should place greater emphasis on climate-smart production and climate-risk management. Extension workers require training in CSA technologies, climate-information interpretation and approaches that respond to gender differences.

Farmer field schools and demonstration plots should be expanded so producers can observe and assess CSA options under local farming conditions.

11.3. Expand Access to Affordable Agricultural Finance

Financial institutions and public programmes should provide credit products suited to smallholder production. Financing arrangements should recognize that certain CSA investments take several seasons before generating returns.

Credit guarantees, concessional loans, savings groups and cooperative lending can help reduce financial barriers faced by resource-constrained households.

11.4. Promote Climate-Resilient Seeds and Planting Materials

Research and seed institutions should emphasize locally suitable drought-tolerant, flood-tolerant, early-maturing, pest-resistant and disease-resistant varieties.

Distribution systems should make improved planting materials both physically accessible and affordable to smallholders.

11.5. Invest in Small-Scale Irrigation and Water Management

Investment in irrigation should increase, especially in locations where rainfall has become more variable. Small-scale and farmer-managed systems can provide practical means of reducing dependence on rainfall.

Water harvesting and efficient irrigation methods should be promoted alongside investment in water infrastructure.

11.6. Strengthen Rural Infrastructure and Agricultural Value Chains

CSA adoption should be supported by improvements in rural roads, storage facilities, processing capacity, electricity and market infrastructure.

Better infrastructure can help ensure that productivity improvements translate into income rather than being lost through post-harvest damage, poor transport and weak market connections.

11.7. Promote Agricultural Insurance and Risk Management

Climate-related agricultural losses require effective mechanisms for transferring and managing risk. Index-based insurance and other innovative products should be designed so that smallholders can understand and afford them.

Insurance initiatives should be linked with credit and extension services to improve awareness and uptake.

11.8. Strengthen Farmer Cooperatives

Cooperatives can improve farmers' access to inputs, finance, machinery, extension advice, climate information and markets. Public agencies and development organizations should therefore support stronger cooperative governance, management and technical capacity.

11.9. Mainstream Gender-Responsive CSA

Climate-smart programmes should deliberately address women's access to land, finance, technology, information and extension services.

Women should participate in designing and implementing adaptation interventions rather than being treated only as passive beneficiaries.

11.10. Integrate Indigenous Knowledge

Policy and extension systems should recognize farmers' accumulated local knowledge and experience. Indigenous adaptation strategies can complement scientific information and may be particularly useful in communities where formal extension services have limited reach.

11.11. Improve Climate Finance for Smallholders

Public and private climate finance should support interventions that can be expanded while producing tangible benefits for smallholder households. Financing mechanisms should reduce the initial cost of CSA adoption and make investment more feasible for low-resource producers.

11.12. Adopt a Place-Based Approach

Nigeria's ecological diversity makes a uniform CSA policy inappropriate. The needs of farmers in the humid Southeast differ from those of producers in the drier northern zones.

CSA strategies should consequently be adapted to local climate hazards, farming systems, socioeconomic conditions and market opportunities.

12. CONCLUSION

Climate change is an important threat to agricultural productivity and rural welfare in Nigeria, particularly for smallholder households whose livelihoods depend heavily on climate-sensitive activities. Rising temperatures, irregular rainfall, drought, flooding and other hazards interact with existing economic and institutional constraints, thereby increasing the vulnerability of farm families.

Climate-smart agriculture offers a useful framework for addressing these challenges. Practices including diversification, intercropping, improved climate-resilient varieties, soil and water conservation, agroforestry, irrigation, crop-livestock integration and better access to climate information can help households manage risk while improving production and income.

However, farmers cannot readily adopt CSA when finance, extension, climate information, quality inputs, irrigation, secure land and reliable markets are unavailable. The major lesson is therefore that promoting CSA requires more than transferring technologies. Farmers need an enabling

socioeconomic and institutional environment in which technologies can be acquired, used correctly and generate worthwhile returns.

The benefits of CSA can extend beyond farm output. More stable production, diversified earnings, protection of natural resources and improved food availability can strengthen rural livelihoods and household food security. These benefits will not necessarily be shared equally, however, because gender, wealth, education, farm size, age, tenure conditions and institutional access influence both adoption and outcomes.

Nigeria's transition toward climate-smart agriculture therefore calls for coordinated action by government institutions, research organizations, extension agencies, financial institutions, private agribusinesses, farmer organizations and development partners. Priority areas include accessible climate information, affordable finance, resilient seed systems, small-scale irrigation, effective extension, agricultural insurance, rural infrastructure and gender-responsive programmes.

Ultimately, CSA should be understood as more than a collection of individual technologies. It is a broader strategy for agricultural and rural development. Its contribution in Nigeria will depend on its capacity to address climate risks while raising productivity, improving household earnings, strengthening food security and supporting inclusive rural livelihoods. A climate-smart transition that places smallholder producers at the centre of agricultural policy can make an important contribution to a more resilient and sustainable Nigerian food system.

KAYNAKÇA

- Adebisi, B. O., Nnamani, C. V., & others. (2020). Progress in climate–agricultural vulnerability assessment in Nigeria. *Atmosphere*, 11(2), 190. <https://doi.org/10.3390/atmos11020190>
- Climate smart agriculture practices by crop farmers: Evidence from south east Nigeria. (2024). *Smart Agricultural Technology*, 8, 100494. <https://doi.org/10.1016/j.atech.2024.100494>
- FAO. (2013). *Climate-smart agriculture sourcebook*. Food and Agriculture Organization of the United Nations.
- FAO, IFAD, UNICEF, WFP, & WHO. (2023). *The state of food security and nutrition in the world 2023: Urbanization, agrifood systems transformation and healthy diets across the rural–urban continuum*. Food and Agriculture Organization of the United Nations.
- Finizola e Silva, M., Van Schoubroeck, S., Cools, J., & Van Passel, S. (2024). A systematic review identifying the drivers and barriers to the adoption of climate-smart agriculture by smallholder farmers in Africa. *Frontiers in Environmental Economics*, 3, 1356335. <https://doi.org/10.3389/frevc.2024.1356335>
- Food and Agriculture Organization of the United Nations. (2017). *Climate-smart agriculture sourcebook* (2nd ed.). FAO.
- IPCC. (2022). *Climate change 2022: Impacts, adaptation and vulnerability*. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press.
- IPCC. (2023). *Climate change 2023: Synthesis report*. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC.
- Mbow, C., Rosenzweig, C., Barioni, L. G., Benton, T. G., Herrero, M., Krishnapillai, M., Liwenga, E. T., Pradhan, P., Rivera-Ferre, M. G., Sapkota, T., Tubiello, F. N., & Xu, Y. (2019). Food security. In P. R. Shukla et al. (Eds.), *Climate change and land: An IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems*. Intergovernmental Panel on Climate Change.

- Shehu, H. (2024). Assessment of small holders farmers' adoption of climate-smart agriculture practices in Borno State, Nigeria. *Journal of Agricultural Economics, Environment and Social Sciences*, 10(2).
- World Bank. (2022). *Nigeria country climate and development report*. World Bank.
- World Bank. (2026). *Nigeria sustainable agricultural value-chains for growth (AGROW) project*. World Bank.
- World Bank. (2022). *Climate change action plan 2021–2025*. World Bank.
- Yaro, A., & others. (2024). Rural farmers' perceptions of and adaptations to climate change in Sub-Saharan Africa: Does climate-smart agriculture (CSA) matter in Nigeria and Ethiopia? *Environmental Economics and Policy Studies*. <https://doi.org/10.1007/s10018-023-00388-8>

CHAPTER 4

BACTERIA AND NANOMATERIALS PROMOTING PLANT GROWTH in SUSTAINABLE AGRICULTURE

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INTRODUCTION

To meet the demands of the growing world population, it is not enough to simply increase agricultural production. In addition to the difficulties faced in agricultural production due to climate change, we need to reduce nutrient element losses, pesticide pollution, soil degradation, and the narrowing of microbial diversity. Microbial inoculants and nano-supported inputs are among the technologies being evaluated for this transformation. A global meta-analysis covering biofertilization trials has shown increases in plant yield and nutrient use efficiency; however, the magnitude of the response varies according to the organism, plant, soil, climate, and management conditions (Schütz et al., 2018). Nanoformulations can similarly enhance targeting or efficacy; however, direct comparisons with traditional products are still insufficient (Kah et al., 2018; Lowry et al., 2019). Unlike a chemical fertilizer or a traditional pesticide, the efficacy of a PGPB inoculant depends on the survival of the live cells within it, their ability to reach the target niche, establish there, and perform the relevant functions. A strain that fixes nitrogen, solubilizes phosphate, produces siderophores, modulates phytohormones, or suppresses pathogens under in vitro conditions may still fail after application. Cells can be lost during storage, may not reach the root zone, can be outcompeted by native organisms, or may encounter soil conditions that suppress the targeted trait (Bashan et al., 2014; Herrmann and Lesueur, 2013). Therefore, in microbial products, formulation is not a packaging decision at the final stage, but a part of the efficacy. The addition of a nanomaterial brings along different issues. The size and morphology of the added particle are important; however, the surface chemistry, coating, aggregation, dissolution, dosage, exposure duration, and the transformations of the material after it enters water, soil, the rhizosphere, or plant tissue are equally important. Metal and metal oxide particles can function as a source of micronutrients or as antimicrobial agents; however, the same particles can release ions or form reactive surfaces that suppress beneficial bacteria. Polymeric and hybrid matrices can protect cells and regulate their release; at the same time, excessive cross-linking can trap microorganisms in the matrix for a long enough period to disrupt root colonization. Therefore, rather than evaluating individual components, the entire bacterium–material–plant–soil system should be assessed (de Moraes et al., 2021; Mgadi et al., 2024). This book chapter

primarily addresses the reasons for the variability in PGPB functions and field responses. Subsequently, the interactions between bacterial cells and nanomaterials will be examined. It provides evidence on material types, synthesis by bacteria, transport methods, biosafety, sustainability, and field transfer. It also provides a phased framework for researchers developing nano-supported microbial products.

2. Biological Inputs as Plant Growth-Promoting Bacteria

2.1 Ecological Niches and Colonization Bacteria

Present in the plant holobiont inhabit various interconnected habitats. Rhizospheric PGPB, while in the soil section affected by root exudates; rhizoplane bacteria adhere to the root surface. Endophytes, on the other hand, enter the internal tissues without causing disease. Each habitat differs in terms of food provision, physical protection, competition, and exposure to agricultural inputs. Root exudates have effects on the diversity of microorganisms; however, they are not the only factor. The plant holobiont is also influenced by the host genotype and developmental stage, soil pH and texture, moisture, and the resident microbial community. Therefore, the same strain may effectively colonize one plant or location while showing poor performance in another (Backer et al., 2018). Among the most frequently studied genera are *Bacillus*, *Pseudomonas*, *Azospirillum*, *Azotobacter*, *Rhizobium*, *Bradyrhizobium*, and related taxa. The ability of *Bacillus* strains to form spores provides them with an advantage during drying and storage. However, non-spore-forming bacteria like *Pseudomonas* need to be better protected during formulation and delivery to the target. However, the genus or species characteristic alone provides very little information about product performance. Beneficial traits are strain-specific, and the type, purity, safety, and metabolic products synthesized by a strain to be used in agriculture must be reliably verified.

2.2. Direct and indirect mechanisms

PGPB can directly affect the plant by altering its nutrition or development. Diazotrophic bacteria convert atmospheric nitrogen into biologically usable forms. Phosphate-solubilizing bacteria, on the other hand, mobilize low-availability phosphorus through acidification, chelation, and

enzymatic reactions, while also increasing microbial iron acquisition through the siderophores they produce and limiting the iron that some pathogens can use. Many PGPB strains can also synthesize or modify auxins, gibberellins, cytokinins, and ethylene-related signals. Bacterial ACC deaminases are particularly important under stress conditions; because they can support root growth during salinity, drought, flooding, or metal exposure by breaking down the precursor of ethylene (Backer et al., 2018).

The indirect effects of PGPB on plants include competing for space and nutrients with pathogenic bacteria present in the soil, and synthesizing various antibiotics and lytic enzymes. Additionally, they can indirectly affect the plant by synthesizing volatile compounds with a high ability to inhibit pathogens, disrupting pathogen signaling, or inducing the plant's systemic resistance. In practice, these processes overlap with each other. A single PGPB strain can mobilize nutrients while simultaneously altering the root microbiome, supporting antioxidant regulation, or suppressing a pathogen. This type of multifunctionality can be beneficial; however, a long list of *in vitro* properties does not necessarily mean it will affect the plant equally under field conditions (Table 1).

2.3. Why is field performance still inconsistent?

A strain that shows promise in the laboratory may not have the same effect in field applications. A bacterial strain whose efficacy is confirmed in the laboratory may lose its viability during production or storage; an insufficient number of cells may reach the target area in the plant; if a carrier is used, the release may be slow; adhesion to the root may be weak, or competition in the soil may hinder establishment. Even established cells may not exhibit the desired characteristic depending on soil properties. Application methods in the field are another source of failure. Incompatible pesticides, concentrated fertilizer solutions, tank mixtures, or inappropriate application conditions can reduce the viability of the inoculant before it reaches the plant. These issues make it more realistic to consider PGPB as a component of integrated nutrient and plant health management rather than a universal substitute for traditional inputs (Bashan et al., 2014; Herrmann and Lesueur, 2013).

Table 1. Functional mechanisms of PGPB and their relevance to nano-enabled formulation.

Mechanism	Principal process	Agronomic endpoint	Nano-coupling implication
Biological N fixation	Reduction of atmospheric N ₂ by diazotrophs	Improved N supply and N-use efficiency	Carrier must maintain viable cell density and energy status; released metals must not inhibit nitrogenase.
P mobilization	Organic acids, chelation, proton release, and phosphatases	Greater access to poorly available phosphorus	Particles may supply micronutrients or change dissolution, but metal oxides can suppress solubilization at high dose.
Siderophores	High-affinity Fe binding and competitive sequestration	Fe acquisition and pathogen competition	Responses can increase under metal stress even when other PGP traits decline; trait-by-trait testing is necessary.
Phytohormone modulation	IAA and other hormones; modification of plant signaling	Root branching, elongation, and establishment	Nanomaterials can stimulate or inhibit hormone production depending on strain, coating, dissolution, and concentration.
ACC deaminase and stress relief	Reduction of stress-associated ethylene precursor	Tolerance to salinity, drought, flooding, and metals	Protective matrices can preserve cells during stress; the material itself may add or intensify oxidative stress.
Biocontrol and ISR	Antibiotics, enzymes, volatiles, competition, and immune priming	Lower disease pressure and improved resilience	Antimicrobial particles may complement biocontrol but can also injure the inoculant and non-target microbiota.

Source: Author synthesis based on Backer et al. (2018), de Moraes et al. (2021), Upadhayay et al. (2023), and Mgadi et al. (2024).

3. PGPB–Nanomaterial Interface

3.1. What defines a nano-supported microbial formulation?

A nanofertilizer is a form of nutrient elements brought to the nanoscale; it is not a biofertilizer. Or adding a microbial inoculant into nanoparticles does not automatically create a nano-biofertilizer. Garg et al. (2023) use the term nano-biofertilizer for next-generation formulations obtained by combinations of biofertilizers (bacteria, fungi, or algae) and nanomaterials (chitosan, polysaccharides, or metal nanoparticles), including encapsulated products. In this book chapter, a more detailed definition is adopted: a nano-supported microbial formulation is the deliberate combination of a beneficial microorganism with a nano-scaled or nano-structured material that has a clearly defined function, such as delivering to the target, protection, retention, nutrient provision, controlled release, or complementary biological effect. In the resulting nano-supported microbial formulation, the purpose of using the nano material should be clearly specified. The nano material can remain as dispersed particles, form larger aggregates, be incorporated within a hydrogel, cover a cell or carrier surface, or be produced by microorganisms. The form of the nano material, how it behaves, and who produces it are all very important. Each form cannot be considered the same as the others. For example, the particle size reported by the manufacturer may differ from the sizes in the culture medium, seed coating slurry, irrigation water, or soil pore water. Additionally, a nanoscale component may not always remain in particle form; it can quickly dissolve and ionize, becoming an active molecule in the resulting ions. Therefore, the characterization of the nanoparticle product should identify the state of the material within the formulation and any structural changes that may occur upon contact with as many different environments as possible.

3.2. Examination of Cell–Nano Material Interactions and Their Compatibility

Nanomaterials can bind to charged and chemically active regions on the cell membranes or walls of microorganisms, surface proteins, lipopolysaccharides, teichoic acids, and extracellular polymeric substances (EPS) (Atapattu et al 2026). Depending on the binding site, it can enhance the nutrient availability of the cell, increase the persistence of cells in roots, or promote biofilm formation. When the appropriate particle dose or type is not

selected, it can also disrupt the cell's membrane integrity, metabolism, redox balance, or gene expression, despite the potential positive effects. In metal oxides, toxicity can also arise from dissolution and ion release, independent of type or dose. Therefore, strong antimicrobial materials like silver can reduce the viability of the inoculum while suppressing the pathogen. There is no single compatible nanomaterial concentration that fits every bacterium. For each bacterium, the specific usable dose of the nanomaterial, contact duration, and appropriate interval should be determined. During the determination of these criteria, the growth kinetics of the inoculum, membrane integrity, viable cell count, biofilm formation, and whether the specific PGP functions proposed for the product are preserved should be tested. When particles adhering to the surface of the inoculum scatter light or when cells persist in a non-culturable state, optical density alone is not reliable for determining cell count (Pan et al., 2014). pH, salts, and natural organic matter can alter the aggregation and bioavailability of nanomaterials (Atapattu et al 2026). Therefore, these tests should not remain in the laboratory environment; they need to be repeated if they come into contact with water during the subsequent storage and field application stages (Figure 1).

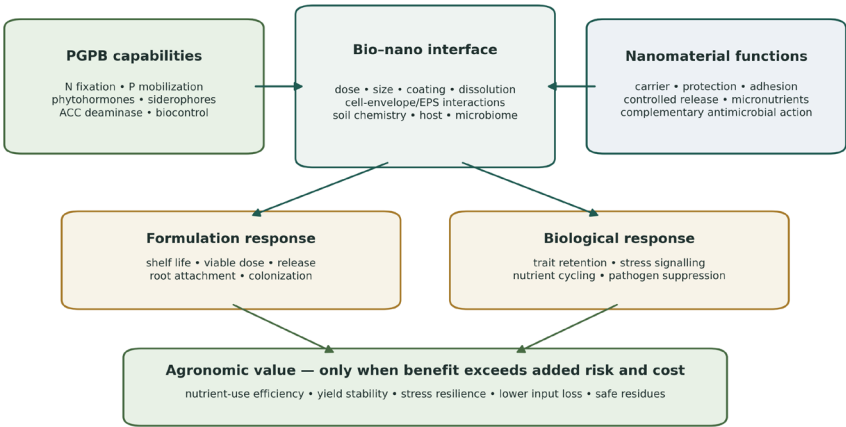


Figure 1. The PGPB–nanomaterial interface as a conditional design space. Material and microbial functions converge through formulation properties and environmental context; agronomic value is achieved only when performance exceeds added risk and cost.

Source: Original synthesis developed for this chapter.

4. Material Platforms and Formulation Strategies

4.1 Inorganic Nanoparticles

Metal and metal oxide nanoparticles are of interest due to their contribution to plant nutrition or their antimicrobial properties. For example, titanium dioxide (TiO₂) combined with *Pseudomonas fluorescens* has been studied for its potential to promote plant growth and phytoremediation. The results have shown that high application doses can suppress plant growth or the nutrient uptake properties of bacteria. Silicon dioxide (SiO₂) has been studied for its abilities to reduce drought and salinity stress in plants, strengthen tissues, and enhance disease resistance. They have determined that the identified silica–PGPB combinations increase plant growth and nutrient uptake. Zinc oxide (ZnO) provides a fundamental micronutrient source; however, its biological effects are variable. In bacterial experiments reported by de Moraes et al. (2021), increasing ZnO concentration reduced IAA production and phosphate solubilization while increasing siderophore production. In separate plant-soil studies, it has been found that high ZnO doses negatively affect nitrogen fixation metabolism and alter microbial diversity (Mgadi et al., 2024). Iron-containing nanoparticles can contribute to meeting the plant's iron needs and may affect redox or microbial activities. Nanoparticles such as copper oxide and silver have a stronger antimicrobial effect; this property can be beneficial in disease management, but it should be considered that while they show high antimicrobial activity against pathogens, they may also reduce inoculant viability. Gold nanoparticles are relatively stable and have been used in detection and experimental systems; however, their high cost limits their large-scale agricultural use. When evaluating these materials, knowing only the total element concentration is not sufficient. The biological effect; the chemical form, ionization capacity, surface coating property, aggregation state, and the actual dose reaching the microbial cell or target tissue must be known (de Moraes et al., 2021; Kah et al., 2019; Zhang et al., 2021).

4.2 Biopolymeric, hydrogel, and hybrid carriers materials

Alginate continues to be one of the most commonly used materials in the immobilization of microbial inoculants. Beads and capsules made from alginate can buffer cells against drying, maintain their viability during storage, and allow for the gradual release of cells after application. Chitosan, on the other

hand, is used in the preparation of films, coatings, and composite matrices. However, due to its antimicrobial activity, strain compatibility should be tested. Nano-structured or nanoparticle-reinforced polymers can help regulate properties such as porosity, mechanical durability, surface adhesion, and controlled release. However, these advantages should be tested in the final formulation rather than inferring from the properties of individual components (Schoebitz et al., 2013; Garg et al., 2023; Upadhayay et al., 2023). Silica, ZnO, micronutrients, salicylic acid, or other functional additives can be added to composite carriers. In a rice seedling experiment, *Pseudomonas* sp. DN18, salicylic acid, and ZnO nanoparticles were encapsulated in alginate capsules. The formulation maintained plant growth-promoting activity and provided greater seedling growth compared to the non-encapsulated bacterial solution (Panichikkal et al., 2021). This result is significant at the laboratory level but should not be interpreted as field validation. In another study, PGPB coated with nanoparticles was evaluated in terms of nutrient uptake and growth in wheat (Karunakaran et al., 2024). As the number of components in these formulations increases, it is necessary to test not only the effect of the formulation but also the effect of each individual component (Table 2).

4.3 Carbon-based and emerging platforms

Carbon nanotubes, graphene derivatives, nanowires, nanofibers, nanogels, and porous nanoparticles have large surface areas and tunable transport properties. Using these materials, more durable coatings can be obtained, and many properties can be adjusted, from water retention to controlled release. However, unless the duration of their persistence in the environment, the presence of production-related catalyst residues, their transformation in the soil, and their effects on microbial communities are addressed, it is quite difficult to judge their practical usability. Their comparison with a simpler carrier is particularly important. If alginate, peat, a traditional polymer, or a liquid formulation provides similar viability and agronomic performance, it is unrealistic to force the use of an additional nanoscale carrier.

Table 2. Comparative design logic for major material platforms used with PGPB.

Platform	Primary formulation role	Potential opportunity	Principal constraint and evidence status
TiO ₂	Reactive surface; growth or remediation co-amendment	May enhance biomass, root association, or metal uptake in selected systems	Dose-dependent phytotoxicity and inhibition of bacterial PGP traits; largely controlled-environment evidence.
SiO ₂ / silica	Stress-mitigation component and carrier surface	Water relations, tissue reinforcement, nutrient availability, and carrier stability	Responses depend on host and soil; distinguish dissolved silicon effects from particle-specific effects.
ZnO	Zn source and functional additive	Micronutrient delivery; potential support for plant growth	Dissolved Zn ²⁺ and reactive surfaces can inhibit viability, IAA, P solubilization, and N fixation above the compatibility window.
Fe / Fe oxides	Fe delivery and redox-active amendment	Micronutrient supply and possible support of microbial/plant metabolism	Oxidation state, dissolution, coating, and soil sorption determine availability; field evidence remains formulation specific.
Ag / CuO	Direct antimicrobial or biocontrol component	Pathogen suppression and possible additive protection	High conflict potential with the inoculant and non-target microbiota; selectivity and exposure control are essential.
Alginate / chitosan	Encapsulation, film, hydrogel, or composite matrix	Improved shelf life, water retention, adhesion, and controlled release	Release rate and bacterial viability depend on polymer composition and formulation conditions; manufacturing reproducibility is critical.
Carbon-based / porous hybrids	High-area carrier, adsorbent, or delivery scaffold	Tunable loading and transport; potential multifunctionality	Persistence, impurities, transformation, and cost may exceed demonstrated agronomic value.

Source: Author synthesis based on de Moraes et al. (2021), Schoebitz et al. (2013), Garg et al. (2023), Upadhayay et al. (2023), Kah et al. (2019), Lowry et al. (2019), Zhang et al. (2021), Mgadi et al. (2024), and Karunakaran et al. (2024).

5. Bacterial Biosynthesis of Nanoparticles

5.1. Bacteria as Nanoparticle Producers

Bacteria can be used in the production of nanoparticles. Bacterial synthesis is defined as more environmentally friendly compared to physical and chemical methods that require high energy and hazardous chemicals. However, the fact that a method is biological does not directly mean it is environmentally friendly and safe. As Arshad et al. (2026) point out, claims that a process is environmentally friendly or safe require consistent batches as well as comparative life cycle analyzes and toxicological evidence. Therefore, useful process reporting should go beyond just particle formation and also encompass the hazards of precursor materials, energy and water requirements, purification, yield, reproducibility, and waste treatment. In bacteria, nanoparticle synthesis can occur intracellularly or extracellularly. or it can occur outside the cell. In intracellular synthesis, ions first interact with the cell membrane and wall, then enter the cell and are converted into nanoparticles by enzymes or redox-active metabolites. Particles can be significantly coated with biological molecules. However, recovery usually requires the breakdown of cells and subsequent purification. Extracellular synthesis, on the other hand, requires the release of enzymes, proteins, etc., produced within the cell into the extracellular space. This also moves nanoparticle synthesis outside the cell. Extracellular production can facilitate recovery. Nitrate reductase, NADH-dependent oxidoreductases, and other electron transfer pathways are often included in the process; however, the dominant mechanism depends on the bacteria and the chemistry of the precursor material.

5.2. Nucleation, Coating, and Process Control

Many different types of microorganisms, such as algae, bacteria, actinomycetes, fungi, and yeasts, have been used for nanoparticle synthesis (Hulkoti & Taranath, 2014). The nucleation, growth, and stabilization rates of nanoparticles are regulated by various factors such as pH, precursor concentration, reaction time, temperature, and other reaction conditions. For example, while pH changes metal speciation, enzyme activity, cell surface charge, and nucleation, temperature affects reaction rate, microbial physiology, and the stability of coating molecules. Incubation time, precursor concentration, oxygen supply, cell density, and growth phase also shape yield and

morphology. As cultures age, reductase activity and exopolysaccharide secretion change, so the growth phase should be among the controlled production parameters. Optimization is more informative when it targets predefined product characteristics rather than the most pronounced visible color change.

5.3. Minimum characterization for agricultural use

It is important to determine the properties of the nanoparticle to be used for agricultural purposes, such as its elemental composition, size, hydrodynamic size and size distribution, particle concentration, ionization capacity, or stability. The properties of the nanoparticle produced through bacteria cannot be determined by a single analytical method. Therefore, various methods such as electron microscopy or FTIR analysis should be used (Arshad et al., 2026). The data obtained from each method should be collected and evaluated together to determine the properties of the particle. A PGPB strain used in nanoparticle production is not suitable for use as a live agricultural inoculant just because it only produces nanoparticles. It is also valid in the reverse case. A purified bacteriophage particle is also not a microbial biofertilizer. Therefore, the active component with efficacy must be clearly defined. Live bacteria, biogenic particles, surface-associated bacterial metabolites, or a deliberately combined system should be used.

6. Application Methods and Agronomic Evaluation

6.1. Seed, root, soil, and foliar application

Seed coating and seed pre-treatment (priming) place the inoculant close to the developing root and can reduce the total amount of material required (Mahmood et al 2016, Rocha et al 2019). However, these are not the same application. In the priming process, the seed is kept in a suspension before planting, while in seed coating, the formulation is applied to the seed surface and is ensured to remain there. Both can support early colonization. However, in the evaluation, germination, seed storage, coating integrity, microbial viability, and the formulation's compatibility with commercial seed chemicals should be considered. The preferred starting point for nanoparticles is the lowest effective dose and the shortest effective exposure. These criteria are used as a practical assessment framework. Root dipping delivers high-density cells

to seedling or transplant roots. In addition, application at the time of planting, direct application to the soil, and fertigation target the rhizosphere during the planting stage or later growth stages. Among these methods, soil application creates the most complex application environment. Because nanoparticles encounter minerals, organic matter, dissolved ions, moving water, roots, and a diverse microbiome in the soil. Foliar application can help with rapid feeding or disease management. However, live bacteria on the leaf surface are exposed to ultraviolet radiation, drying, temperature fluctuations, and shear forces caused by spraying (Preininger et al 2018). Additionally, aerosol and applicator exposure should also be considered. Therefore, the route of administration should be chosen not only based on ease of application but also in accordance with the biological target.

6.2, Interpretation of claims regarding growth, stress, biological control, and remediation It has been reported that compatible PGPR-nanomaterial applications often increase germination or biomass under controlled conditions. Silicon-containing systems can contribute to drought or salinity tolerance. PGPB, on the other hand, can contribute to phytohormonal mechanisms, antioxidant functions, osmotic functions, and nutrient mobilization. In plant protection, antimicrobial nanoparticles can complement bacterial antagonism or help in the preservation of microbial metabolites. The main issue is the limited selectivity of nanoparticles. Therefore, when evaluating the success of nanoparticle-bacteria combinations to be used in agriculture, evidence of pathogen suppression, inoculant survival, and the response of non-target communities should be assessed simultaneously, or it will be incomplete (Upadhayay et al., 2023; Wang et al., 2022). PGPB–nanomaterial applications can also serve a different purpose in phytoremediation; here, better plant adhesion can lead to changes in metal availability, sorption, or redox state, thereby increasing the plant's uptake of pollutants. While this result is desirable in a remediation site, it may be unacceptable in a food plant if metals accumulate in edible tissues. In this study, the intended use of the land is important.

7. Stepwise Decision Framework for Field Transfer

The majority of studies related to the use of the PGPB-Nanoparticle combination are still based on short-term laboratory or greenhouse experiments. For a formulation to be widely adopted in agriculture, it must successfully pass through several key stages. First, the product's content and properties must be clearly defined, and similar results should be obtained across different production batches. Secondly, it should be demonstrated that the microorganism and the nanomaterial remain compatible with each other at the targeted application dose and throughout the planned storage period. Thirdly, the combined use of these two components should provide a justifiable additional benefit in controlled but sufficiently representative natural condition experiments compared to their use individually. These three fundamental stages should be tested in different regions, growing seasons, and agricultural management conditions to demonstrate whether their success in agriculture continues. It is also important that the combination passing all stages is safe, can be produced on a large scale, is economically viable, and complies with relevant legal regulations (Figure 2, Table 3).

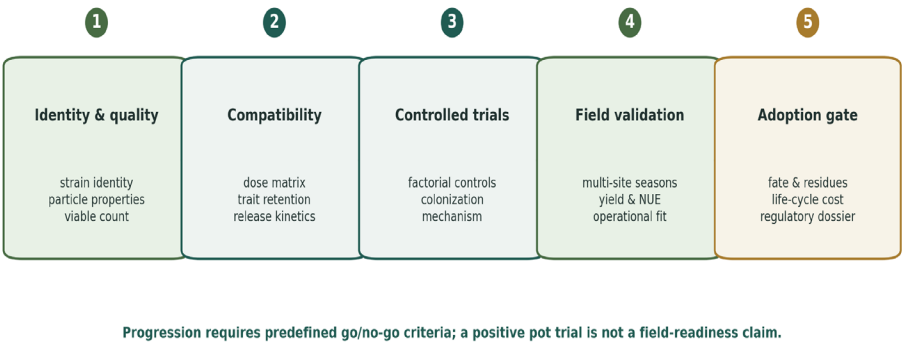


Figure 2. Stage-gated pathway from formulation concept to defensible agricultural use. Predefined go/no-go criteria prevent promising early endpoints from being misrepresented as field readiness.

Source: Original synthesis developed for this chapter.

Table 3. Minimum evidence package for development and reporting of PGPB–nanomaterial systems.

Stage	Decision question	Minimum evidence	Go/no-go principle
1. Identity and quality	Reproducible product definition	Strain identity and purity; viable count; particle composition, primary and hydrodynamic size, morphology, surface chemistry, concentration, dissolution; batch variability	No progression if product identity or dose cannot be reproduced.
2. Compatibility	Define the usable dose and shelf-life window	Dose × time matrix; growth and viability; retained PGP traits; aggregation; release kinetics; storage stability; dilution–water compatibility	No progression if the material defeats the microbial function it is intended to deliver.
3. Controlled efficacy	Demonstrate added combination value	Untreated, carrier-only, particle-only, PGPB-only, combination, and conventional benchmark; colonization; mechanism; plant and microbiome endpoints	Claim synergy only when the combination exceeds both single components with a plausible mechanism.
4. Field performance	Test robustness and operational fit	Multi-site and multi-season trials; yield and quality; NUE or water productivity; application compatibility; persistence; farmer-relevant handling	Report variability and failure conditions, not only mean positive response.

Stage	Decision question	Minimum evidence	Go/no-go principle
5. Adoption and stewardship	Establish net benefit and responsible use	Residues and fate; non-target effects; occupational exposure; manufacturing QC; lifecycle and cost analysis; jurisdiction-specific regulatory dossier	Adopt only when agronomic benefit exceeds added cost, complexity, exposure, and ecological burden.

Source: Proposed reporting framework synthesized from Herrmann and Lesueur (2013), Kah et al. (2018), Lowry et al. (2019), Mgadi et al. (2024), and Arshad et al. (2026).

8. Conclusions

The combined application of PGPB and nanomaterials can help in the efficient delivery of inputs of biological origin to the plant and can generate more reliable results from the applications. But the functions of these two parts in the system are not equivalent. The PGPB contributes to the absorption of nutrient elements by the plants, influences the hormonal balance, increases resistance to stress conditions and can suppress some pathogens. However, nanomaterials can perform functions such as protecting bacterial cells, improving surface adhesion, controlled release, and carrying micronutrients. Furthermore, the surface of the bacteria-synthesized nanoparticles may also contain natural biomolecules which can impart these particles with different properties. Nevertheless, the agricultural benefit and the environmental suitability of the production method and the obtained product have to be proved experimentally. The point here is that a nanoscale material should not make a microbial inoculant more successful than its own success. Under certain circumstances, beneficial results can be obtained from nanoparticles such as TiO₂, SiO₂, ZnO, Fe, Ag and CuO and polymeric or carbon-based carriers. In contrast, higher doses or changed environmental conditions can inhibit beneficial bacteria, negatively affect plant growth or alter the natural microbial balance in the soil. Therefore, each formulation has to be assessed on a case-by-case basis, considering the bacterial strain, the plant and the soil conditions where it will be applied. It would be wrong to simply take the safe and effective dose range from another system. It is expected that the products that will be

applied soon enough will be formulations that give solutions to well defined problems. Some of these problems are the loss of viability of bacterial cells during storage, insufficient adhesion to the root, the inability to co-transport micronutrients or the uncontrolled release of the active substance. But it must be clearly better than simple, cheaper options to justify the use of a more complex nanoformulation. More reliable demonstrations of the true value of these systems can be achieved by correctly defining product characteristics, including necessary control groups in experiments, and by repeating field studies in different regions and over multiple seasons. Under these conditions, the products of PGPB-nanomaterials could be an effective option for the integrated management of plant nutrition, stress resistance, and plant health.

REFERENCES

- Arshad, M., Nadeem, A., Maqbool, H., Khan, B., Khan, F., Naseem, R., . . . Chaudhary, H. J. (2026). Harnessing plant growth-promoting bacteria for nanoparticle biosynthesis: A systematic review of mechanisms, agricultural applications, and biomedical potential. *Bioprocess and Biosystems Engineering*, 49(5), 1077–1121. doi:10.1007/s00449-026-03291-0
- Atapattu, G. N., Giltrap, M., & Tian, F. (2026). Inorganic nanoparticle–bacteria interaction systems: Mechanistic, functional and agricultural applications. *Plant and Soil*, 524, 973–1011. doi:10.1007/s11104-026-08701-6
- Backer, R., Rokem, J. S., Ilangumaran, G., Lamont, J., Praslickova, D., Ricci, E., . . . Smith, D. L. (2018). Plant growth-promoting rhizobacteria: Context, mechanisms of action, and roadmap to commercialization of biostimulants for sustainable agriculture. *Frontiers in Plant Science*, 9, 1473. doi:10.3389/fpls.2018.01473
- Bashan, Y., de-Bashan, L. E., Prabhu, S. R., & Hernandez, J.-P. (2014). Advances in plant growth-promoting bacterial inoculant technology: Formulations and practical perspectives (1998–2013). *Plant and Soil*, 378, 1–33. doi:10.1007/s11104-013-1956-x
- de Moraes, A. C. P., Ribeiro, L. S., de Camargo, E. R., & Lacava, P. T. (2021). The potential of nanomaterials associated with plant growth-promoting bacteria in agriculture. *3 Biotech*, 11(7), 318. doi:10.1007/s13205-021-02870-0
- Garg, D., Sridhar, K., Stephen Inbaraj, B., Chawla, P., Tripathi, M., & Sharma, M. (2023). Nano-biofertilizer formulations for agriculture: A systematic review on recent advances and prospective applications. *Bioengineering*, 10(9), 1010. doi:10.3390/bioengineering10091010
- Herrmann, L., & Lesueur, D. (2013). Challenges of formulation and quality of biofertilizers for successful inoculation. *Applied Microbiology and Biotechnology*, 97, 8859–8873. doi:10.1007/s00253-013-5228-8
- Hulkoti, N. I., & Taranath, T. C. (2014). Biosynthesis of nanoparticles using microbes—A review. *Colloids and Surfaces B: Biointerfaces*, 121, 474–483. doi:10.1016/j.colsurfb.2014.05.027

- Kah, M., Kookana, R. S., Gogos, A., & Bucheli, T. D. (2018). A critical evaluation of nanopesticides and nanofertilizers against their conventional analogues. *Nature Nanotechnology*, 13, 677–684. doi:10.1038/s41565-018-0131-1
- Kah, M., Tufenkji, N., & White, J. C. (2019). Nano-enabled strategies to enhance crop nutrition and protection. *Nature Nanotechnology*, 14, 532–540. doi:10.1038/s41565-019-0439-5
- Karunakaran, A., Fathima, Y., Singh, P., Beniwal, R., Singh, J., & Ramakrishna, W. (2024). Next-generation biofertilizers: Nanoparticle-coated plant growth-promoting bacteria biofertilizers for enhancing nutrient uptake and wheat growth. *Agriculture*, 14(4), 517. doi:10.3390/agriculture14040517
- Lowry, G. V., Avellan, A., & Gilbertson, L. M. (2019). Opportunities and challenges for nanotechnology in the agri-tech revolution. *Nature Nanotechnology*, 14, 517–522. doi:10.1038/s41565-019-0461-7
- Mahmood, A., Turgay, O. C., Farooq, M., & Hayat, R. (2016). Seed biopriming with plant growth promoting rhizobacteria: A review. *FEMS Microbiology Ecology*, 92(8), fiw112. doi:10.1093/femsec/fiw112
- Mgadi, K., Ndaba, B., Roopnarain, A., Rama, H., & Adeleke, R. (2024). Nanoparticle applications in agriculture: Overview and response of plant-associated microorganisms. *Frontiers in Microbiology*, 15, 1354440. doi:10.3389/fmicb.2024.1354440
- Pan, H., Zhang, Y., He, G.-X., Katagori, N., & Chen, H. (2014). A comparison of conventional methods for the quantification of bacterial cells after exposure to metal oxide nanoparticles. *BMC Microbiology*, 14, 222. doi:10.1186/s12866-014-0222-6
- Panichikkal, J., Prathap, G., Nair, R. A., & Krishnankutty, R. E. (2021). Evaluation of plant probiotic performance of *Pseudomonas* sp. encapsulated in alginate supplemented with salicylic acid and zinc oxide nanoparticles. *International Journal of Biological Macromolecules*, 166, 138–143. doi:10.1016/j.ijbiomac.2020.10.110
- Preininger, C., Sauer, U., Bejarano, A., & Berninger, T. (2018). Concepts and applications of foliar spray for microbial inoculants. *Applied Microbiology and Biotechnology*, 102, 7265–7282. doi:10.1007/s00253-018-9173-4

- Rocha, I., Ma, Y., Souza-Alonso, P., Vosátka, M., Freitas, H., & Oliveira, R. S. (2019). Seed coating: A tool for delivering beneficial microbes to agricultural crops. *Frontiers in Plant Science*, 10, 1357. doi:10.3389/fpls.2019.01357
- Schoebitz, M., López, M. D., & Roldán, A. (2013). Bioencapsulation of microbial inoculants for better soil–plant fertilization: A review. *Agronomy for Sustainable Development*, 33, 751–765. doi:10.1007/s13593-013-0142-0
- Schütz, L., Gattinger, A., Meier, M., Müller, A., Boller, T., Mäder, P., & Mathimaran, N. (2018). Improving crop yield and nutrient use efficiency via biofertilization—A global meta-analysis. *Frontiers in Plant Science*, 8, 2204. doi:10.3389/fpls.2017.02204
- Su, Y., Zhou, X., Meng, H., Xia, T., Liu, H., Rolshausen, P., . . . Jassby, D. (2022). Cost–benefit analysis of nanofertilizers and nanopesticides emphasizes the need to improve the efficiency of nanoformulations for widescale adoption. *Nature Food*, 3, 1020–1030. doi:10.1038/s43016-022-00647-z
- Upadhayay, V. K., Chitara, M. K., Mishra, D., Jha, M. N., Jaiswal, A., Kumari, G., . . . Sharma, A. (2023). Synergistic impact of nanomaterials and plant probiotics in agriculture: A tale of two-way strategy for long-term sustainability. *Frontiers in Microbiology*, 14, 1133968. doi:10.3389/fmicb.2023.1133968
- Wang, D., Saleh, N. B., & Su, C. (2022). Nano-enabled pesticides for sustainable agriculture and global food security. *Nature Nanotechnology*, 17, 347–360. doi:10.1038/s41565-022-01082-8
- Zhang, P., Guo, Z., Ullah, S., Melagraki, G., Afantitis, A., & Lynch, I. (2021). Nanotechnology and artificial intelligence to enable sustainable and precision agriculture. *Nature Plants*, 7, 864–876. doi:10.1038/s41477-021-00946-6

CHAPTER 5

THE DIFFUSION OF DIGITAL AGRICULTURE WITHIN RURAL DEVELOPMENT SUPPORT MECHANISMS IN TÜRKİYE: A POLICY ANALYSIS OF THE KKYDP AND IPARD PROGRAMS

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1. INTRODUCTION AND THEORETICAL FRAMEWORK: AGRICULTURE 4.0 AND RURAL POLICY

Digital transformation in agriculture—widely conceptualized as "Agriculture 4.0"—represents a structural transition from mechanization-driven production (Agriculture 2.0) and early computerized automation (Agriculture 3.0) toward fully integrated, data-driven, and cyber-physical agricultural systems (Klerkx et al., 2019; Walter et al., 2017). This paradigm relies on the convergence of the Internet of Things (IoT), autonomous machinery, unmanned aerial vehicles (UAVs), remote sensing, artificial intelligence (AI), and real-time decision-support platforms. In economic terms, Agriculture 4.0 addresses dual objectives: optimizing input-output efficiency at the farm level (e.g., reducing chemical fertilizers, fuel, and water usage) while mitigating environmental externalities and labor shortages in rural areas (Finger et al., 2019).

Despite its transformative potential, the adoption of digital technologies in agriculture is neither automatic nor spatially uniform. The literature on agricultural technology adoption emphasizes that capital-intensive innovations often encounter systemic barriers, particularly in emerging economies characterized by smallholder, fragmented farm structures, aging rural demographics, and low technical literacy (Feder et al., 1985; Sunding & Zilberman, 2001). Under the framework of the Technology-Organization-Environment (TOE) model and the Innovation Diffusion Theory (Rogers, 2003), public intervention acts as a critical external catalyst. Without targeted subsidy regimes, high initial capital expenditure (CAPEX) for smart farming technologies creates a digital divide between large-scale commercial agro-enterprises and family farms (Eastwood et al., 2019).

In the European Union, the Common Agricultural Policy (CAP) Post-2020 has systematically mainstreamed the "twin transition" (green and digital transformation), recognizing that climate targets and economic resilience are inseparable from data-driven farm management (European Commission, 2021). As an EU candidate country, Türkiye faces a structural imperative to harmonize its domestic rural support framework with EU standards while addressing distinct local agro-structural challenges. In Türkiye, agricultural policy mechanisms have historically favored input and direct income supports;

however, rural development schemes have increasingly shifted toward investment subsidies aimed at capital modernization.

The two central policy pillars governing capital and technology grants in rural Türkiye are the nationally funded **Rural Development Investments Support Program (KKYDP)**, administered by the Ministry of Agriculture and Forestry, and the EU-co-financed **Instrument for Pre-Accession Assistance for Rural Development (IPARD)**, executed through the Agricultural and Rural Development Support Institution (TKDK). While both programs have injected substantial capital into rural enterprises over the past two decades, academic inquiry into how these programs explicitly address and operationalize digital agricultural transformation remains sparse. Most existing studies evaluate these programs from a broad socioeconomic perspective (e.g., regional income disparities or general mechanization; Şahin & Kan, 2022) without deconstructing the specific technology items, grant conditionalities, and structural bottlenecks related to smart farming.

Therefore, the main objective of this study is to conduct a comprehensive policy analysis of the KKYDP and IPARD programs regarding their contribution to the adoption and diffusion of digital agriculture in Türkiye. Specifically, the study aims to:

1. Systematically evaluate the institutional frameworks, eligible digital technology portfolios, and grant mechanisms of KKYDP (2006–2026) and IPARD (Periods I, II, and III).
2. Compare the policy architectures, co-financing structures, and target criteria of both programs.
3. Assess the empirical outcomes of recent digital pilot implementations and identify structural bottlenecks (e.g., human capital, infrastructure, software localization) from an agricultural economics perspective.

2. MATERIAL AND METHODS

To evaluate the digital transformation trajectory within Turkish rural development policies, this study employs a **Qualitative Policy and Document Analysis Framework** (Bowen, 2009; Denzin, 2017) combined with **Comparative Policy Analysis** (Heidenheimer et al., 1990). The research design is structured into three methodological stages: document corpus

compilation, systematic content categorization, and comparative policy assessment.

2.1. Data Sources and Document Corpus

The primary empirical material of this study consists of legislative, administrative, and statistical official records covering the 2006–2026 period. The corpus was compiled directly from primary public institutions responsible for rural development in Türkiye:

- **Ministry of Agriculture and Forestry (TOB):** Official implementation guidelines (*Uygulama Rehberleri*), communiqués published in the Official Gazette (*Resmi Gazete*), and official rural development statistics reports covering KKYDP phases between 2006 and 2025/2026 (Tarım ve Orman Bakanlığı, 2023, 2026a, 2026b, TÜİK, 2024).
- **Agricultural and Rural Development Support Institution (TKDK):** IPARD I (2007–2013), IPARD II (2014–2020), and IPARD III (2021–2027) multiannual programming documents, sector monitoring reports, call-for-application brochures, and the technical investment lists approved by the European Commission and the Republic of Türkiye (TKDK, 2025).
- **Research and Technology Institutions:** Project reports and performance outcomes published by the General Directorate of Agricultural Research and Policies (TAGEM), the Central Research Institute of Field Crops, and joint R&D initiative documents (e.g., ASELSAN Smart Agriculture projects).

2.2. Analytical Framework and Categorization Matrix

The document corpus was evaluated through qualitative content analysis using a structured policy evaluation matrix. Technological investment items eligible for grant funding under KKYDP and IPARD were classified into four functional digital agriculture categories based on the taxonomy proposed by Wolfert et al. (2017) and Finger et al. (2019):

1. *Precision Field Agriculture:* GPS/GNSS-guided auto-steering systems, variable rate application (VRA) machinery (fertilizer/pesticide), and yield monitoring systems.

2. *Livestock Smart Automation*: Robotic milking systems, automated feeding and manure scraping robots, and biometric sensor collars/pedometers for herd health and estrus monitoring.
3. *Environmental and Climate Control*: AI-supported greenhouse automation systems, smart sensor-based pressurized irrigation networks, and remote climate monitoring stations.
4. *Data and Decision Support Systems (DSS)*: UAV-based multispectral imaging, digital pheromone traps, and farm management software platforms.

2.3. Comparative Policy Dimension

A comparative matrix was constructed to systematically evaluate KKYDP and IPARD III across six structural policy dimensions:

- Financial architecture (national vs. supranational co-financing ratios, grant ceilings).
- Fiscal incentives (VAT exemption status).
- Geographic allocation and accessibility (provincial coverage).
- Governance, application, and ex-post audit procedures.
- Targeting criteria (prioritization of young/female farmers and mountainous zones).
- Digital and green transition conditionalities ("Twin Transition" weighting).

Finally, quantitative investment data (number of projects, grant amounts, capital formation, and employment impact) were compiled, cross-verified across institutional reports to eliminate numerical discrepancies, and analyzed chronologically to evaluate public spending trends.

3. INSTITUTIONAL FRAMEWORK AND POLICY COMPARISON: KKYDP AND IPARD

In Türkiye, capital subsidization in the agricultural sector operates primarily through two distinct policy vehicles administered by the Ministry of Agriculture and Forestry (TOB): the nationally financed Rural Development Investments Support Program (**KKYDP**) and the European Union co-financed Instrument for Pre-Accession Assistance for Rural Development (**IPARD**). Although both instruments share the overarching objective of modernizing

agricultural assets and fostering rural resilience, their institutional governance, funding structures, and operational procedures exhibit substantial divergent characteristics.

3.1.. Governance and Operational Discrepancies

A comparative analysis of the policy architectures reveals fundamental differences in the project lifecycle:

- 1. Application and Call Mechanism:** KKYDP operates via annual implementation communiqués and guidelines published on the central Ministry portal (*kirsalkalkinma.tarimorman.gov.tr*). In contrast, IPARD does not follow an open-ended annual schedule; rather, the Agricultural and Rural Development Support Institution (TKDK) announces competitive, time-bound "Calls for Applications" (typically open for 30–60 days) tied to specific investment measures under multiannual programming (TKDK, 2025).
- 2. Evaluation and Selection Committees:** KKYDP applications are evaluated at the sub-national level by Provincial Project Evaluation Commissions composed of local technical personnel within Provincial Directorates of Agriculture and Forestry. In contrast, IPARD employs a centralized, multi-tier evaluation system adhering to EU accreditation standards, executed by specialized TKDK experts across administrative, technical, and economic eligibility stages (including net present value [NPV] and internal rate of return [IRR] assessments of business plans).
- 3. Procurement and Price Determination:** KKYDP utilizes a pre-determined "Reference Price List" established centrally by the Ministry for standard machinery and construction units; grant payouts are calculated based on these normative benchmark costs (Şahin & Kan, 2022). Conversely, IPARD enforces rigorous EU procurement regulations requiring competitive bidding (a minimum of three independent, verifiable price offers) and market price cross-verification against TKDK's reference databases to prevent price distortions.
- 4. Fiscal and Tax Regimes:** A primary structural advantage of IPARD investments is full exemption from Value Added Tax (VAT) and

customs duties pursuant to Framework Agreements between Türkiye and the European Commission. Under KKYDP, VAT has historically constituted an out-of-pocket operational expenditure for the beneficiary, although recent regulatory revisions for the 2026 phase have introduced VAT-inclusive calculation modalities to ease farm-level cash constraints.

5. Post-Investment Monitoring (Ex-post Control): Both programs enforce a five-year binding monitoring period post-disbursement. Beneficiaries are legally prohibited from transferring asset ownership, modifying production lines, or leasing subsidized hardware. However, IPARD subjects projects to independent, unannounced multi-tier audits conducted by both national auditors and the European Court of Auditors (ECA).

Table 1 synthesizes the structural and comparative parameters governing both programs.

Table 1. Comparative Matrix of KKYDP and IPARD Policy Frameworks

Comparative Criterion	KKYDP (National Program)	IPARD III (EU Co-Financed)
Funding Architecture	100% National Budget (Republic of Türkiye)	Multi-donor (75% EU Instrument for Pre-Accession, 25% National Co-financing)
Implementing Agency	General Directorate of Agricultural Reform (TOB)	Agricultural and Rural Development Support Institution (TKDK)
Grant Intensity	50% baseline (tiered up to 70% in 2026 for youth, women, and technical graduates)	50%–75% (maximized for young farmers, mountainous zones, and certified organic production)
Tax Status	Historically VAT-exclusive; converted to VAT-inclusive support structures in the 2026 program	Fully exempt from VAT, customs duties, and transaction taxes
Financial Ceilings	Moderate (increased up to 30,000,000 TL [~€750,000–800,000] for economic investments in 2026)	Substantial (up to €3,000,000 for agro-processing and renewable energy infrastructures)

Territorial Coverage	Nationwide (All 81 Provinces since inception)	Phased expansion: 20 provinces (IPARD I) :42 provinces (IPARD II) :All 81 provinces (IPARD III, 2024–2026)
Procurement Protocol	Central reference price schedule	Mandatory three-bid tender protocol and market price verification database
Digital Integration	Machine-level modernization and modular hardware upgrades	Integrated "Twin Transition" (green and digital criteria embedded in ranking scoring)

4. EMPIRICAL INVESTMENT DYNAMICS AND DIGITAL TECHNOLOGY PORTFOLIOS

4.1. Program Analysis and Capital Formation Trends

The empirical scale of public rural investments mobilized through KKYDP and IPARD underscores substantial capital formation across the Turkish agrifood landscape. Over the 2006–2025 period, cumulative public-private investment under both frameworks exceeded 327.4 billion TL, supporting over 160,000 individual and enterprise-level projects (Table 2).

Table 2. Cumulative Public Rural Development Investment Statistics in Türkiye (2006–2025) (*Values adjusted based on official Ministry records; monetary figures in Million TL*)

Program Sub-Measure	Implementation Period	Completed Projects (Number)	Total Grants Disbursed (Million TL)	Generated Employment (Persons)	Total Investment Volume (Million TL)
KKYDP (Economic Investments)	2006-2024	19.413	59.302	124.056	125.322
	2025	3.412	5.205	5.543	11.113
	Total	22.825	64.507	129.599	136.435
KKYDP Machinery & Equipment	2006-2023	-	17.997	-	-
Expert Hands (Uzman Eller)	2020-2023	2.413	931	2.413	1.133

Young Farmer (Genç Çiftçi)	2016-2018	47.775	17.565	47.775	-
Individual	2007-2024	57294	11.315		22.630
Pressurized Irrigation	2025	2.788	1.141	-	2.853
	Total	60.082	12.456		25.483
IPARD (Phases I, II, III)	2007-2024	25.612	96.283	105.292	148.364
	2025	809	7.431	1.626	13.024
	Total	26.421	103.714	106.918	161.388
Disadvantaged Area Projects	2018-2024	429	1.168		2.127
	2025	130	709	-	917
	Total	559	2.377		3.044
GRAND TOTAL	2006-2024	153396	205.061	279.536	299.575
	2025	7.139	14.486	7.169	27.907
	Total	160.535	219.547	286.705	327.482

Source: Compiled and calculated by the author from Tarım ve Orman Bakanlığı (2026a) and TKDK (2025) monitoring datasets.

As illustrated in Table 2, KKYDP Economic Investments financed 22,825 high-capacity agro-processing and storage facilities, creating nearly 130,000 permanent on-farm and agro-industrial jobs. Concurrently, the IPARD program channeled 103.7 billion TL in direct grants across 26,421 modern enterprise investments. A critical nuance noted in the evaluation is the separation between individual machinery subsidies (which supported 17,997 distributed machinery components between 2006 and 2023) and high-value capital assets.

4.2. Evolution of Eligible Digital Technology Portfolios

The policy instruments have evolved from subsidizing conventional mechanical implements (e.g., standard plows, mechanical seeders) toward sophisticated digital components. Under the latest **2026 KKYDP Implementation Guide**, targeted investments in information communication technologies (ICT), IoT, and robotics have been officially classified into specialized eligible expenditure chapters with minimum farm-scale eligibility constraints:

1. Precision Crop Farming and Guidance Systems:

- *Automatic Steering and GNSS Guidance Systems:* Eligible for single-parcel holdings ≥ 75 decares or aggregate holdings ≥ 150

decares, reducing input overlap during tillage, planting, and harvesting.

- *Variable Rate Application (VRA)*: Automated variable rate fertilization and chemical spraying systems (minimum holding scale: 100 decares in consolidated parcels).
- *Agricultural Unmanned Aerial Vehicles (UAVs)*: Subsidies are restricted strictly to registered agricultural producer cooperatives and producer unions, requiring certified UAV remote pilot licensing at the final payment request stage.
- *Smart Soil and Canopy Tillage*: Inter-row sensor-controlled tillers for vineyards and orchards (≥ 150 decares, minimum 90 HP tractor capacity).

2. **Smart Livestock Automation and Biometrics:**

- *Robotic Milking Systems*: Autonomous units serving commercial dairy herds (≥ 25 head), monitoring milk conductivity, somatic cell counts, and yield per teat.
- *Autonomous Feeding and Facility Cleaners*: Autonomous feed pushing robots (≥ 100 head), autonomous manure clearing robots (≥ 100 head), and calf automatic milk feeder robots (≥ 20 head).
- *Precision Biometric Collars and Pedometers*: Wearable IoT sensors tracking rumination, physical activity, estrus onset, and sub-clinical mastitis detection (≥ 50 head).

3. **Data Management, IoT, and Artificial Intelligence:**

- Solar-powered digital pheromone traps incorporating optical insect cameras and automated algorithmic pest population counting (≥ 100 decares).
- Remote-sensing enabled agrometeorological and soil moisture probe arrays directly interfacing with cloud-based pressurized irrigation valves.

4.3. **IPARD III: Operationalizing the "Twin Transition"**

In the IPARD III (2021–2027) programming period, digital transformation is no longer treated as an incidental upgrade but as a decisive evaluation benchmark. The policy introduces three institutional mechanisms:

- **Ranking Score Weighting:** Project applications containing verified digital transformation components (e.g., smart herd tracking, VRA implements, or closed-loop climate sensors in protected horticulture) receive preferential ranking bonus points. In over-subscribed application calls, this criteria dictates project survival.
- **Geographical Expansion:** The scaling of IPARD from 42 to all 81 provinces eliminates spatial inequities, allowing high-technology intensive regions in Western and Central Anatolia to access substantial EU funding envelopes.
- **Measure 6 (M6 - Rural Public Infrastructure):** Expanding the scope to rural municipalities to fund smart village pilot infrastructures, local sensory data hubs, and micro-grid renewable energy installations with grant support limits up to €3 million.

5. EVALUATION OF PILOT DIGITAL AGRICULTURE INITIATIVES: PERFORMANCE METRICS AND EMPIRICAL EVIDENCE

A recurrent limitation in policy evaluation studies is citing pilot applications without establishing objective performance metrics. In the context of Türkiye, public R&D institutions and defense-industrial partnerships have spearheaded multiple smart farming initiatives to test technical viability and economic feasibility before scaling investments through KKYDP and IPARD. To assess these interventions systematically, projects are evaluated across three primary techno-economic dimensions: input-use efficiency (chemical fertilizers, pesticides, irrigation water, fuel), labor and operational optimization, and domestic value-added (import substitution).

5.1. Agronomic and Resource-Efficiency Metrics in Field Trials

Recent state-sponsored and institutional R&D projects provide quantifiable evidence regarding the returns on digital agricultural investments:

- **Variable-Rate Fertilizer Application in Irrigated Maize (Çukurova Pilot):** Integrating high-resolution satellite vegetation indices (NDVI) with on-the-go optical sensors and soil electrical conductivity mapping demonstrated that localized Variable Rate

Application (VRA) reduced nitrogenous fertilizer usage by 14% to 22% without yield penalties compared to conventional homogeneous broadcast applications. Economically, this translated into significant unit-cost reductions and curtailed groundwater nitrate leaching.

- **Integrated Precision Cereal Farming (Central Anatolia - AOC, Ankara, and Konya Trials):** Multi-year field trials executed by the Central Research Institute of Field Crops and the Bahri Dağdaş International Agricultural Research Institute across fragmented dryland plots showed that implementing RTK-corrected auto-steering and prescription seeding curtailed input overlap during sowing and herbicide spraying by 7% to 11%, while tractor fuel consumption per hectare decreased by 8.5%. The central institutional contribution of this initiative was establishing a localized, web-interfaced agronomic database enabling micro-climate risk monitoring and spatial-temporal yield forecasting.

From a farm-level investment economics perspective, empirical cost-benefit simulations indicate that the rapid amortization of smart implements is heavily dependent on public co-financing. For instance, in medium-to-large-scale field crop enterprises (150–300 ha) investing in domestic RTK auto-steering or retrofit VRA sprayers, unsubsidized capital investment payback periods typically range from 4.8 to 6.2 years based purely on input savings (diesel, agrochemicals, and labor). However, when leveraged with maximum public grant intensities (up to 70% under KKYDP and 75% under IPARD III), the net capital payback period contracts sharply to 1.8–2.4 years. This substantial compression in capital recovery cycles demonstrates that targeted public grant intensities effectively mitigate private financial risk and accelerate technology uptake for commercial producers.

5.2. Technological Sovereignty and Industrial Partnerships (TAGEM – ASELSAN Initiatives)

The capital intensity of Agriculture 4.0 often exacerbates external trade deficits due to heavy reliance on imported sensor arrays, GPS receivers, and telematics modules. To address this structural vulnerability, joint public-industrial collaborations have developed indigenous hardware-software architectures:

- **Domestic Tractor Automatic Steering (OTAK System):** Developed to mitigate reliance on foreign satellite-guidance hardware, the system achieved RTK positioning accuracy within a ± 2.5 cm pass-to-pass margin in field validations. The economic metric of success lies in capital cost reduction: the domestic system lowers hardware acquisition costs by approximately 35% to 40% relative to imported market counterparts, expanding access for medium-scale Turkish producers.
- **Harvest Loss and Yield Monitoring Telematics:** Combining optoelectronic sensors with CAN-bus data loggers in combine harvesters enabled real-time grain-loss monitoring, curbed field losses during wheat harvesting by 1.8% to 2.5%, and, when scaled to national cereal production volumes, represented significant aggregate food security gains.

Table 3. Empirical Performance Indicators of Public Precision Agriculture Projects in Türkiye

Project Initiative	Implementing Body	Core Technology Deployed	Evaluated Performance Benchmark	Agro-Economic Impact
VRA Maize Fertilization	TOB / TAGEM Çukurova	Satellite NDVI & VRT Spreaders	Input-use efficiency	14–22% nitrogen savings; reduced input costs
Precision Cereal Management	TAGEM (Ankara & Konya)	Auto-steering & Sensor Networks	Operational overlap & fuel efficiency	8.5% fuel reduction; 7–11% input overlap mitigation
OTAK Auto-Steering System	TOB & ASELSAN	Domestic RTK Guidance Unit	Capital expenditure (CAPEX) & localization	± 2.5 cm accuracy; ~40% lower

Project Initiative /	Implementing Body	Core Technology Deployed	Evaluated Performance Benchmark	Agro-Economic Impact
				equipment cost
Combine Harvester Loss Tracker	TOB & ASELSAN	Optical Loss Sensors & Telematics	Harvest efficiency and yield preservation	1.8–2.5% decrease in grain loss during harvesting

TÜME, which falls outside of these, offers a different experience. The TÜME (Agricultural Technologies Cluster) initiative was established with the goals of strengthening Turkey's food supply security, basing production on technology and science, making modern agricultural technologies accessible, equipping young producers with future professional skills, and connecting these young producers with investors to enable the establishment of next-generation agricultural businesses (TUME, 2026).

6. DISCUSSION: STRUCTURAL BOTTLENECKS IN POLICY IMPLEMENTATION

The empirical trajectories of KKYDP and IPARD reveal that while capital subsidization is an indispensable catalyst for Agriculture 4.0, direct financial grants alone cannot resolve structural adoption bottlenecks. Interpreting the findings through the lens of the Technology Acceptance Model (TAM) and farm-level production economics highlights several systemic dynamics:

6.1. Scale Bias, Capital Constraints, and the Digital Divide

Precision agriculture hardware exhibits distinct economies of scale. High initial fixed costs (CAPEX) create long payback periods for smallholders. Even with 50%–70% grant support under KKYDP or IPARD, the remaining equity requirement and initial working capital (OPEX) pose substantial hurdles for family farms operating fragmented parcels (<50–100 decares). The eligibility thresholds introduced in the 2026 KKYDP guide (e.g., minimum 100 decares for VRA sprayers, 150 decares for auto-steering, 25 head of dairy cattle for

milking robots) structurally favor consolidated, commercial agro-enterprises. Consequently, without institutional aggregation mechanisms, policy subsidies inadvertently risk widening the productivity gap between capital-endowed agribusinesses and resource-constrained family farms.

6.2. Rural Connectivity and the Data Infrastructure Void

Precision agriculture is fundamentally contingent on telemetry, cloud analytics, and seamless data exchange between field-level sensor networks and centralized servers (Bacco et al., 2019). Across rural Anatolia, terrestrial broadband coverage remains deficient, and mobile cellular data infrastructures exhibit persistent latency and dead zones in agricultural fields. Without high-speed rural connectivity, advanced IoT sensor arrays and autonomous systems cannot transmit operational data in real-time, effectively reducing intelligent platforms to offline, modular mechanization.

6.3. Human Capital Deficits and Technological Literacy

As evidenced by the Technology-Organization-Environment (TOE) framework, technological availability does not equate to effective technological utilization. Subsidizing advanced robotics (e.g., automated milking robots or autonomous manure scrapers) without addressing rural human capital results in suboptimal operational efficiency. Beneficiaries frequently utilize only basic functionality, failing to exploit predictive biometric analytics, herd estrus algorithms, or variable-rate soil prescription maps. The shortage of qualified agricultural engineers capable of acting as "agricultural data intermediaries" represents a severe non-financial barrier.

6.4. Data Sovereignty and Software Localization

The vast majority of digital farming hardware and decision-support algorithms subsidized through IPARD are manufactured by multinational corporations based in North America or Western Europe. These platforms rely on proprietary, closed-loop ecosystems that aggregate farm-level agronomic data on foreign servers, raising critical questions regarding national data sovereignty and security. Furthermore, proprietary yield prediction and fertilization algorithms are frequently calibrated to temperate European soil and climatic regimes, resulting in suboptimal performance when applied to the

semi-arid, high-pH, low-organic-matter soil conditions prevalent across Türkiye.

7. POLICY RECOMMENDATIONS AND CONCLUSION

To ensure that capital subsidies under KKYDP and IPARD translate into systemic, widespread digital transformation, agricultural policymakers must move beyond conventional asset purchase subsidies toward an integrated systemic model.

7.1. Policy Implications and Strategic Interventions

1. **Institutionalizing "Digital Shared Cooperativism":** To mitigate parcel fragmentation and capital barriers for smallholders, KKYDP and IPARD should establish dedicated grant envelopes for machinery-sharing cooperatives and agricultural producer unions. Subsidizing high-value capital assets (e.g., agricultural drone fleets, autonomous harvesters, self-propelled VRA sprayers) exclusively for collective use allows smallholder clusters to benefit from economies of scale without incurring prohibitive debt.
2. **Integrating Subsidies with Mandatory Digital Extension and Training:** Grants for digital machinery should be conditionally linked to certified digital capacity-building programs. Beneficiaries of advanced robotic or precision implements under KKYDP/IPARD should be required to complete accredited precision agriculture training modules delivered via university agricultural faculties and provincial research institutes (TAGEM).
3. **Open-Source Architecture and Domestic Software Subsidies:** Public policy must actively incentivize the development of indigenous, open-architecture farm management information systems (FMIS). Financial frameworks should allocate specific innovation vouchers for domestic software developers working on API integrations that calibrate international sensor hardware with domestic spatial databases (such as TOB's ÇKS and TARSİM infrastructure).
4. **Rural Public Digital Infrastructure as a Public Good:** Leveraging IPARD III Measure 6 (Rural Infrastructure), rural local authorities

should prioritize broadband telecommunication infrastructure and rural 5G/IoT gateways, recognizing connectivity as an essential agricultural infrastructure on par with pressurized irrigation networks.

7.2. Conclusion

The digital transformation of the agricultural sector represents a profound structural transition from conventional mechanical inputs to data-driven, precision decision-making. In Türkiye, the Rural Development Investments Support Program (KKYDP) and the EU-co-financed IPARD program serve as the primary institutional engines mobilizing rural capital formation. The strategic evolution observed in the 2026 KKYDP implementation guide and the multiannual framework of IPARD III clearly signals a decisive policy pivot toward the "twin transition"—integrating decarbonization, resource efficiency, and digital innovation.

Over the 2006–2025 period, cumulative investments under KKYDP and IPARD have exceeded 327 billion TL across more than 160,000 projects, creating substantial technological capacity and generating rural employment. Recent policy reforms—notably increasing grant intensities up to 70%–75%, incorporating VAT relief modalities, and assigning explicit scoring bonuses to green-digital components—have considerably reduced farm-level investment risks.

However, as demonstrated in this policy analysis, maximizing the long-term return on public capital investments requires transcending mere hardware procurement. Overcoming the rural digital divide demands an integrated policy ecosystem that pairs capital grants with robust digital extension, data governance frameworks, local hardware-software development, and cooperative asset-sharing models. By empowering young agricultural engineers and tech-literate producers through structured public support, digital agriculture can simultaneously bolster national food security, ensure sustainable resource stewardship, and elevate the socioeconomic welfare of rural communities.

References

- Bacco, M., Barsocchi, P., Ferro, E., Gotta, A., & Ruggeri, M. (2019). The digitization of agriculture: A survey of research activities on smart farming. *Array*, 3, 100009. <https://doi.org/10.1016/j.array.2019.100009>
- Bowen, G. A. (2009). Document analysis as a qualitative research method. *Qualitative Research Journal*, 9(2), 27–40. <https://doi.org/10.3316/QRJ0902027>
- Denzin, N. K. (2017). *The research act: A theoretical introduction to sociological methods*. Routledge.
- Eastwood, C., Klerkx, L., Ayre, M., & Rue, B. D. (2019). Managing socio-ethical challenges in the development of smart farming: From a technology hype to a technology with hope. *Journal of Agricultural and Environmental Ethics*, 32(5), 741–765. <https://doi.org/10.1007/s10806-017-9704-5>
- European Commission. (2021). *A long-term vision for the EU's rural areas – Towards stronger, connected, resilient and prosperous rural areas by 2040* (COM(2021) 345 final). Directorate-General for Agriculture and Rural Development.
- Feder, G., Just, R. E., & Zilberman, D. (1985). Adoption of agricultural innovations in developing countries: A survey. *Economic Development and Cultural Change*, 33(2), 255–298. <https://doi.org/10.1086/451461>
- Finger, R., Swinton, S. M., El Benni, N., & Walter, A. (2019). Precision farming at the nexus of agricultural production and the environment. *Annual Review of Resource Economics*, 11, 313–335. <https://doi.org/10.1146/annurev-resource-100518-093929>
- Heidenheimer, A. J., Hecl, H., & Adams, C. T. (1990). *Comparative public policy: The politics of social choice in America, Europe, and Japan* (3rd ed.). St. Martin's Press.
- Klerkx, L., Jakku, E., & Labarthe, P. (2019). A review of social science on digital agriculture, smart farming and agriculture 4.0: New perspectives and a roadmap. *NJAS – Wageningen Journal of Life Sciences*, 90–91, 100315. <https://doi.org/10.1016/j.njas.2019.100315>
- Rogers, E. M. (2003). *Diffusion of innovations* (5th ed.). Free Press.

- Sunding, D., & Zilberman, D. (2001). The agricultural innovation process: Research and technology adoption in a changing agricultural sector. In B. L. Gardner & G. C. Rausser (Eds.), *Handbook of agricultural economics* (Vol. 1, Part A, pp. 207–261). Elsevier. [https://doi.org/10.1016/S1574-0072\(01\)10007-5](https://doi.org/10.1016/S1574-0072(01)10007-5)
- Şahin, A. E., & Kan, A. (2022). Kırsal Kalkınma Yatırımlarının Desteklenmesi Programı: Kırsal Ekonomik Altyapı Projeleri 2021 yılı Bolu örneği [Rural Development Investment Support Program: Rural Economic Infrastructure Projects 2021 Bolu case]. *Kırşehir Ahi Evran Üniversitesi Ziraat Fakültesi Dergisi*, 2(2), 121–132. <https://izlik.org/JA27DF24ZK>[cite: 4]
- Tarım ve Orman Bakanlığı. (2023). *Tarım makineleri ve teknolojileri sektör politika belgesi 2023–2027* [Agricultural machinery and technologies sector policy document 2023–2027]. Tarım ve Orman Bakanlığı.[cite: 4]
- Tarım ve Orman Bakanlığı. (2026a). *Kırsal kalkınma istatistikleri raporu (2006–2025)* [Rural development statistics report (2006–2025)]. Tarım Reformu Genel Müdürlüğü.[cite: 4]
- Tarım ve Orman Bakanlığı. (2026b). *Kırsal Kalkınma Yatırımlarının Desteklenmesi Programı (KKYDP) 2026 yılı uygulama rehberi* [Rural Development Support Program (RDIP) 2026 implementation guide]. Tarım Reformu Genel Müdürlüğü. <https://kirsalkalkinma.tarimorman.gov.tr>[cite: 4]
- TKDK. (2025). *IPARD III Programı (2021–2027) uygulama ve başvuru çağrı rehberi* [IPARD III Programme (2021–2027) implementation and call for applications guide]. Tarım ve Kırsal Kalkınmayı Destekleme Kurumu.[cite: 4]
- TÜİK. (2024). *Genel tarım sayımı ve tarımsal işletme yapı araştırması verileri* [General agricultural census and farm structure survey data]. Türkiye İstatistik Kurumu.
- TUME. (2026). *Tarımsal Teknolojiler Kümelenmesi ve Model Envanteri web portalı* [Agricultural Technologies Cluster and Model Inventory web portal]. <https://www.tume.org.tr/>[cite: 4]
- Walter, A., Finger, R., Huber, R., & Buchmann, N. (2017). Opinion: Smart farming is key to developing sustainable agriculture. *Proceedings of the*

- National Academy of Sciences*, 114(24), 6148–6150.
<https://doi.org/10.1073/pnas.1707462114>
- Wolfert, S., Ge, L., Verdouw, C., & Bogaardt, M. J. (2017). Big data in smart farming – A review. *Agricultural Systems*, 153, 69–80.
<https://doi.org/10.1016/j.agsy.2017.01.023>

CHAPTER 6

GOVERNING FRESH PRODUCE VALUE CHAINS FOR MEASURABLE LANDSCAPE OUTCOMES

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INTRODUCTION

A buyer's environmental commitment reaches the farm through decisions about specifications, prices, delivery and the duration of a purchasing relationship. These decisions shape the resources growers can commit to land management and the risks they accept. Research on horticultural exports and value-chain governance provides a basis for examining this commercial influence (Dolan & Humphrey, 2000; Gereffi, Humphrey, & Sturgeon, 2005). Yet the area supplying a retailer is rarely a self-contained ecological unit. Water crosses property boundaries, and habitat networks may connect supplying farms with land outside the buyer's reach. A consignment that meets a private standard can therefore originate in a catchment where nutrient pollution or habitat loss persists. The analytical problem is to connect commercial responsibility with evidence about that wider landscape.

In fresh produce, this problem is complicated by the need to preserve saleable quality between harvest and purchase. Studies of perishability and sustainability address production together with packaging, distribution and the decisions of successive chain participants (Kirci, Isaksson, & Seifert, 2022; Tort, Vayvay, & Çobanoğlu, 2022). Environmental objectives can pull these decisions in different directions. Additional cooling may extend shelf life but consume more energy. Cosmetic specifications may make minor pest damage commercially unacceptable, while annual purchasing agreements may give growers little reason to maintain habitats whose benefits emerge over several seasons. The question pursued here is how buyers and their partners can organise environmental improvement under these operational and financial constraints.

The chapter develops a framework for following an environmental commitment from procurement through farm intervention to an observed landscape result. Its argument concerns a gap in responsibility: a buyer can require a practice from a supplier, but cannot infer the condition of a shared catchment or habitat network from that supplier's compliance. Bridging the gap requires finance and advice that make implementation feasible, agreements with actors outside the purchasing relationship, and observations of the ecological response. Certification and product records can document parts of this process. Their usefulness depends on the objectives and variables they

cover, a concern examined in reviews of agricultural indicators and sustainability standards (Konefal, de Olde, Hatanaka, & Oosterveer, 2023; Meemken et al., 2021).

The contribution is developed at the interface of procurement, landscape coordination and environmental accounting. Buyer-controlled instruments are examined alongside decisions that require collective action. Ecological interventions are distinguished from changes in refrigeration, packaging and logistics, whose effects follow other pathways. A monitoring menu then links each type of decision to evidence of implementation, pressure, ecosystem condition or service delivery. The distinctions draw on ecosystem accounting, but the menu is designed for programme management; it does not constitute a complete ecosystem account (United Nations et al., 2024).

The chapter is a critical narrative synthesis and conceptual contribution. It reports neither a field experiment nor a validated assessment of a particular sourcing programme. The following sections establish its scope and causal logic, examine governance instruments, assess intervention options, develop measurement and assurance arrangements, and discuss implementation and relevance to the Sustainable Development Goals (SDGs). A hypothetical horticultural partnership illustrates the decisions the framework is intended to inform.

1. CONCEPTUAL FOUNDATIONS AND ANALYTICAL APPROACH

1.1. Literature selection and limits

The literature was organised around four questions: how purchasing relationships influence growers; which ecological processes can connect farm practices to landscape outcomes; how those outcomes can be measured; and how perishability constrains commercial choices. These questions guided a purposive reading across value-chain governance, landscape management and nature-based solutions (NbS), ecosystem accounting, and fresh produce operations. Foundational studies supplied the governance concepts, while reviews, selected empirical papers and official frameworks informed the intervention and measurement discussions. Publication details were checked using publisher metadata, journal records and institutional repositories. The

synthesis develops design propositions from this material; it does not calculate an average treatment effect.

The selection was purposive rather than exhaustive. No systematic database search, complete screening flow or meta-analysis was undertaken for this chapter. Evidence is consequently interpreted within the setting of each study. Research on arable crops, tropical commodities or an individual retail network can suggest a mechanism relevant to horticulture without establishing its size or reliability in another production system. The framework and indicators developed below remain propositions to be applied and tested.

The principal scope is commercial fruit and vegetable production and its links to packing, distribution and retail. Open-field vegetables, orchards and protected cropping differ in their exposure to landscape processes and in the interventions available. Pollination-dependent fruit production, for example, raises different questions from crops harvested for vegetative tissues or grown under tightly controlled conditions. Applicability should therefore be decided by a materiality assessment covering crop biology, production technology, local ecological pressures and the commercial relationships through which change could be supported.

1.2. Connecting commercial and ecological boundaries

Commercial coordination depends partly on whether a buyer can communicate its requirements in a codified form and whether suppliers have the capabilities to fulfil them. The difficulty of the transaction also shapes the governance relationship (Gereffi et al., 2005). For a landscape programme, this firm-level account must be extended to actors whose land or decisions affect the intended ecological result. A neighbouring farm may influence a stream even though it supplies a different market. Landscape approaches address this wider setting through participation, negotiated objectives, attention to multiple land functions and revision of management as conditions change (Sayer et al., 2013).

Three boundaries should be recorded separately. The sourcing boundary identifies participating farms, products, suppliers and purchasing periods. The ecological boundary identifies the catchment, habitat network or other spatial unit relevant to the outcome. The decision boundary identifies the actors with authority or resources to implement change. These boundaries may overlap

only partly. A retailer may purchase from farms in several catchments, while pollution at a monitored outlet may also originate from non-supplying farms or settlements. The retailer's purchasing share is consequently not a direct measure of its influence over the observed water-quality outcome.

A programme should map these relationships before choosing interventions. For water, this requires hydrological connections and upstream pressures. For biodiversity, it requires the spatial distribution and quality of habitats relevant to the focal organisms. For operational reporting, it also requires a record of supplier entry, exit and changing purchasing volumes. Maintaining both a fixed-area record and a current-supplier record helps distinguish ecological change from changes in the composition of the sourcing portfolio.

1.3. A chain of evidence rather than an assumed impact

The proposed causal sequence begins with governance instruments, such as contracts, technical assistance and collective funding. These instruments may change practices, including cover management, nutrient application or habitat maintenance. Practices can alter pressures, such as soil disturbance, pollutant transport or pesticide exposure. Changes in pressures may affect ecosystem condition; changes in condition may affect service delivery and benefits. Each transition is a proposition requiring evidence, appropriate timescales and attention to competing explanations.

For example, a funded buffer may be installed and maintained, yet intercept little runoff if its location misses the dominant flow path. Improved habitat condition may support natural enemies without generating detectable reductions in crop damage during the monitoring period. Biodiversity can contribute to pollination, pest control and production, but these relationships do not make every habitat intervention effective in every crop (Dainese et al., 2019; Landis, 2017). Reporting should therefore retain evidence at several stages rather than compressing all observations into a single sustainability score.

This causal sequence also clarifies the role of NbS. The IUCN framework connects responses to societal challenges with biodiversity and ecosystem integrity, feasibility, inclusive governance, management of trade-offs and adaptive learning (IUCN, 2026). Evidence on climate adaptation identifies

potential benefits alongside trade-offs and gaps in geographical coverage and integrated evaluation (Chausson et al., 2020). In this chapter, a practice is considered a candidate component of an NbS programme when its ecological mechanism and intended benefits are specified and monitored. A label such as regenerative agriculture does not itself establish these properties. Refrigeration and packaging improvements can complement an NbS programme, but their benefits arise through different mechanisms and require separate assessment.

2. GOVERNANCE INSTRUMENTS AND SHARED RESPONSIBILITIES

2.1 Procurement, incentives and supplier capabilities

Research on fresh vegetable exports shows that buyer specifications and access to markets can influence production practices (Dolan & Humphrey, 2000). A landscape programme must also address the practical conditions under which growers can meet and sustain a requirement. If restoration takes several seasons but sales are renegotiated each year, the grower faces an immediate investment with an uncertain commercial return. Procurement design therefore needs to address the duration of support as well as the environmental obligation.

The framework combines three procurement functions. Minimum requirements define necessary practices, records and safeguards. Capability support provides advice, finance, equipment or shared monitoring services. Performance incentives reward evidence of improvement against agreed objectives. These functions should be designed together: a premium offered only after an uncertain ecological response may provide insufficient finance for initial investment, while support without follow-up can leave maintenance responsibilities unclear.

Contracts can specify installation and maintenance payments, a multi-year purchasing commitment and a separately defined outcome component. Payments for actions under a grower's control should be distinguished from rewards for collective results affected by weather, neighbouring land use and other external factors. This distinction preserves an incentive to improve outcomes without transferring all ecological uncertainty to suppliers. Procurement teams should also examine whether delivery changes, rejection rules or price negotiations undermine the environmental commitments requested from farms.

A practical contract should identify eligible activities, evidence requirements, payment timing, exceptions, review dates and remedies for non-performance. Any adjustment for drought or pest emergencies should be agreed in advance and documented. Such flexibility is an instrument of adaptive management when it preserves the programme's objectives and records the reasons for departure. Repeated undocumented exemptions, by contrast, make both environmental evaluation and supplier accountability difficult.

2.2. Standards, inclusion and the distribution of costs

Private standards can codify requirements and establish audit routines, but their scope, institutional design and consequences differ (Hatanaka, Bain, & Busch, 2005; Henson & Humphrey, 2010). A valid certificate provides evidence about conformity within a defined scope and period. It should not be treated as evidence that all relevant ecosystem conditions have improved. A landscape programme can use existing records to reduce duplicate administration, then add locally relevant observations and coordination arrangements where the standard's coverage is insufficient.

Who finances compliance can affect which suppliers remain in a chain. In the Peruvian asparagus export sector, certification was associated with greater vertical integration and less purchasing from external growers, especially smaller producers (Schuster & Maertens, 2013). The case warrants attention to exclusion; it does not establish an inevitable effect of certification in other settings. The broader review of agrifood standards also places limits on what certification can achieve across environmental and social objectives (Meemken et al., 2021). A programme should assess participation and costs alongside its compliance rate.

The proposed response is to make supplier participation an explicit design objective. Group services can spread the cost of mapping, advice and sample collection; phased requirements can allow investment before more demanding evidence is expected. Producer organisations should help define monitoring workloads and compensation. Programmes should record participation, withdrawal, net payments and unpaid work by farm-size group, together with reasons for exclusion. High aggregate adoption can otherwise conceal a shift towards suppliers already able to finance compliance.

Financing records should distinguish public support from buyer contributions. Several buyers operating in one territory may pool resources for monitoring or advice, reducing duplicate demands on growers. Such an arrangement still needs rules for maintenance after a buyer leaves, access to shared data and attribution of collective achievements. Without those rules, changes in purchasing relationships can leave a funded intervention without a responsible maintainer, while several organisations may each report the same result as their own.

2.3. Traceability and the limits of information

Traceability supports product identification and the reconstruction of movements through a supply chain (Aung & Chang, 2014). Research on fresh produce also highlights interoperability and information-sharing problems across different systems (Tagarakis, Benos, Kateris, Tsotsolas, & Bochtis, 2021). For landscape accountability, these operational records need an additional spatial link: a product lot should be associated, as far as feasible, with the producing parcel or a transparently defined sourcing unit and period.

Three claims must remain distinct. Product traceability establishes an identity or movement record. Spatial provenance links the record to a location. Environmental attribution concerns whether an intervention caused an observed change. Geolocation improves the ability to connect purchases and observations, but cannot by itself establish attribution. Mixing produce from several farms also requires clear aggregation rules; a favourable measurement from one participating location cannot be attached automatically to all products handled by the same packhouse.

A proportionate information system can combine parcel identifiers, intervention dates, purchasing records and selected measurements. It should document missing observations, changes in methods and uncertainty in the links between lots and farms. Data governance should give producers access to their own records, define permitted uses and provide a correction procedure. Independent checks can combine risk-based inspections with a probability-based sample for estimating programme-wide performance. Expensive digital infrastructure is justified only where it resolves a specific information problem.

Table 1 translates the procurement and coordination discussion into a set of programme design choices. For each instrument, it identifies a proposed

mechanism and observations that could be used to examine its operation. The table sets out hypotheses for evaluation; no effect sizes have been estimated.

Table 1: Governance instruments, intended mechanisms and evidence requirements

Instrument	Intended mechanism	Evidence and main qualification
Multi-year procurement	Extend the investment horizon for habitat establishment and maintenance.	Contract length, payments and maintained habitat area. Longer commitments do not guarantee improvement.
Supplier support	Reduce financial and technical barriers through shared advice, equipment and monitoring.	Participation, net costs and retention by farm-size group. Check for exclusion and unpaid work.
Spatial coordination	Locate complementary measures along runoff pathways or within relevant habitat networks.	Maps and ecological observations across the relevant area. Include material pressures from non-suppliers.
Traceability and data rules	Connect purchasing records, locations, implementation dates and monitoring observations.	Verified links, coverage and correction logs. Provenance alone does not establish causation.
Outcome incentives and review	Use credible evidence to reward improvement and revise management.	Specified outcomes, evaluation design and uncertainty. Recognise external drivers and shared contributions.

Source: Author's framework, based on the literature discussed in Sections 1–3. The mechanisms are propositions for evaluation, not measured effects.

3. INTERVENTIONS AND THEIR ECOLOGICAL CONDITIONS

3.1 Soil management and context-dependent benefits

Cover crops, organic amendments, diversified rotations and reduced disturbance can form part of an intervention portfolio, subject to crop and site

suitability. Soil quality is multidimensional: organic carbon is relevant, but cannot represent physical structure, nutrient dynamics and biological functioning on its own (Bünemann et al., 2018). A programme should first identify the limiting functions and then choose practices and observations capable of detecting change in those functions.

Cover-crop research illustrates why intervention labels need to be interpreted in context. A meta-analysis reported gains in soil organic carbon while identifying uncertainties in the wider greenhouse-gas balance (Poepflau & Don, 2015). An arable-system experiment further showed that cover-crop performance varied across production systems (Wittwer, Dorn, Jossi, & van der Heijden, 2017). These findings justify local trials and monitoring. They do not supply a carbon accumulation rate or yield expectation that can be applied indiscriminately to orchards, open-field vegetables and protected crops.

Practical design begins with the crop calendar: which cover species can establish, when it must be terminated, and how it interacts with irrigation and harvesting. In a water-limited setting, competition with the cash crop is a specific issue to assess. Amendments need checks on nutrient supply and contamination, while changes in tillage must still allow reliable crop establishment. Implementation records should be read alongside soil observations, yield, labour requirements and profitability. This makes any cost of an environmental measure visible rather than assuming that ecological and commercial performance move together.

For accounting purposes, the area under a practice is an implementation measure. Soil organic carbon concentration is a condition variable. Carbon stock estimates additionally require a defined depth, bulk density and treatment of coarse fragments; changes in soil mass require an appropriate comparison method. None of these measurements alone establishes a net climate benefit, which would also depend on other emissions, the counterfactual and the persistence of the change. Procurement claims should follow the evidence actually collected.

3.2. Water, buffers and treatment wetlands

An irrigation meter answers a narrower question than a water-footprint assessment. It records water abstracted or delivered within its measurement boundary. Consumptive use concerns the portion that is not immediately

available for reuse in the relevant system. Water-footprint accounting additionally distinguishes consumption supplied by rainfall from that supplied by surface water or groundwater, and includes a modelled dilution requirement for pollution (Mekonnen & Hoekstra, 2011). A programme should identify which of these quantities it reports before comparing farms or claiming a water benefit.

A buffer or treatment wetland can intercept pollution only if the relevant flow reaches it. For nutrient and sediment control, siting and hydraulic design are therefore part of the intervention, not background details. Reviews of treatment systems describe how plants, substrates, flow conditions and removal processes affect performance (Li et al., 2021; Mancuso, Bencresciuto, Lavrnić, & Toscano, 2021). The implication for a sourcing programme is to require a site assessment before adopting a standard buffer dimension or assuming a removal rate. Maintenance and the accumulation or subsequent movement of pollutants also belong in that assessment.

Buyer requirements can support mapped buffer protection, nutrient planning and participation in catchment monitoring. However, a water-quality result at a shared outlet depends on more than the participating farms. Agricultural water stewardship accordingly benefits from coordination around shared water risks and supply-chain relationships (Jia, Hubbard, Zhang, & Chen, 2019). Programmes should involve the relevant water authority and other users when their activities materially affect the intended outcome.

Reporting should combine absolute withdrawals, an explicitly defined production intensity and local water-availability information. A fall in cubic metres per kilogram can coexist with an increase in total abstraction if output expands. Similarly, a lower pollutant concentration may reflect dilution rather than a smaller pollutant load. Sampling should record season, rainfall and flow conditions; estimating loads requires concentration data combined with an appropriate discharge measurement or model. Water testing for food-safety compliance belongs in the assurance record and should not substitute for ecological water-quality monitoring.

3.3. Biodiversity, habitat networks and crop protection

Landscape simplification can weaken natural pest control, and wider synthesis links biodiversity with pollination, pest regulation and crop

production (Dainese et al., 2019; Rusch et al., 2016). These relationships give a productive rationale for maintaining ecological infrastructure, while biodiversity also has value beyond the services supplied to a particular crop. Habitat design should therefore identify both conservation objectives and the service pathways the programme expects to influence.

The design of hedgerows, flower strips and other semi-natural areas should start from the organisms and seasonal resources the programme intends to support. Location and management then need to fit the crop system and the surrounding habitats. A meta-analysis in annual field crops found support for natural enemies from diverse flower strips (Jachowicz & Sigsgaard, 2025). That biological response cannot be read directly as a quantified reduction in pesticide applications, crop damage or lost yield. Testing those outcomes requires observations of pests, damage and crop-management decisions.

Habitat management and crop-protection decisions should be planned together. Integrated pest management (IPM) combines prevention and monitoring with thresholds for intervention, reasoned selection of controls and review of their effectiveness (Barzman et al., 2015). A programme can examine its implementation through scouting records and the decisions that followed. Reviews of IPM practice identify persistent gaps between these principles and pesticide-dependent management, directing attention to the agronomic and organisational conditions of farmers' choices (Deguine et al., 2021). Merely recording that a farm has adopted IPM provides little evidence about those choices.

Monitoring should bring habitat observations and pesticide records into the same management discussion. Harmful exposure may undermine an investment in habitat, while a smaller mass of pesticide does not necessarily imply a proportionate decline in ecological risk. Agronomic advice and buyer specifications both matter: cosmetic rejection rules, for example, may encourage treatment that conflicts with the habitat objective. Where connectivity is a priority, the programme should specify the organisms or ecological process concerned and assess how habitat arrangement serves that purpose. Mapped area alone cannot answer that question.

3.4. Perishability, materials and burden shifting

Cold-chain management, packaging and ordering practices affect how much harvested produce reaches the intended destination. Empirical analysis of retail spoilage identifies several operational drivers, including inventory, delivery and quality-related factors (Kirci et al., 2022). This makes loss prevention a shared commercial responsibility. Growers cannot resolve losses generated by changing orders or poorly coordinated distribution through field-level environmental measures alone.

The environmental case for cooling or protective packaging depends on the losses prevented and the burdens added. Cold-chain modelling combined with life-cycle assessment provides a way to examine energy use, refrigerants and materials within the same comparison (Wu, Beretta, Cronje, Hellweg, & Defraeye, 2019). For a programme-level application, alternatives should be compared for an equivalent delivered service: a stated quantity of edible produce, of a specified quality, reaching the same destination. The assessment boundary must identify the production, transport, packaging, refrigeration and end-of-life processes counted.

Agricultural plastics also require attention before produce leaves the farm. Research in California found persistent plastic contamination in mulched fields and associations between accumulated macroplastic and several soil properties (Tiwari & Sistla, 2024). Such evidence supports controls on retrieval and contamination, but does not justify attributing the same effect size to every soil or production system. Programmes should record plastic inputs and verified destinations, distinguishing collection from recycling or final recovery.

Loss reduction should not be translated automatically into claims of avoided land occupation, water consumption or emissions. The eventual resource effect depends on how production, demand and prices respond (Food and Agriculture Organization of the United Nations [FAO], 2019). Operational savings can be reported directly; avoided upstream impacts require a separate, explicit model. This distinction keeps the complementary role of logistics visible while preserving the ecological meaning of NbS.

4. MEASUREMENT, EVALUATION AND ASSURANCE

4.1 An accounting structure for landscape evidence

The System of Environmental-Economic Accounting—Ecosystem Accounting (SEEA EA) separates accounts of ecosystem extent, condition and services and locates them in a defined spatial area (United Nations et al., 2024). This separation is useful when a programme reports a restored wetland. Its area describes extent; observations of its characteristics describe condition; its contribution to water purification concerns a service. The quantities are connected, but an increase in restored area cannot substitute for evidence of the other two.

The proposed reporting structure borrows these distinctions for management purposes. It makes no claim of complete SEEA EA conformity and does not assign monetary values to ecosystem assets. Contracts, practice records and operational pressures remain programme information; they are linked to ecological observations without being renamed ecosystem accounts. Producing a complete account would require broader spatial coverage, consistent classifications and additional measurement procedures. The more limited purpose here is to make the connection between an organisational decision and its environmental evidence inspectable.

A starting measurement, an ecological reference and a causal comparison serve different purposes. The historical baseline records conditions when the programme begins. An ecological reference helps judge ecosystem integrity. The counterfactual describes the outcome expected in the absence of the programme. A site may improve from its baseline and still fall short of an ecological target; comparable untreated sites may also improve more. Reporting should therefore identify which comparison supports each claim and record any negotiated target separately.

Reports should follow a defined area through stated observation periods and explain its relationship to the supplier population. Some records can be updated every year, whereas soil or habitat measurements may be less frequent. Their dates must remain attached to the results: carrying an earlier value forward does not make it a new observation. Aggregated results should retain their denominators, sampling coverage and absolute quantities. Measured and

modelled values, missing observations and uncertainty should be visible so that readers can judge what the account supports.

4.2. Indicator selection and monitoring protocols

A monitoring variable is useful when it helps resolve a programme decision. Selection should therefore follow the diagnosis of the pressure and the proposed mechanism of intervention. Reviews of agricultural initiatives show that indicator systems differ in their treatment of practices, performance and targets (Konefal et al., 2023). The methodological distinction between observing an action and evaluating progress towards a sustainability objective reinforces this point (Schreefel et al., 2024). The framework consequently offers a context-specific selection process rather than treating a universal score as a sufficient account of performance.

Table 2 offers sixteen candidate measures across six domains. It is a menu from which a programme selects a coherent subset, not a requirement that every crop or supplier measure everything. Each selected priority should include evidence of implementation and at least one observation closer to the intended ecological or operational result. More demanding service measurements can be concentrated in representative study sites while routine records cover the wider programme. Extrapolation beyond the measured sites requires a stated sampling or modelling basis.

Each protocol should specify the variable, unit, denominator, boundary, observation method, sampling design, timing, data owner, quality controls and uncertainty. It should also state the expected direction of change and conditions under which that direction would be misleading. For example, reduced pesticide use following a crop failure cannot be interpreted in the same way as reduced use with maintained production and effective pest control. Ecological targets should be locally justified rather than inferred from an arbitrary percentage improvement.

Table 2: A monitoring menu for fresh produce landscape programmes

Indicator and type	Specification and suggested schedule	Interpretation and safeguards
S1. Soil cover Implementation	Percentage of monitored soil surface covered by living vegetation or residues; distinguish the two. Observe fixed plots during locally critical erosion periods.	A seasonal observation of cover, not proof of reduced soil loss. Record crop stage and sampling dates.
S2. Soil organic carbon Condition	Carbon stock in Mg C/ha for a stated depth, with concentration, bulk density and coarse fragments. Resample stratified plots over a justified multi-year interval.	Keep sampling methods comparable; address soil-mass changes. Stock change alone is not a net climate balance.
S3. Infiltration Functional capacity	Infiltration rate in mm/hour using a consistent method and replicated locations; repeat in a comparable season and soil-moisture range.	A site-specific capacity measure. It does not directly quantify a catchment's realised flood-regulation service.
W1. Irrigation withdrawals Pressure	Metered m ³ per season and m ³ /kg of marketable farm-gate output. Record water source, cultivated area and crop-specific volumes each season.	Report absolute and intensity values with local water availability. Withdrawals differ from consumptive use.
W2. Buffer maintenance Implementation	Hectares of mapped buffer maintained to the agreed protocol, alongside the total area requiring intervention. Inspect at least annually and after major disturbance.	Document location, continuity and condition. Installed area is not a measure of pollutant removal.

Indicator and type	Specification and suggested schedule	Interpretation and safeguards
W3. Water quality Condition	Nitrate-N and relevant phosphorus concentrations in mg/L at fixed sites; use seasonal and event-based sampling suited to the catchment.	Record rainfall and flow. Concentrations alone do not establish changes in pollutant loads or their source.
W4. Nutrient retention Service estimate	Where feasible, estimate kg N or P retained annually from monitored inflow and outflow loads in a defined treatment system.	Account for storage changes, bypass flows and uncertainty. System removal is not automatically the net catchment benefit.
B1. Habitat extent Extent	Mapped hectares and percentage of semi-natural habitat within a fixed landscape boundary, updated annually. Record hedgerow length separately.	Use consistent habitat classes and avoid double counting. Area does not establish habitat quality or connectivity.
B2. Focal organisms Condition proxy	Counts or richness for selected pollinators or natural enemies under a standardised seasonal protocol, with sampling effort recorded.	Control for weather, timing and observer effects. Organism abundance does not directly measure service delivery.
B3. Pollination response Service proxy	For suitable crops, fruit-set difference in percentage points between replicated open and insect-excluded flowers during flowering.	Control for exclusion artefacts and crop biology. This reproductive response is not a complete service account or yield valuation.
P1. Pesticide inputs Pressure	Kilograms of each active substance per crop season and per cultivated hectare, reconciled with application records and stock movements.	Retain substance-level detail. Equal masses can differ substantially in hazard and exposure.

Indicator and type	Specification and suggested schedule	Interpretation and safeguards
P2. Programme pesticide index Pressure proxy	Optional hazard-weighted use index with published coefficients, reference year and coverage; update annually alongside P1.	Label as a programme index, not official HRI 1. It is not a direct measure of ecological risk; see Section 4.3.
C1. Operational emissions Pressure	Tonnes CO ₂ e annually and kg CO ₂ e/kg delivered edible produce for a fixed boundary; disclose activity data, factors and refrigerant losses.	Keep boundaries and factors comparable. Avoid treating soil-carbon estimates as automatic offsets against emissions.
C2. Cold-chain energy Pressure	Metered kWh annually and kWh/kg delivered edible produce, separated by facility or process where feasible.	Interpret with losses, throughput and energy source. Energy intensity alone does not establish climate performance.
M1. Produce losses Operational outcome	Kilograms leaving the human-food chain at each defined stage and percentage of edible input; reconcile stock changes and record destinations.	Track edible redistribution separately from disposal. Loss reduction does not automatically quantify avoided upstream impacts.
M2. Material recovery Operational outcome	Kilograms of agricultural plastic and packaging placed in use, collected and accepted for specified recovery routes; reconcile annually.	Separate material types and moisture or contamination. Collection is not proof of recycling; verify the receiving route.

Source: Author's proposed monitoring menu, informed by the sources discussed in Sections 3–4. Types refer to the role of each measure in the proposed causal sequence; they are not official SEEA classifications. S = soil; W = water; B = biodiversity; P = pesticides; C = climate and energy; M = materials and losses. Select measures according to materiality and monitoring capacity.

The schedules in Table 2 are starting points for programme design. Sampling intensity should reflect heterogeneity, expected rates of change, measurement error and the decisions at stake. Fixed sites can support temporal

comparisons, but a representative sampling frame is needed for landscape-wide estimates. Missing measurements should be identified explicitly; substituting an average from a different site requires disclosure and an uncertainty assessment. Results should be disaggregated where aggregation would obscure a material deterioration in a subcatchment or supplier group.

4.3. Pesticide indicators and interpretive discipline

The EU's Harmonised Risk Indicator 1 (HRI 1) weights quantities of active substances placed on the market according to regulatory groupings. HRI 2 uses a different basis, concerning emergency authorisations (European Commission, 2026). These indicators should not be confused with direct measurements of ecological damage at farm level. In particular, sales quantities do not specify where, when or under which exposure conditions a substance was applied.

A sourcing programme may construct its own hazard-weighted use measure from farm application records. If it does, it should call this a programme pesticide pressure index, publish the substances, coefficients, reference year and treatment of missing data, and report it alongside unweighted quantities. It should not present the result as the official HRI. Changes in substance classifications or coefficients require a consistent recalculation of the comparison series or a clearly marked break.

Such a measure remains a proxy. Exposure depends on application method, timing, weather, transport pathways and the organisms present. Interpretation should therefore combine use records with relevant buffer, handling and IPM evidence, and, where justified, residue or biological monitoring. No single index establishes safety for all organisms or permits increases in one serious pressure to be offset automatically against an unrelated environmental improvement.

4.4. Additionality, leakage, persistence and scale

A favourable time trend is evidence of change within the reporting boundary. Establishing an intervention effect requires a further comparison with the trajectory expected without the programme. Weather, prices, regulation, neighbouring land uses and changes in suppliers can all affect the observed series. Research on land-based mitigation makes this dependence of

additionality on the counterfactual explicit (Nolan, Van Paasschen, & Field, 2024). The principle is relevant to the other landscape objectives considered here, although the comparison design must suit the ecological response and the available data.

Where feasible, evaluation should compare changes in participating sites with changes in suitable non-participating sites, using pre-intervention observations and a documented approach to comparability. Matching can address observed differences but does not remove every source of selection bias. Before–after designs with comparison sites are also vulnerable to spillovers if a shared catchment or habitat network transmits the intervention's effects. The evaluation should identify these limitations rather than describe a comparison group as an unquestionable counterfactual.

Where the available design cannot isolate a causal effect, evaluation can examine the programme's contribution through its proposed mechanism. The questions are whether the actions occurred, the expected intermediate changes followed, and plausible alternative explanations were examined. Consistency across this evidence can support a qualified contribution claim. It cannot quantify the ecological gain attributable to one buyer when several actors, public investment or external changes also helped produce the observed result.

Leakage concerns pressures displaced beyond the reporting boundary. A buyer may improve its current supplier average by ceasing to purchase from higher-pressure farms without changing those farms' practices. Production may also move elsewhere following restrictions or yield changes. Monitoring should therefore record sourcing changes and plausible displacement pathways. A fixed-area series and a purchasing-portfolio series should be reported separately, because each reveals a different part of the intervention's consequences.

Persistence concerns how long improvements endure and who maintains them. Vegetation can be removed, soil carbon can be lost, and treatment systems can cease to function. Contracts should assign maintenance obligations, funding and responses to reversals over an explicit horizon. Finally, scale matters: isolated adoption may be insufficient to alter a catchment outcome or provide habitat resources over the area required by focal species. The relevant test is whether the intervention's distribution and intensity match

its ecological mechanism, not merely whether a target number of farms participated.

4.5. Assurance and the credibility of claims

Monitoring responsibilities should be separated from claim approval. Producers and technical partners may collect data; a programme secretariat can maintain records and run consistency checks; a reviewer with appropriate independence can examine the evidence and reporting scope. This allocation does not make a review a formal assurance engagement under a professional standard. Any such engagement would require separately defined criteria, scope and reporting arrangements.

The evidence record should identify how a value was obtained, who supplied it and which checks it passed. These are separate attributes. A laboratory result, a grower's field measurement and a modelled estimate have different origins and methods; any of them may undergo internal or independent review. External checking does not turn a calculation into an observation, just as supplier collection does not by itself invalidate a measurement. Review should trace how the underlying records became a public claim, including aggregation, omitted data and changes in method.

Claims can then be calibrated to their evidential scope. Verified implementation supports a statement about an installed or maintained practice. Repeated observations support a statement about a measured trend within the sampled area. A causal effect claim additionally requires a defensible evaluation design. The report should disclose the reporting boundary, coverage, uncertainty and unresolved adverse effects alongside positive findings. Shared outcomes should be accompanied by a contribution register identifying participating funders and actors, so that overlapping reports do not imply several independent ecological gains.

5. IMPLEMENTATION, SDG RELEVANCE AND RESEARCH PRIORITIES

5.1 Organising a landscape partnership

The commercial reach of an individual buyer rarely coincides with the full area relevant to water or biodiversity. A landscape partnership can connect procurement with public planning, producer cooperation and the interests of

other land users. Research on jurisdictional approaches highlights efforts to organise sustainability across administrative territories and multiple commodity actors (Macdonald et al., 2024). Administrative coordination can help implement decisions, but its boundaries should still be checked against the ecological processes the programme intends to influence.

The proposed sequence starts with a joint diagnosis of pressures, dependencies and affected groups. Producers, buyers, technical advisers, public authorities and relevant community representatives then negotiate objectives, decision rights and a funded programme. Participation requires more than attendance: actors need access to the information used to set priorities and a procedure for challenging decisions. Public authorities retain their regulatory functions, while private purchasing commitments provide a distinct source of incentives and resources.

Implementation should begin with interventions for which responsibilities and evidence requirements can be specified. A common protocol, a baseline programme and agreed maintenance arrangements should precede broad claims of success. Periodic review should consider ecological observations, production outcomes, participation and cost distribution together. If a measure performs poorly, the review should distinguish weak implementation from an unsuitable mechanism or an external shock before revising contracts.

The partnership also needs a financial record that separates establishment, recurring maintenance, monitoring, verification, opportunity costs and transfers between participants. A payment to a grower is a financing flow, not a valuation of the ecological benefit. Similarly, reducing the monitoring budget may weaken the evidence needed for a decision. Reviewing expenditure alongside data coverage and decision needs helps identify where shared services are efficient and where a saving would leave an important outcome unobserved.

5.2. A hypothetical Mediterranean horticultural partnership

Consider a hypothetical sourcing district containing orchards, open-field vegetables, several producer organisations, a packhouse and two major buyers. This example is illustrative and contains no empirical findings. The partnership identifies seasonal water scarcity, nutrient transport towards a stream and

fragmented semi-natural habitat as its priorities. It maps participating parcels and the wider catchment, including important non-supplier land uses. An initial protocol specifies which observations will describe the whole area and which will cover a representative sample.

The buyers offer multi-year purchasing commitments and share the cost of establishment and monitoring. Producer organisations coordinate advice and maintenance. Riparian measures are located using runoff pathways, while cover management is adapted to crop calendars and water availability. Habitat measures are linked with scouting and documented IPM decisions. The partnership records both the support received and the costs borne by different supplier groups, and agrees in advance how a dry season could require changes in cover management.

Suppose that, during a dry year in this illustrative district, maintained buffer area expands but downstream nutrient concentrations rise. The two observations do not establish the buffers' effectiveness. Reduced streamflow could alter concentration, so pollutant loads would need to be examined separately. Nor would the larger buffer area justify reporting cleaner water. The partnership would document the completed work and the water observations, investigate flow pathways and other nutrient sources, and limit its claim to the evidence obtained.

A fall in irrigation use per kilogram would also be examined alongside total abstraction and cultivated area. If total withdrawals increased, the partnership could describe an intensity improvement while acknowledging that pressure on water availability had not necessarily declined. Similarly, higher natural-enemy counts would be reported as a biological observation; reduced crop damage would require additional evidence. These distinctions allow management to respond to mixed results without converting every favourable intermediate observation into an outcome claim.

The point of this example is organisational. Monitoring has a purpose when it affects the allocation of funds, agronomic advice, purchasing specifications or the wording of a claim. Mixed results may call for a different intervention or reveal that the observation period was too short. Recording those distinctions makes the evidence useful for the next decision; an aggregate score can conceal them.

5.3. Relating local programmes to SDG targets

The SDGs locate local programme objectives within a wider public agenda. Targets in the 2030 Agenda concern agricultural resilience, water, food losses, chemical management, biodiversity and partnerships (United Nations, 2015). Table 3 identifies relevant connections for the proposed framework. It is a thematic mapping: a programme observation is neither an official global SDG indicator nor evidence of achievement at national scale. Claims should specify the local objective, the evidence available and the limits of the connection to the target.

Table 3: Programme objectives and their relevance to selected SDG targets

Programme objective	SDG targets	Evidence relevant to a local contribution
Resilient production and soils	2.4; 15.3	Soil-condition trends, sustained production and the documented extent of restoration, interpreted against local degradation pressures.
Water stewardship	6.3; 6.4; 6.6	Water quality, withdrawals and aquatic ecosystem condition. Efficiency and absolute pressure should be reported separately.
Loss and material management	12.3; 12.5	Stage-specific produce losses, waste prevention and verified material destinations within a stated boundary.
Chemical and biodiversity pressures	12.4; 15.5	Substance-level pesticide records combined with exposure information, habitat condition and relevant biological observations.
Adaptation to climate hazards	13.1	Performance during specified hazards and evidence supporting the intended adaptation mechanism. A practice label alone is insufficient.

Programme objective	SDG targets	Evidence relevant to a local contribution
Effective partnerships	17.17	Defined responsibilities, sustained resources, inclusive decisions and evidence that cooperation affects implementation and results.

Source: Author's thematic mapping to the targets of the 2030 Agenda (United Nations, 2015). These programme measures do not replace official global SDG indicators or demonstrate national target achievement.

An SDG connection is most informative once the intervention and its expected result have been specified. Reduced produce spoilage can contribute to the objective addressed by target 12.3; plastic retrieval concerns waste and materials management. Installing habitat can be relevant to biodiversity objectives without demonstrating that biodiversity loss has declined. A programme report should retain adverse effects and tensions between objectives, even where one intervention appears relevant to several SDGs.

5.4 Limits and priorities for empirical research

The framework combines evidence generated for different units of analysis, production systems and evaluation purposes. It remains uncertain which contractual arrangements and indicator combinations will work together in a given horticultural setting. Limited baseline data, slow ecological responses, monitoring costs and unequal bargaining power can restrict both implementation and evaluation. These limits should shape the initial design and the strength of any subsequent public claim.

Three priorities follow for empirical research. First, comparative studies can examine whether longer purchasing commitments and shared finance improve intervention maintenance and supplier retention. Second, ecological evaluation can test when coordinated measures produce outcomes beyond those associated with isolated adoption. Third, accounting research can investigate how measurement costs, data rights and assurance arrangements influence whose impacts become visible and whose responsibilities remain unexamined. These studies should assess adverse effects and distributional consequences alongside environmental gains.

Future applications should therefore pre-specify their principal outcomes, sampling plans and comparison logic where feasible. Mixed methods can connect contract analysis and interviews with biophysical monitoring, revealing whether an apparent implementation gap reflects resource constraints, conflicting incentives or an unsuitable intervention. The framework's value will depend on whether it improves these empirical tests and the decisions they inform, rather than on the number of indicators a programme reports.

CONCLUSION

Governing fresh produce value chains for landscape outcomes requires a connection between commercial decisions, ecological processes and verifiable evidence. Procurement can influence land management, but its effectiveness depends on supplier capabilities, the distribution of costs and coordination with actors beyond a single chain. NbS provide a set of possible ecological interventions whose suitability and results must be assessed in context. Complementary changes in refrigeration, packaging and logistics require their own boundaries and trade-off analysis.

The chapter's contribution is an integrated framework that keeps implementation, environmental pressures, ecosystem condition and service delivery analytically distinct while connecting them through a proposed causal sequence. Its monitoring menu and assurance logic make that sequence operational without treating a certificate, traceability record or favourable proxy as proof of ecological impact. Counterfactual reasoning, attention to displacement and persistence, and transparent treatment of uncertainty define the limits of defensible claims.

For practice, the central implication is to assign environmental responsibilities when purchasing and funding arrangements are negotiated. Each programme should be able to explain the action taken, its financing, the observations collected and the decisions changed by those observations. Connections to SDG objectives follow from that evidence. The framework now requires empirical application across horticultural settings to establish where its proposed combination of procurement, coordination and measurement sustains improvement and distributes its costs fairly.

REFERENCES

- Aung, M. M., & Chang, Y. S. (2014). Traceability in a food supply chain: Safety and quality perspectives. *Food Control*, 39, 172–184. <https://doi.org/10.1016/j.foodcont.2013.11.007>
- Barzman, M., Bàrberi, P., Birch, A. N. E., Boonekamp, P., Dachbrodt-Saaydeh, S., Graf, B., . . . Sattin, M. (2015). Eight principles of integrated pest management. *Agronomy for Sustainable Development*, 35, 1199–1215. <https://doi.org/10.1007/s13593-015-0327-9>
- Bünemann, E. K., Bongiorno, G., Bai, Z., Creamer, R. E., De Deyn, G., de Goede, R., . . . Brussaard, L. (2018). Soil quality – A critical review. *Soil Biology and Biochemistry*, 120, 105–125. <https://doi.org/10.1016/j.soilbio.2018.01.030>
- Chausson, A., Turner, B., Seddon, D., Chabaneix, N., Girardin, C. A. J., Kapos, V., . . . Seddon, N. (2020). Mapping the effectiveness of nature-based solutions for climate change adaptation. *Global Change Biology*, 26, 6134–6155. <https://doi.org/10.1111/gcb.15310>
- Dainese, M., Martin, E. A., Aizen, M. A., Albrecht, M., Bartomeus, I., Bommarco, R., . . . Steffan-Dewenter, I. (2019). A global synthesis reveals biodiversity-mediated benefits for crop production. *Science Advances*, 5(10), eaax0121. <https://doi.org/10.1126/sciadv.aax0121>
- Deguine, J.-P., Aubertot, J.-N., Flor, R. J., Lescouret, F., Wyckhuys, K. A. G., & Ratnadass, A. (2021). Integrated pest management: Good intentions, hard realities. A review. *Agronomy for Sustainable Development*, 41(3), 38. <https://doi.org/10.1007/s13593-021-00689-w>
- Dolan, C., & Humphrey, J. (2000). Governance and trade in fresh vegetables: The impact of UK supermarkets on the African horticulture industry. *The Journal of Development Studies*, 37, 147–176. <https://doi.org/10.1080/713600072>
- European Commission. (2026). *Trends in Harmonised Risk Indicators for the European Union*. Retrieved September 23, 2026, from https://food.ec.europa.eu/plants/pesticides/sustainable-use-pesticides/harmonised-risk-indicators/trends-eu_en

- Food and Agriculture Organization of the United Nations. (2019). *The state of food and agriculture 2019: Moving forward on food loss and waste reduction*. Rome, Italy: Author. Retrieved from <https://www.fao.org/4/ca6030en/ca6030en.pdf>
- Gereffi, G., Humphrey, J., & Sturgeon, T. (2005). The governance of global value chains. *Review of International Political Economy*, 12, 78–104. <https://doi.org/10.1080/09692290500049805>
- Hatanaka, M., Bain, C., & Busch, L. (2005). Third-party certification in the global agri-food system. *Food Policy*, 30, 354–369. <https://doi.org/10.1016/j.foodpol.2005.05.006>
- Henson, S., & Humphrey, J. (2010). Understanding the complexities of private standards in global agri-food chains as they impact developing countries. *The Journal of Development Studies*, 46, 1628–1646. <https://doi.org/10.1080/00220381003706494>
- IUCN. (2026). *IUCN Global Standard for Nature-based Solutions: A user-friendly framework for assessing, implementing, and monitoring scalable, high-integrity NbS* (2nd ed.). Gland, Switzerland: Author. <https://doi.org/10.2305/KKSO4573>
- Jachowicz, N., & Sigsgaard, L. (2025). Highly diverse flower strips promote natural enemies more in annual field crops: A review and meta-analysis. *Agriculture, Ecosystems & Environment*, 381, 109412. <https://doi.org/10.1016/j.agee.2024.109412>
- Jia, F., Hubbard, M., Zhang, T., & Chen, L. (2019). Water stewardship in agricultural supply chains. *Journal of Cleaner Production*, 235, 1170–1188. <https://doi.org/10.1016/j.jclepro.2019.07.006>
- Kirci, M., Isaksson, O., & Seifert, R. (2022). Managing perishability in the fruit and vegetable supply chains. *Sustainability*, 14(9), 5378. <https://doi.org/10.3390/su14095378>
- Konefal, J., de Olde, E. M., Hatanaka, M., & Oosterveer, P. J. M. (2023). Signs of agricultural sustainability: A global assessment of sustainability governance initiatives and their indicators in crop farming. *Agricultural Systems*, 208, 103658. <https://doi.org/10.1016/j.agsy.2023.103658>

- Landis, D. A. (2017). Designing agricultural landscapes for biodiversity-based ecosystem services. *Basic and Applied Ecology*, 18, 1–12. <https://doi.org/10.1016/j.baae.2016.07.005>
- Li, J., Zheng, B., Chen, X., Li, Z., Xia, Q., Wang, H., . . . Yang, H. (2021). The use of constructed wetland for mitigating nitrogen and phosphorus from agricultural runoff: A review. *Water*, 13(4), 476. <https://doi.org/10.3390/w13040476>
- Macdonald, K., Diprose, R., Grabs, J., Schleifer, P., Alger, J., Bahrudin, . . . Hopkinson, W. (2024). Jurisdictional approaches to sustainable agro-commodity governance: The state of knowledge and future research directions. *Earth System Governance*, 22, 100227. <https://doi.org/10.1016/j.esg.2024.100227>
- Mancuso, G., Bencresciuto, G. F., Lavrnić, S., & Toscano, A. (2021). Diffuse water pollution from agriculture: A review of nature-based solutions for nitrogen removal and recovery. *Water*, 13(14), 1893. <https://doi.org/10.3390/w13141893>
- Meemken, E.-M., Barrett, C. B., Michelson, H. C., Qaim, M., Reardon, T., & Sellare, J. (2021). Sustainability standards in global agrifood supply chains. *Nature Food*, 2, 758–765. <https://doi.org/10.1038/s43016-021-00360-3>
- Mekonnen, M. M., & Hoekstra, A. Y. (2011). The green, blue and grey water footprint of crops and derived crop products. *Hydrology and Earth System Sciences*, 15, 1577–1600. <https://doi.org/10.5194/hess-15-1577-2011>
- Nolan, C., Van Paasschen, C. A., & Field, C. B. (2024). Additionality, baselines, and the proper accounting for land-based climate change mitigation efforts. *Oxford Open Climate Change*, 4(1), kgae012. <https://doi.org/10.1093/oxfclm/kgae012>
- Poeplau, C., & Don, A. (2015). Carbon sequestration in agricultural soils via cultivation of cover crops – A meta-analysis. *Agriculture, Ecosystems & Environment*, 200, 33–41. <https://doi.org/10.1016/j.agee.2014.10.024>

- Rusch, A., Chaplin-Kramer, R., Gardiner, M. M., Hawro, V., Holland, J., Landis, D., . . . Bommarco, R. (2016). Agricultural landscape simplification reduces natural pest control: A quantitative synthesis. *Agriculture, Ecosystems & Environment*, 221, 198–204. <https://doi.org/10.1016/j.agee.2016.01.039>
- Sayer, J., Sunderland, T., Ghazoul, J., Pfund, J.-L., Sheil, D., Meijaard, E., . . . Buck, L. E. (2013). Ten principles for a landscape approach to reconciling agriculture, conservation, and other competing land uses. *Proceedings of the National Academy of Sciences*, 110, 8349–8356. <https://doi.org/10.1073/pnas.1210595110>
- Schreefel, L., Creamer, R. E., van Zanten, H. H. E., de Olde, E. M., Koppelmäki, K., Debernardini, M., . . . Schulte, R. P. O. (2024). How to monitor the ‘success’ of agricultural sustainability: A perspective. *Global Food Security*, 43, 100810. <https://doi.org/10.1016/j.gfs.2024.100810>
- Schuster, M., & Maertens, M. (2013). Do private standards create exclusive supply chains? New evidence from the Peruvian asparagus export sector. *Food Policy*, 43, 291–305. <https://doi.org/10.1016/j.foodpol.2013.10.004>
- Tagarakis, A. C., Benos, L., Kateris, D., Tsotsolas, N., & Bochtis, D. (2021). Bridging the gaps in traceability systems for fresh produce supply chains: Overview and development of an integrated IoT-based system. *Applied Sciences*, 11(16), 7596. <https://doi.org/10.3390/app11167596>
- Tiwari, E., & Sistla, S. (2024). Agricultural plastic pollution reduces soil function even under best management practices. *PNAS Nexus*, 3(10), pgae433. <https://doi.org/10.1093/pnasnexus/pgae433>
- Tort, Ö. Ö., Vayvay, Ö., & Çobanoğlu, E. (2022). A systematic review of sustainable fresh fruit and vegetable supply chains. *Sustainability*, 14(3), 1573. <https://doi.org/10.3390/su14031573>
- United Nations. (2015). *Transforming our world: The 2030 Agenda for Sustainable Development* (A/RES/70/1). Retrieved from <https://sdgs.un.org/2030agenda>

- United Nations, European Union, Food and Agriculture Organization of the United Nations, International Monetary Fund, Organisation for Economic Co-operation and Development, & World Bank. (2024). *System of Environmental-Economic Accounting—Ecosystem Accounting* (Statistical Papers, Series F, No. 124). New York, NY: United Nations.
- Wittwer, R. A., Dorn, B., Jossi, W., & van der Heijden, M. G. A. (2017). Cover crops support ecological intensification of arable cropping systems. *Scientific Reports*, 7, 41911. <https://doi.org/10.1038/srep41911>
- Wu, W., Beretta, C., Cronje, P., Hellweg, S., & Defraeye, T. (2019). Environmental trade-offs in fresh-fruit cold chains by combining virtual cold chains with life cycle assessment. *Applied Energy*, 254, 113586. <https://doi.org/10.1016/j.apenergy.2019.113586>

CHAPTER 7

CASCADING EFFECTS ON FOOD-SYSTEM STABILITY, NUTRITION AND MARKETS OF POLLINATION AS CRITICAL INFRASTRUCTURE

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1. INTRODUCTION: POLLINATION AS HIDDEN INFRASTRUCTURE FOR FOOD SYSTEMS

Pollination is foundational for the yields, stability and nutritional content of foods across a myriad of crops and landscapes, yet it remains hidden from sight in systems of food governance and sustainability (Aizen & Harder, 2009; Biesmeijer et al., 2006; Klein et al., 2007; Potts et al., 2016; Rader et al., 2016). This hiding-from-sight skews how much of crop production, yield stability and system reliability depends on biotic interactions not easily replaced with other technological inputs, rendering systems more vulnerable to decline as agricultural systems become increasingly pollinator dependent (Aizen et al., 2019; Garibaldi et al., 2011; Kovács-Hostyánszki et al., 2017).

Declines of pollinators are driven by multiple, heterogeneous pressures across spatial and temporal scales manifesting as habitat loss and fragmentation, pesticide exposure, spillover of pathogens and parasites, climate-driven phenological mismatching and agricultural intensification (Dicks et al., 2021; Food and Agriculture Organization of the United Nations [FAO], 2019; Quaresma et al., 2026). These drivers also rarely act in isolation: statistically explicit and synthetic empirical assessments suggest that for pollinators, it is more often cumulative and synergistic, not single, drivers that dominate observed declines amplifying vulnerability through feedback loops that accentuate losses and erode functional resilience (Hallmann et al., 2017; Sánchez-Bayo & Wyckhuys, 2019). While the response of pollinators and species in general to interacting stressors tends to be governed by threshold dynamics where an incremental cumulative ‘priming’ of the stress imposed can propel a sudden and relatively permanent (or cyclical) decline once a certain tipping point threshold is passed, experimental and other studies indicate that even relatively slight changes in habitat availability, foraging success or mortality can set in motion self-perpetuating feedback loops (via e.g. diminished efficiency in pollination, stunted growth in colony populations or populations, and extent of preferential susceptibility to compounding stressors) toward system collapse (Oliver et al., 2015). Thus, pollinator decline may be better considered not as an irrefutably linear process rationalized by drives arise from a ‘single source’, but as a cascading failure process of interacting pressures that continuously shave margins of resilience and potential for recovery from thriving ecosystems to total collapse. Dicks et al. (2021) offer an

overview of these ‘drivers of speed and failure’ in ecological time and space cascades as being they helped formulate in graphic format that we refer to as Figure 1.

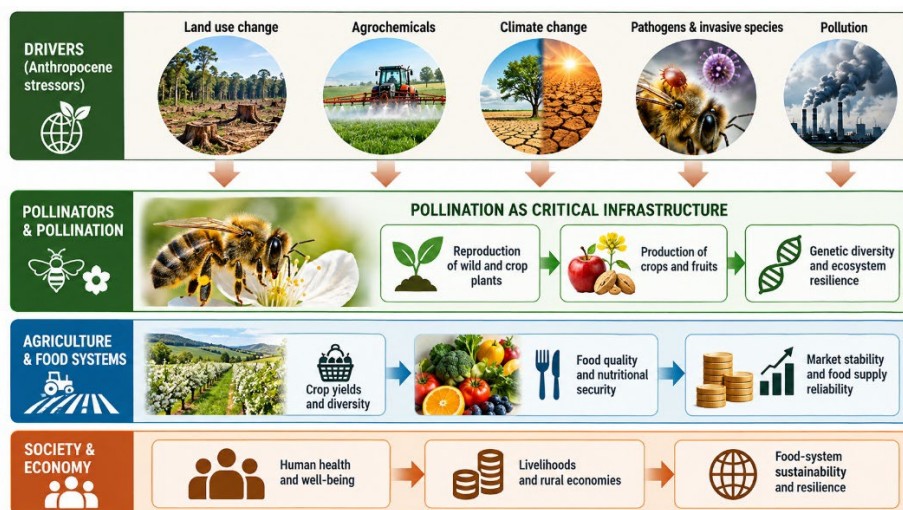


Figure 1: Pollination as critical infrastructure linking environmental change, agricultural production, and societal well-being.

2. THE POLLINATION COLLAPSED CASCADE

Figure 1 illustrates how interacting stressors can produce a cascading ‘collapse’ in pollination via transitions, across thresholds, from the populations and/or colonies of the pollinator being affected to food system outcomes. Initial pressures acting at the level of the colony or population (e.g. foraging inefficiency, increased mortality, altered phenology) may overcome functional resilience and drive pollinators rapidly towards declines in abundance and pollination service delivery (Dicks et al., 2021; Potts et al., 2016). As that loss accumulates, cross-scale feedback emerges amplifying the impacts on crop yield stability, nutritional quality, and market delivery capacity. The rapidly ramping sliding scale of crop loss becomes constrained pathways to recovery and further increased reliance on management techniques to augment pollination service delivery, such as introducing European honey bees (*Apis mellifera*) to farms each year (Garibaldi et al., 2011; Gazzea et al., 2023). Crucially, pollinator loss is not limited to the agricultural ecological unit in collapse, but cascades through the food system across production, nutrition, and economic domains that interoperate peer-to-peer (Dicks et al., 2021; Potts et

al., 2016). Put simply, aberrant environmental change (e.g. through ‘shocks’ to pollination processes) is transformed into systemic food system risk (Bauer & Sue Wing, 2016; Feuerbacher et al., 2025). Pollination collapse cascades usually manifest themselves through more disproportionate impacts on crop yield metrics and nutritional outcomes, for example crop subject matter dissemination within markets, biophysics of dependency across the interacting columns of plants deeply intertwined to pollinators (Figure 1).

In agroecosystems that underpin human nutrition -where non-staple food crops such as fruits, vegetables and nuts are produced- the initial effects of losses of yield owing to reduced pollinator visitations may be perceptually muted, because of physiological buffering within the crops being harvested. However, as pollination deficits grow and persist, the stability/consistency of productivity and quality of these crops becomes increasingly compromised, manifesting itself in diminishing volumes of harvests, as well as declining micronutritional provision of vitamins and minerals. The ecological consequences of these disruptions may be transmitted between points within the food system for instance, by becoming a source of market instability and increased trade volatility, undermining the economic resilience of emerging and smallholder farming systems (Breeze et al., 2016; Feuerbacher, 2025; Gallai et al., 2009; Gazzea et al., 2023; Timberlake et al., 2024). These processes may compound constituting reinforcing feedback across ecological integrity, nutrition security, and flows of income distribution, provisioning systemic risk (Gazzea et al., 2023). With the synergies of healthy ecology that support pollinator-assisted nutrition as increasingly degraded, the social and economic machinery that supports producer income and persistence to produce nutritionally rich crops may also be undermined.

3. UNEVEN VULNERABILITY ACROSS CROPS, NUTRIENTS, AND REGIONS

Vulnerability to pollination loss is uneven across food systems, conditioned by differential reliance on crop pollination, nutritional function, and socio-economic buffering of shocks (Myers et al., 2017). Pollinator-dependent crops such as fruits, nuts, and vegetables tend to be more unstable in yield when pollinators decline but remarkably drive much wider nutritional intake per capita than other food groups and have relatively high species

diversity (Chaplin-Kramer et al., 2014; Garibaldi et al., 2011, Garibaldi et al., 2016; Requier et al., 2023; Timberlake et al., 2024). The spatiality of dependence concentrates vulnerability to certain food groups, and heightens risk where many ranges of diet intake of food groups over per capita availability is disparate (Chaplin-Kramer et al., 2019; Giannini et al., 2021). Pollination loss does not have homogeneous impacts but rather redistributes vulnerability across food systems, thereby deepening existing inequalities.

Market-mediated mechanisms can buffer local pollination losses and redistribute risk, but they may also intensify volatility through price transmission and trade dependence (Feuerbacher, 2025; Murphy et al., 2022). Initially, shortfalls in production of pollinator-dependent foodstuffs are absorbed via importing, adjusting stock levels etc. or relayed through prices but such adjustments consistently redistribute across borders and deepen the exposure of populations reliant on water and air afraid of only 1 dollar, more food is in the ground that makes it through the trade networks delivers in time for hungry mouths (Feuerbacher, 2025; Gallai et al., 2009). As scale ensues this buffer diminishes and mechanisms of translation through price and supply volatility emerge - are constraining nutrient delivery to the low-income consumer and regarding nutritionally important foods (Gazzea et al., 2023; Uwingabire & Gallai, 2024).

In these inter-dependent ways the pollination problem is not resolvable through isolated interventions or siloed single-sector responses. The shift and resale of risk across crops, regions and trade networks call for collaborative governance approaches of natural capital alongside agricultural production, nutrition, and market factors. Table 1 synthesizes these interdependencies by mapping how pollination decline propagates across food-system domains and identifying leverage points where coordinated policy interventions can reduce vulnerability and strengthen systemic resilience.

Table 1: Pollination-driven risks across food-system domains and intervention scales

Food-system domain	Pollination-related risk	Primary driver(s)	Sustainability implication	Policy-relevant intervention
Crop diversity	Decline of pollinator-dependent crops	Habitat loss; pesticide exposure	Reduced agrobiodiversity and resilience	Landscape diversification; pollinator-friendly farming
Agricultural production	Yield instability in fruits, vegetables, and nuts	Pollinator population loss; climate stress	Increased production volatility	Integrated pest and pollinator management
Nutritional security	Reduced availability of micronutrient-rich foods (e.g. vitamin A, iron, zinc)	Loss of pollination services	Elevated risk of hidden hunger	Nutrition-sensitive agricultural policies
Market stability	Price volatility and supply shocks	Uneven crop losses; trade sensitivity	Economic instability and inequity	Market regulation; diversification of supply chains
Rural livelihoods	Income loss for smallholders	Crop failure; pollination deficits	Increased socio-economic vulnerability	Targeted support for pollinator-dependent farmers
Governance systems	Fragmented response to pollination decline	Sectoral policy silos	Ineffective risk mitigation	Integrated food-system governance frameworks

The interconnectedness of these domains demonstrates the need to consider pollination to be a crucial component of a sustainability-focused food-system governance framework and calls for coordinated interventions that align ecological protection, agricultural production, nutritional security, and market stability in a manner that promotes the sustainability of all sectors involved.

4. WHY TECHNOLOGY CANNOT PROTECT POLLINATION

Experts promote increasing forms of technological substitution ranging from managed pollination services, precision agriculture, through breeding to digital monitoring technologies yet there is little evidence that technology alone can protect pollination loss. Technology and other approaches may offset temporary losses but fail to account for many of the underlying causes of loss

(such as habitat and land-use changes, cumulative toxic exposures, climate related stress) and routes through which these stressors can feedback across multiple scales amplifying vulnerability and loss (Bommarco et al., 2013; Potts et al., 2016). Studies of the marriage of technology and agriculture through agro-ecological assessments of food-systems provide some evidence of how reinforcing dependencies and masking risk through patterns of substitution strengthens tendencies that delay governance that could navigate, parking governance in a space of reduced long-term options (Dicks et al., 2021; Kovács-Hostyánszki et al., 2017). The preservation of pollinators requires a framework of policy that integrates technological tools within a wider regime of policy for ecological restoration, coordinated management and institutional connectivity across borders of domains of the food system. Governance failures work to undermine pollination protection through mismatching temporal and spatial scale of pollination processes, and the institutional scale and clock faces on which policy action is founded. Pollination service flows across space, and indeed across seasons, while the way that risk is managed is fragmented by the administrative disabling of policy instruments across administrative boundaries of long and short planning horizons and domains (Dicks et al., 2021; Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services [IPBES], 2016). Mismatching means that local enlightened steps of management can be offset by regional land works, change of production from genetic cul-de-sac processes via trade, and/or from ecological blinkers blinded to act as green backup when slow-moving blueprints run amok. Instead of answers falling from the trees, pollination will be lost not through lack of this, but because existing governance never coordinated action across the three or more scales (ecological, economic and institutional) upon which pollination risk was presumed to generate and wedged into sub-scales of act and inertia for risk transmission (IPBES, 2016; Kovács-Hostyánszki et al., 2017).

5. COORDINATED RESPONSES ACROSS FOOD-SYSTEM DOMAINS

Addressing pollination loss productively requires responsive, cross-system interventions which recognize pollination not as a standalone process but as a fundamental bridge between ecological integrity, agricultural production, nutritional outcomes and market stability. Rather than single

interventions in isolation, the balanced evidence points to the value of aligning habitat conservation, agroecological management, pest and weed regulation, and food-system planning across space and governance (Bommarco et al., 2013; FAO, 2019; Kovács-Hostyánszki et al., 2017). The rewards are processes that multiply benefits across domains - making pollinators more resilient while stabilizing yields and nutrition - as well as reducing the risk that gains in one domain are simply offset by losses elsewhere (Dicks et al., 2021; Potts et al., 2016). Framed in this lens, pollination-safe pathways depend not on single responses but on coherent responses which embed ecology within food-system governance. Figure 2 describes how such coordinated responses must be conceived to reach across mismatched ecological, agricultural and governance scales, and where efforts to align across scales concentrate risk and where cross-scalar interventions will serve to effectuate a happy stabilization of beehive-dependent food systems.

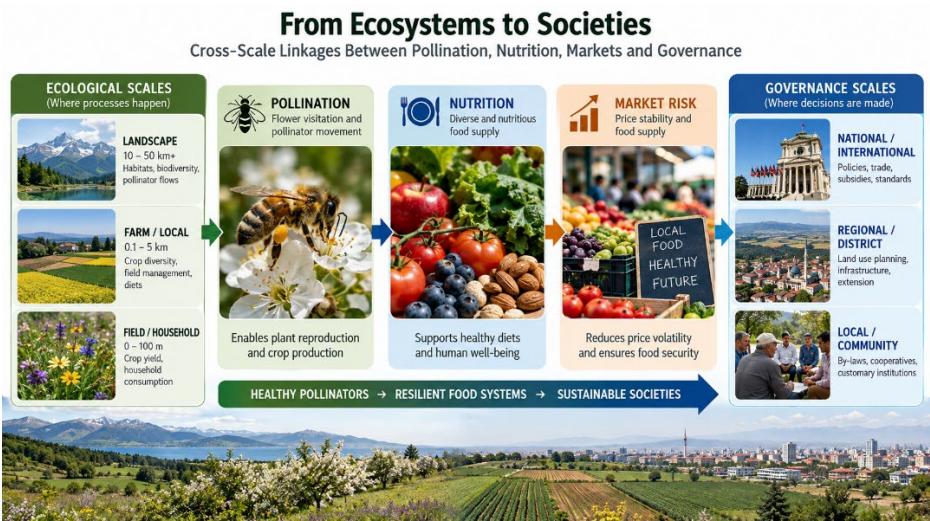


Figure 2. Cross-scale linkages between ecological processes, pollination, nutrition, markets, and governance in food systems.

Figure 2 defines the notion that risk publication from pollination loss emerges not from single points of failure, but rather from misalignments across risks capes composed of different ecological, agricultural and governance scales which lie behind decisions in the food system. At the ecological level of the food system, processes such as habitat connectivity, phenological synchrony, population resilience, etc. work across landscapes and over seasons,

while agricultural management and policy interventions are made at field actions and farm and administrative scales that don't match (Dicks et al., 2021; IPBES, 2016). This cross-scale mismatch allows local gains to be undone by harms elsewhere - or mitigated by uplifting production or trade or delayed modelling responses - which simply re-distribute risk. The practicality of looking-for cross-scalar intervention is foregrounded in Figure 2, that "protecting pollination" looks not towards fixing pollination itself, but seeking coherence where decisions announced ecological processes, actions made, and instruments written into place (IPBES, 2016; Kovács-Hostyánszki et al., 2017).

6. POLICY INSTRUMENTS AND IMPLEMENTATION PATHWAYS

Turning coordinated responses into actions requires policy instruments that work at multiple sectors and scales whilst being sensitive to local ecological and socio-economic context. Regulatory tools (pesticide risk frameworks, land-use planning and habitat protection standards) provide a necessary baseline, but without additional incentive-based and participatory tools facilitating uptake at the farm/landscape level, they are inadequate (Dicks et al., 2021; IPBES, 2016). Agri-environment schemes, conditional subsidies and results-based payments, can promote farmer decisions to be more pollinator-conducive when implemented by both reflecting ecological thresholds (spatially and temporally) and addressing cumulative risk. At broader levels, integrating pollination issues into food-system planning, trade policy, and nutritional strategies avoids the cross-border displacement of risk, and ensures coherence between production objectives and sustainability (IPBES, 2016). Together, these pathways indicate that it is less the relative novelty of individual instruments that matter, but the ways in which they are tied together, sequenced and aligned across domains of governance.

7. CONCLUSION

In summary, the loss of pollinators is not only a result of ecological damage; it threatens the stability of our food systems, how we obtain food, and how we distribute that food through changing or broken market channels. The studies reviewed in this paper clearly show that when pollination is viewed as

an external factor to agriculture, or as an alternative source of nutrients, it does not accurately capture the significance of pollination or of how the ecosystem supports the food systems we rely on being durable. To address the challenges of pollinator decline, it is critical that we build coordinated systems of policies, agricultural processes and ecological processes that incorporate these factors to work towards effective responses to pollution, market instability and the need for sustainable food systems to avoid the increased risk of food insecurity and to mitigate the effects of climate change.

REFERENCES

- Aizen, M. A., & Harder, L. D. (2009). The global stock of domesticated honeybees is growing slower than agricultural demand for pollination. *Current Biology*, 19(11), 915–918. <https://doi.org/10.1016/j.cub.2009.03.071>
- Aizen, M. A., Aguiar, S., Biesmeijer, J. C., Garibaldi, L. A., Inouye, D. W., Jung, C., Martins, D. J., Medel, R., Morales, C. L., Ngo, H. T., Pauw, A., Paxton, R. J., Sáez, A., Seymour, C. L., & Dicks, L. V. (2019). Global agricultural productivity is threatened by increasing pollinator dependence without a parallel increase in crop diversification. *Global Change Biology*, 25(10), 3516–3527. <https://doi.org/10.1111/gcb.14736>
- Bauer, D. M., & Sue Wing, I. (2016). The macroeconomic cost of catastrophic pollinator declines. *Ecological Economics*, 126, 1–13. <https://doi.org/10.1016/j.ecolecon.2016.01.011>
- Biesmeijer, J. C., Roberts, S. P. M., Reemer, M., Ohlemüller, R., Edwards, M., Peeters, T., Schaffers, A. P., Potts, S. G., Kleukers, R., Thomas, C. D., Settele, J., & Kunin, W. E. (2006). Parallel declines in pollinators and insect-pollinated plants in Britain and the Netherlands. *Science*, 313(5785), 351–354. <https://doi.org/10.1126/science.1127863>
- Bommarco, R., Kleijn, D., & Potts, S. G. (2013). Ecological intensification: Harnessing ecosystem services for food security. *Trends in Ecology & Evolution*, 28(4), 230–238. <https://doi.org/10.1016/j.tree.2012.10.012>
- Breeze, T. D., Gallai, N., Garibaldi, L. A., & Li, X. S. (2016). Economic measures of pollination services: Shortcomings and future directions. *Trends in Ecology & Evolution*, 31(12), 927–939. <https://doi.org/10.1016/j.tree.2016.09.002>
- Chaplin-Kramer, R., Dombeck, E., Gerber, J., Knuth, K. A., Mueller, N. D., Mueller, M., Ziv, G., & Klein, A.-M. (2014). Global malnutrition overlaps with pollinator-dependent micronutrient production. *Proceedings of the Royal Society B: Biological Sciences*, 281(1794), 20141799. <https://doi.org/10.1098/rspb.2014.1799>
- Chaplin-Kramer, R., Sharp, R. P., Weil, C., Bennett, E. M., Pascual, U., Arkema, K. K., Brauman, K. A., Bryant, B. P., Guerry, A. D., Haddad,

- N. M., Hamann, M., Hamel, P., Johnson, J. A., Mandle, L., Pereira, H. M., Polasky, S., Ruckelshaus, M., Shaw, M. R., Silver, J. M., ... Daily, G. C. (2019). Global modeling of nature's contributions to people. *Science*, 366(6462), 255–258. <https://doi.org/10.1126/science.aaw3372>
- Dicks, L. V., Breeze, T. D., Ngo, H. T., Senapathi, D., An, J., Aizen, M. A., Basu, P., Buchori, D., Galetto, L., Garibaldi, L. A., Gemmill-Herren, B., Howlett, B. G., Imperatriz-Fonseca, V. L., Johnson, S. D., Kovács-Hostyánszki, A., Kwon, Y. J., Lattorff, H. M. G., Lungharwo, T., Seymour, C. L., ... Potts, S. G. (2021). A global-scale expert assessment of drivers and risks associated with pollinator decline. *Nature Ecology & Evolution*, 5(10), 1453–1461. <https://doi.org/10.1038/s41559-021-01534-9>
- Food and Agriculture Organization of the United Nations. (2019). *The state of the world's biodiversity for food and agriculture*.
- Feuerbacher, A. (2025). Pollinator declines, international trade and global food security: Reassessing the global economic and nutritional impacts. *Ecological Economics*, 232, 108565. <https://doi.org/10.1016/j.ecolecon.2025.108565>
- Feuerbacher, A., Kempen, M., Steidle, J. L. M., & Wieck, C. (2025). The economic, agricultural, and food security repercussions of a wild pollinator collapse in Europe. *Nature Communications*, 16, 9892. <https://doi.org/10.1038/s41467-025-65414-7>
- Gallai, N., Salles, J.-M., Settele, J., & Vaissière, B. E. (2009). Economic valuation of the vulnerability of world agriculture confronted with pollinator decline. *Ecological Economics*, 68(3), 810–821. <https://doi.org/10.1016/j.ecolecon.2008.06.014>
- Garibaldi, L. A., Aizen, M. A., Klein, A.-M., Cunningham, S. A., & Harder, L. D. (2011). Global growth and stability of agricultural yield decrease with pollinator dependence. *Proceedings of the National Academy of Sciences*, 108(14), 5909–5914. <https://doi.org/10.1073/pnas.1012431108>
- Garibaldi, L. A., Carvalho, L. G., Vaissière, B. E., Gemmill-Herren, B., Hipólito, J., Freitas, B. M., Ngo, H. T., Azzu, N., Sáez, A., Åström, J., An, J., Blochtein, B., Buchori, D., Chamorro García, F. J., Oliveira da Silva, F., Devkota, K., Ribeiro, M. F., Freitas, L., Goss, M., ... Zhang, H.

- (2016). Mutually beneficial pollinator diversity and crop yield outcomes in small and large farms. *Science*, 351(6271), 388–391. <https://doi.org/10.1126/science.aac7287>
- Gazzea, E., Batáry, P., & Marini, L. (2023). Global meta-analysis shows reduced quality of food crops under inadequate animal pollination. *Nature Communications*, 14, 4463. <https://doi.org/10.1038/s41467-023-40231-y>
- Giannini, T. C., Costa, W. F., Borges, R. C., Miranda, L., da Costa, C. P. W., Saraiva, A. M., & Imperatriz-Fonseca, V. L. (2021). Pollinator-dependent crops in Brazil yield nearly half of nutrients for humans and livestock feed. *Global Food Security*, 31, 100587. <https://doi.org/10.1016/j.gfs.2021.100587>
- Hallmann, C. A., Sorg, M., Jongejans, E., Siepel, H., Hofland, N., Schwan, H., Stenmans, W., Müller, A., Sumser, H., Hörden, T., Goulson, D., & de Kroon, H. (2017). More than 75 percent decline over 27 years in total flying insect biomass in protected areas. *PLoS ONE*, 12(10), e0185809. <https://doi.org/10.1371/journal.pone.0185809>
- Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. (2016). *The assessment report on pollinators, pollination and food production* (S. G. Potts, V. L. Imperatriz-Fonseca, & H. T. Ngo, Eds.). <https://doi.org/10.5281/zenodo.3402856>
- Klein, A.-M., Vaissière, B. E., Cane, J. H., Steffan-Dewenter, I., Cunningham, S. A., Kremen, C., & Tscharntke, T. (2007). Importance of pollinators in changing landscapes for world crops. *Proceedings of the Royal Society B: Biological Sciences*, 274(1608), 303–313. <https://doi.org/10.1098/rspb.2006.3721>
- Kovács-Hostyánszki, A., Espíndola, A., Vanbergen, A. J., Settele, J., Kremen, C., & Dicks, L. V. (2017). Ecological intensification to mitigate impacts of conventional intensive land use on pollinators and pollination. *Ecology Letters*, 20(5), 673–689. <https://doi.org/10.1111/ele.12762>
- Murphy, J. T., Breeze, T. D., Willcox, B., Kavanagh, S., & Stout, J. C. (2022). Globalization and pollinators: Pollinator declines are an economic threat to global food systems. *People and Nature*, 4(3), 773–785. <https://doi.org/10.1002/pan3.10314>

- Myers, S. S., Smith, M. R., Guth, S., Golden, C. D., Vaitla, B., Mueller, N. D., Dangour, A. D., & Huybers, P. (2017). Climate change and global food systems: Potential impacts on food security and undernutrition. *Annual Review of Public Health*, 38, 259–277. <https://doi.org/10.1146/annurev-publhealth-031816-044356>
- Oliver, T. H., Isaac, N. J. B., August, T. A., Woodcock, B. A., Roy, D. B., & Bullock, J. M. (2015). Declining resilience of ecosystem functions under biodiversity loss. *Nature Communications*, 6, 10122. <https://doi.org/10.1038/ncomms10122>
- Potts, S. G., Imperatriz-Fonseca, V., Ngo, H. T., Aizen, M. A., Biesmeijer, J. C., Breeze, T. D., Dicks, L. V., Garibaldi, L. A., Hill, R., Settele, J., & Vanbergen, A. J. (2016). Safeguarding pollinators and their values to human well-being. *Nature*, 540(7632), 220–229. <https://doi.org/10.1038/nature20588>
- Quaresma, A., Baveco, J. M., Brodschneider, R., Buddendorf, W. B., Carreck, N. L., Gratzer, K., Hatjina, F., Kilpinen, O., Roessink, I., Vejsnaes, F., van der Steen, J., Pinto, M. A., & Keller, A. (2026). Honey bee food resources under threat from climate change. *Nature Communications*, 17(1), 1331. <https://doi.org/10.1038/s41467-025-68085-6>
- Rader, R., Bartomeus, I., Garibaldi, L. A., Garratt, M. P. D., Howlett, B. G., Winfree, R., Cunningham, S. A., Mayfield, M. M., Arthur, A. D., Andersson, G. K. S., Bommarco, R., Brittain, C., Carvalheiro, L. G., Chacoff, N. P., Entling, M. H., Foully, B., Freitas, B. M., Gemmill-Herren, B., Ghazoul, J., ... Woyciechowski, M. (2016). Non-bee insects are important contributors to global crop pollination. *Proceedings of the National Academy of Sciences*, 113(1), 146–151. <https://doi.org/10.1073/pnas.1517092112>
- Requier, F., Pérez-Méndez, N., Andersson, G. K. S., Blareau, E., Merle, I., & Garibaldi, L. A. (2023). Bee and non-bee pollinator importance for local food security. *Trends in Ecology & Evolution*, 38(2), 196–205. <https://doi.org/10.1016/j.tree.2022.10.006>
- Sánchez-Bayo, F., & Wyckhuys, K. A. G. (2019). Worldwide decline of the entomofauna: A review of its drivers. *Biological Conservation*, 232, 8–27. <https://doi.org/10.1016/j.biocon.2019.01.020>

- Timberlake, T. P., Cirtwill, A. R., Sapkota, S., Bhusal, D. R., Devkota, K., Karki, R., Joshi, D., Saville, N. M., Kortsch, S., Baral, S., Roslin, T., & Memmott, J. (2024). Agricultural specialization increases the vulnerability of pollination services for smallholder farmers. *Journal of Applied Ecology*, 61(9), 2123–2134. <https://doi.org/10.1111/1365-2664.14732>
- Uwingabire, Z., & Gallai, N. (2024). Impacts of degraded pollination ecosystem services on global food security and nutrition. *Ecological Economics*, 217, 108068. <https://doi.org/10.1016/j.ecolecon.2023.108068>

CHAPTER 8

DIOXIN-LIKE CONTAMINANTS: SOURCES, EMISSIONS, HEALTH EFFECTS AND REGULATIONS

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INTRODUCTION

Dioxin-like compounds constitute a category of persistent organic pollutants (POPs), in the same way as pesticides Solomon and Weiss (2002). They include polychlorinated dibenzo-p-dioxins (PCDDs), polychlorinated dibenzofurans (PCDFs) and certain polychlorinated biphenyls (PCBs)(Fig. 1), which are among the most closely monitored pollutants in the world (Kulkarniet al., 2017).

These ubiquitous substances, listed in the Stockholm Convention (Pollutants, 2011), are known in English as the ‘dirty dozen’. In this text, the term ‘dioxins’ refers to PCDD, PCDF and PCB compounds, which are persistent organic pollutants (POPs) included by the World Health Organization and the FAO (Van den Berg et al., 2006) in the Toxic Equivalency Factor (TEF) system, which was developed and implemented a system for mitigating risks and assessing regulatory oversight control of exposure to these mixtures (Safe, 1990). These environmental and food contaminants have a long half-life in the environment(Themba et al., 2023), where they persist and resist degradation due to their high lipophilicity (Mehouel et al., 2021). Dioxins are by-products generated unintentionally by various industrial processes, including industrial manufacturing, chemical synthesis and the metallurgical industry (Ae et al., 2018; WHO, 2017). Although these pollutants may also be released by certain natural processes, their presence in the environment results primarily from atmospheric emissions arising from a number of industrial activities: waste incineration (hazardous, municipal and medical waste), thermal and combustion processes, chlorine bleaching of pulp, metal smelting, cement production, and road traffic, with emissions from the latter primarily originating from diesel vehicles (Dopico and Gómez, 2015) .Added to this is the illegal incineration of waste, often carried out at night in agricultural areas, which releases a number of hazardous chemicals, including dioxins, a large family of chlorinated compounds comprising 17 highly toxic congeners (McKay, 2002), including the molecule 2,3,7,8-tetrachlorodibenzo-p-dioxin (TCDD), classified as a carcinogen in animals and humans by the International Agency for Research on Cancer (IARC) (Steenland et al., 2004). A growing body of data has enabled these pollutants to be measured in various water bodies around the world (Kalantzi et al., 2017). However, in North Africa, these

pollutants are emitted locally but may also be transported via the atmosphere from Europe (Bogdal et al., 2013; Xu and Cai, 2015). In Algeria, atmospheric concentrations ranging from 210 to 780 fg I-TEQ/m³ have been measured in industrial areas (Moussaoui et al., 2012). A passive sampling campaign carried out in the north of the country also measured concentrations of PCDD/F and dioxin-like PCBs ranging from 18 to 84 pg m⁻³ in rural and industrial areas. With regard to aquatic matrices, the study of sediments from the Soummam River (Bejaia region) (Bensadi and Azzoug, 2026), which constituted the first comprehensive analysis of these contaminants in river sediments in this catchment, concluded that there were non-carcinogenic risks to children (Bensadi, Azzoug, & Benlaribi, 2024). The study by Mehoul et al. (2021), which examined the concentrations of PCDD/F and DL-PCBs in swordfish caught in Algiers, Bejaia and Oran (37 samples analysed using the DR-CALUX bioassay), confirms that the daily and weekly intakes were indeed higher in Bejaia (0.45 and 3.15 pg TEQ/kg fw/day and week) and in Algiers (0.31 and 2.17 pg TEQ/kg fw/day and week), and that these values exceeded the tolerable. This is attributable to the high levels of marine pollution in this area caused by the discharge of urban wastewater from the commercial port and industrial zones, as well as from watercourses. The lowest average value was recorded in swordfish from Oran (0.08 pg TEQ g⁻¹ f.w). The concentrations of total PCDD/F and DL-PCBs studied in swordfish caught in Algerian waters were below the thresholds set by Algerian and European regulations (namely 8 and 6.5 pg TEQ g⁻¹ f.w. respectively) (Regulation, 2010 ; Nadjiba, 2011). Data on the transfer of dioxins to food of terrestrial origin (milk, meat, eggs) remain very limited (Ssebugere et al., 2019).

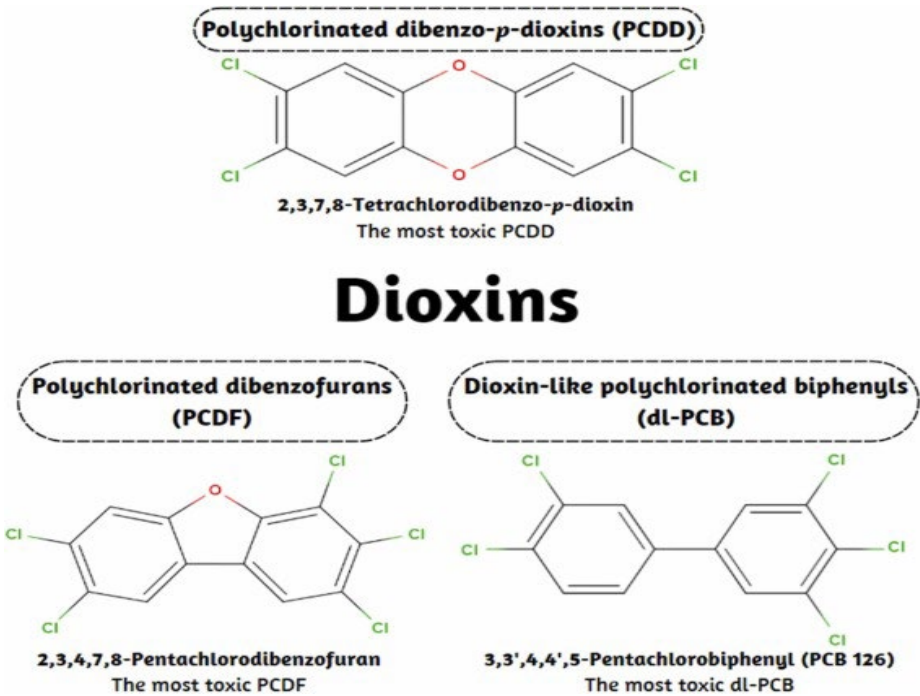


Fig. 1. Dioxin groups and their most toxic congeners (Sobol et al., 2025).

1. SOURCES AND EMISSIONS

Global inventories of PCDD/F emissions have been compiled for various substances (Quaß et al., 2004). In Algeria, monitoring of PCDD/Fs and dlPCBs in ash is of paramount importance, as there are unacceptable common practices involving their direct disposal in landfill sites, which could damage adverse effects on environmental ecosystems (Kerchich et al., 2018). In northern Algeria, particulate matter and ash samples from incinerator emissions released by the country’s sole clinical and industrial waste incineration plant contain concentrations of PCDD/F and dl-PCBs. The plant has four static-type furnaces, each fitted with a wet scrubber with acid gas neutralization, serving as an air pollutant control device (APCD). Incineration is presented as a suitable method for the disposal of these substances, and the Algerian authorities have made this waste management process a priority (Makhoukh, 2004; Kehila, 2014). The destruction of industrial by-products by incineration reduces the weight and volume of the original waste by 80 per cent, depending on the composition of the raw materials burned(Chen et al.,

2008). Waste treatment processes are a significant source of dioxin emissions into the environment (Szajner al., 2021). Despite decades of emission control measures, contamination remains widespread. The most affected areas are now concentrated in Asia and Africa, and global emissions are estimated at approximately 97 to 100 kg TEQ per year (Mathew et al., 2025). Africa has experienced exponential urbanisation and industrialisation over the last two periods (Turok and McGranahan, 2019). This growth, combined with growing vitality needs for a rapidly expanding systems (Gioia et al., 2014; Ssebugere et al., 2019) population, have led to increased pollution of the continent's environmental.

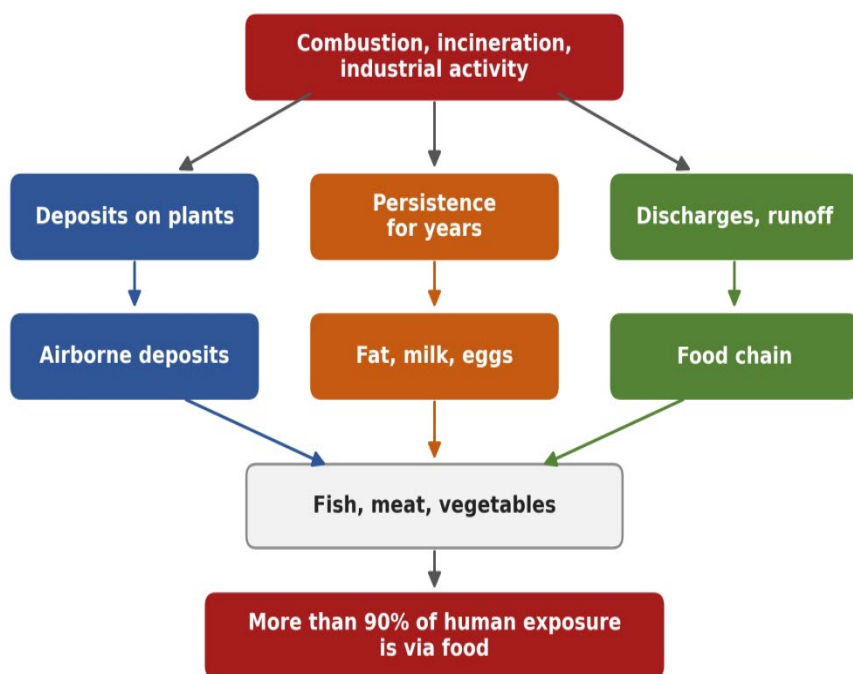


Fig. 2. Sources and emissions (OMS, 2016 ; EFSA, 2018).

2. CONTAMINATION OF THE FOOD CHAIN

Food contamination results primarily from the deposition on agricultural land of emissions from various sources (waste incineration, chemical production, the metallurgical industry), followed by their accumulation in the food chain, where these lipophilic compounds are stored

mainly in fats (Matei et al., 2023). Other sources of contamination include contaminated feed intended for livestock, poultry and farmed fish; the inappropriate spreading of sewage sludge; the flooding of pastureland; industrial effluents; and certain stages of food processing (Djien Liem al., 2000; Oltramare et al., 2026). Polluted soil is the primary source of exposure for livestock, particularly for lipophilic POPs such as PCBs and PCDD/Fs (Diletti, 2018). When animals ingest soil, POPs deposited on the topsoil may be absorbed by them (Jones et al., 1989). Transfers to livestock have also been reported following atmospheric deposition contaminating water, soil and vegetation (Pan et al., 2013) (Fig. 3), or following periodic flooding (Rose, 2016).

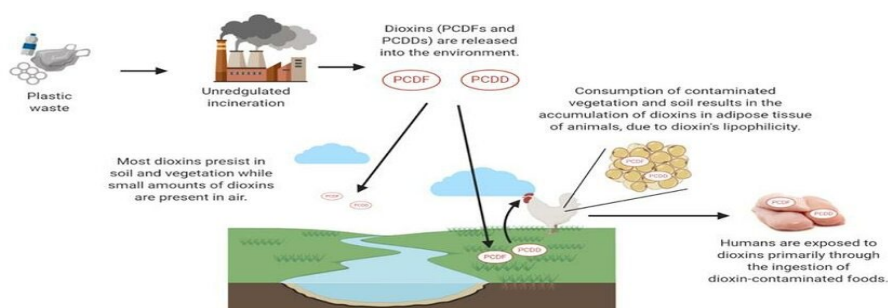


Fig. 3. Sources, pathways, and effects of dioxin contamination (Guo et al., 2020).

According to the study (Mehouel et al., 2021), humans are exposed to persistent organic pollutants (POPs) through various routes, including inhalation of air, ingestion of food and non-food products, and skin contact (Hoogenboom et al., 2015). PCDD/Fs and dl-PCBs are mainly ingested via high-fat foods, such as eggs, fish, meat and animal fats, as well as dairy products, which are highly lipophilic (Perelló et al., 2015) and constitute the main source of dioxins in humans according to the World Health Organization (WHO, 2017).

It is therefore necessary to evaluate data on the concentrations and presence of PCDD/F and dl-PCBs in the main foods of animal origin. PCDD/Fs and dl-PCBs are generally present in small quantities in fruit, vegetables, nuts and cereals, but high consumption of these foods can lead to dietary exposure to these pollutants (Bramwell et al., 2017; Weber et al., 2018). Other sources of contamination include contaminated feed for livestock, poultry and farmed fish; the inappropriate spreading of sewage

sludge; the flooding of pastureland; industrial effluents; and certain stages of food processing (Djien Liem et al., 2000; McLachlan and Richter, 1998).

3. HEALTH EFFECTS

PCDD/Fs and DL-PCBs have been classified by the International Agency for Research on Cancer as carcinogenic to humans (IARC 199) and may also cause immunosuppression and behavioral changes and increase the risk of cardiovascular disease in humans and animals the risk of cardiovascular disease in humans and animals (Cui et al., 2018). Exposure to PCDD/Fs and PCBs has been linked to endocrine disruption in humans and animals (Sanderson, 2006; Rennert et al., 2012), as well as to effects on reproduction and brain development (Hoogenboom et al., 2015).

3.1. In Humans

These compounds accumulate in the body over the long term and disrupt homeostatic mechanisms, the endocrine, immune, nervous, and reproductive systems, the course of pregnancy, and fetal development (Szajner et al., 2021) (Tab:1). Acute exposure results in skin chanan increased incidence of chloracne (55.7%), attributed to actinic elastosis of the skin, ges and chloracne (Takiguchi et al., 2022) among 204 workers exposed to 2,4,5-trichloroacetophenol contaminated with TCDD (Suskind and Hertzberg, 1984). Recent studies also suggest an increased risk of liver and lung cancers and lymphoid neoplasms associated with 2,3,7,8-TCDD (Pizzuti et al., 2005 ; Comba et al., 2006), although the link to overexposure to dioxins remains debated and has yet to be demonstrated(EPA, 2006; Murray et al., 2014).

Table 1. Effects of dioxins on health human.

Effects	Consequences	References
Bioaccumulation	Accumulation mainly in the liver and fatty tissues persistence in the body and possible transfer from mother to child.	(Kołłataj et al., 2017; Zouboulis, 2020).
Endocrine disruption	Hormones thyroïdiennes et sexuelles et de la signalisation hormonale.	(Eskenazi et al., 2018; Samer et al., 2020).
Reproduction	Impaired reproductive function and certain sperm parameters	(Faïad et al., 2022; Zhang, Buekens and Li, 2016).

Effects	Consequences	References
Development	Effects on the neurological, cognitive, immune and reproductive development of the foetus and the child.	(Chmielewski et al., 2020).
Immune system	Alterations in the immune response and immunotoxicity.	
Cardiovascular system	High blood pressure, atherosclerosis and cardiovascular disorders.	(Pavuk et al., 2019 ; Donat-Vargas et al., 2020; Jarosław et al., 2020).
	Increased risk of certain cancers, particularly following exposure to TCDD.	(Kogevinas, 2011 ; Kogevinas, 2011; Samer et al., 2020).
Skin	Chloracne and other skin conditions.	(Sorg et al., 2009 ; Chmielewski et al., 2020 ; Zouboulis, 2020).
Nervous system	Impaired memory, learning, cognition and psychomotor functions	(Schantz et al., 2001).

3.2. In animals

When animals ingest soil, POPs deposited on the topsoil may be absorbed into their bodies (Stevens and Gerbec, 1988; Jones et al., 1989). In animals, sheep reared in contaminated areas show increased chromosomal fragility, a higher mortality rate and more foetal developmental abnormalities (Perucatti et al., 2006). In animals, foetal and postnatal exposure to TCDD affects the development of molars, leading to malformations, delayed eruption and impaired calcification (Tab.2). The early stages of dental morphogenesis during the foetal period are the most sensitive to TCDD. In vitro studies on the effects of TCDD on tooth formation, conducted using mouse molar embryos, have shown that alteration of the epidermal growth factor receptor (EGFR) (Salmela et al., 2011) and the promotion of epithelial apoptosis (Yongkai et al., 2025) may play an important role in the toxic effects of TCDD in fetuses.

Furthermore, Kiukkonen et al. (2006) investigated the links between TCDD-induced impaired mineralization of mandibular molars in mouse embryos at the E18 budding stage and the expression of dentin

sialophosphoprotein (Dspp), Bono1 and matrix metalloproteinase-20 (MMP-20), which are involved in the calcification of hard tissues (Gonçalves et al., 2020). Although no notable differences were observed in the localization and intensity of Bono1 and MMP-20 expression, Dspp expression in secretory odontoblasts and pre-secretory ameloblasts was reduced in embryos incubated with TCDD. These results suggest that TCDD may lead to impaired dentine calcification due to toxicity specific to Dspp expression.

Table 2. Effects of dioxins in health animals.

Effects	Impact	References
Bioaccumulation and biomagnification	Food chain.	(Kołłataj et al., 2017; Zouboulis, 2020).
Reproduction	Reducedviability of offspring.	(Aldeli et al., 2024).
Développement	Growth retardation and congenital malformations.	(Charest, 2024).
Immune system	Suppression of certain immune responses and immunotoxicity.	(Ssebugere et al., 2019).
Endocrine system	Hyperplasia of the thyroid and adrenal glands.	(Estaquier et al., 2021 ; Barouki, 2010).
Reproductive system	Atteintes des ovaires et autres organes reproducteurs.	(Faiaad et al., 2022).
Liver and metabolism	Hyperplasia of the thyroid and adrenal glands.	(White and Birnbaum, 2009).

4. SITUATION IN AFRICA AND ALGERIA

4.1. African Context

Africa is one of the continents more influenced by this type of contamination, which alter the relationship of the ratio of dioxin accumulation with the ratio of dioxin production per country. Evidences of this tendency are proved by the fact that 11 countries from Africa are placed in the top20 most impacted countries when compare the ambient concentration with the ratio of production (Bogdal et al., 2013).

This behavior can be found in countries from the north of Africa like Egypt, where besides their own attributable production of dioxins, they receive pollutants from Europe according to the different transportation and dispersion mechanisms of PCDD/Fs. Typical ambient air concentrations in African countries can be found between 18-532 fg WHO-TEQ/m³ (mean

value of 51 fg WHO-TEQ/m³) for urban sites (Bogdal et al., 2013). More concrete results for industrial areas have shown concentrations between 210-780 fg I-TEQ/m³ in Algeria, although these are expected to be even higher in countries like Egypt (≈ 1000 fg I-TEQ/m³) (Moussaoui et al., 2012). Africa shows the same behavior where industrial locations show higher ambient concentrations than urban and rural (Quinn et al., 2009; Moussaoui et al., 2012; Arinaitwe et al., 2018; Ssebugere et al., 2019). Across the continent, concentrations of PCDD/F and dioxin-like PCBs are generally higher in urban and industrialized areas than in remote and sparsely urbanized areas. In North Africa, these pollutants are emitted locally but may also originate from atmospheric transport from Europe (Bogdal et al., 2013; Xu and Cai, 2015)

4.2. Available Data in Algeria

In Algeria, there is a lack of data on emissions of PCDD/F and dl-PCBs. A scientific publication by Moussaoui et al. (2012) has reported concentrations of polychlorinated dibenzo-p-dioxins, dibenzofurans (PCDD/F) and dioxin-like polychlorinated biphenyls (dl-PCBs) at an urban/industrial site and at an industrial site. The concentrations of PCDD/F and dl-PCBs, analysed by HRGC/HRMS, ranged from 249 to 923 fg TEQ m³. In addition to passive sampling, active sampling using an isokinetic sampler was also carried out in an industrial waste incinerator. The measured concentrations of PCDD/F and dl-PCBs amounted to 268 pg TEQ m³. More specific results for industrial areas have shown concentrations between 210 and 780 fg I-TEQ/m³ in Algeria, although these are expected to be even higher in countries such as Egypt (≈ 1000 fg I-TEQ/m³) (Moussaoui et al., 2012). Africa exhibits the same pattern, with industrial locations showing higher ambient concentrations than urban and rural areas (Quinn et al., 2009; Ssebugere et al., 2013). PCDD/Fs and DL-PCBs were analysed in 37 samples of swordfish (*Xiphias gladius*) from three regions along the Algerian coast: Algiers, Bejaia and Oran, using the DR-CALUX bioassay method. The overall mean (and standard deviation) of the concentrations of PCDD/Fs and DL-PCBs were 0.19 (0.13), 0.27 (0.24) and 0.08 (0.05) pg TEQ g⁻¹ wet weight (ww), respectively, which is below the national and European regulatory limits. The daily and weekly intake values for PCDD/F and DL-PCBs were higher for samples from Bejaia (0.45 and 3.15 pg TEQ kg⁻¹ body

weight (bw) per day and per week, respectively) and for samples from Algiers (0.31 and 2.17 pg TEQ kg⁻¹ body weight per day and per week, respectively), which exceeded the tolerable weekly intake of 2 pg TEQ kg⁻¹ body weight per week recently established by the European Food Safety Authority (Mehouel et al, 2021).

Compared with European guidelines, PM10 concentrations (particles 10 µm or smaller) in Algeria frequently exceed the maximum limits. Measurement of (PCDD/F) and (PCB) in the PM10 fraction (n = 23) at the Sour El Ghozlane cement works (Khedidji et al., 2013), analysed using the DRE-CALUX biological assay, the measured bioanalytical equivalents (BEQs) were: average PM10 concentration (µg/m³) 46.8 (range 14.9–162), similar to those observed at other international industrial sites around the world.

5. INTERNATIONAL AND EUROPEAN REGULATORY FRAMEWORK

Regulations on persistent organic pollutants aim to reduce the impact of pollution, eliminate existing pollutants or prevent any potential contamination (Curtean–Bănăduc et al., 2016). According to the European Chemicals Agency (ECHA 2021), at least 12 types of organic substances, known as the ‘black dozen’, were included in 2001 on the Stockholm Convention’s list of POPs (Tab.3). The Convention aimed to protect human health and the environment, in particular by safely disposing of, reducing the production of, and curtailing the use of these 12 hazardous substances; it was originally signed by 115 States. Currently, the Stockholm Convention has been signed by 152 States and ratified by 184 States (ECHA, 2021). The list of banned or restricted organic pollutants currently comprises around 28 hazardous chemicals (SCHP, 2020) and includes three categories of POPs distinguished according to their anthropogenic origin (Curtean–Bănăduc et al., 2016; Pham and Sillanpaa 2020; Xie et al., 2021).

5.1. The Stockholm Convention

Adopted in 2001 and entered into force in 2004, the Stockholm Convention on Persistent Organic Pollutants is an international treaty aimed at eliminating or restricting the production and use of POPs(Zeitler, 2020). It

commits signatory states to reducing, or even eliminating, emissions of dioxins and furans, which are classified among the most concerning unintentionally produced substances worldwide. L'Algérie conscient des risques que les polluants organiques persistants (POP) font peser sur la santé des personnes et l'environnement, La Convention de Stockholm sur les POP est entrée en vigueur pour l'Algérie le 21 décembre 2006 (M.E.E. R ,2018).

5.2. The WHO global monitoring program

Since the mid-1980s, the World Health Organization (WHO) has coordinated a global monitoring program for PCBs, PCDDs, and PCDFs (Malisch et al., 2010; WHO, 2017). This program focuses in particular on the exposure of breastfed infants and aims to assess the impact of measures taken to reduce or prevent environmental exposure to these substances (van den Berg et al., 2017).

5.3. Role of the codex alimentarius and the WHO

Codex Alimentarius (FAO/WHO): establishes codes of good practice and recommendations to limit dioxin contamination in food and feed, without necessarily setting globally harmonized numerical limits as the European Union does. WHO: conducts reference toxicological assessments (TEF factors) and contributes to the establishment of tolerable intake levels used by national and regional regulators.

5.4. Risk assessment by the WHO and EFSA

The assessment of the tolerable intake is based on the concept of the tolerable weekly intake (TWI), that is, the maximum amount that can be ingested each week, over a lifetime, without significant health risk. This value was set in 2018 at 2 picograms per kilogram of body weight per week, based on the WHO's toxicological equivalence factors established in 2005.

This threshold has recently undergone a major revision: based on the WHO's updated toxicological equivalence factors (2022), the European Food Safety Authority (EFSA) confirmed in 2026 a new tolerable weekly intake, set at 0.6 picograms per kilogram of body weight per week for combined exposure to dioxins and dioxin-like PCBs a value three times stricter than the previous one. This revision reflects a more nuanced assessment of low-dose toxic effects and, according to the EFSA, confirms a genuine health concern

for a portion of the European population whose dietary exposure exceeds this new threshold.

5.5. European union regulations

The European Union regulates the presence of dioxins and dioxin-like PCBs in foodstuffs using a two-tiered approach: maximum levelsbinding regulatory thresholds above which a product cannot be placed on the marketand action levelsearly warning values below the maximum levels, intended to trigger investigations into the source of contamination even before the regulatory threshold is exceeded. This framework has evolved in line with scientific reviews: Regulation (EC) No. 1881/2006 established the first harmonized maximum levels; Commission Regulation (EU) 2023/915 of April 25, 2023, is now the reference text; it repealed and replaced Regulation 1881/2006 and consolidated the previous texts (including Regulation 1259/2011 for non-dioxin-like PCBs); this regulation has itself Le 24 octobre 2022, Regulation (EU) 2022/2022 on maximum levels of dioxins and PCBs was published in the Official Journal of the European Union. It has been in force since 1 January 2023. It has since been amended, in particular by Regulation (EU) 2024/1756.

The EU regulatory limits for chlorinated dioxins are 2.5 pg TEQ/g for dioxins and furans (PCDD/F) as determined by chemical analysis. For dioxin-like PCBs, an action limit of 1.75 pg TEQ/g has been set, while for the sum of dioxins, this limit is 5.0 pg TEQ/g [to be verified: food product in question and levels]. For raw milk and dairy products, including butterfat, the maximum levels in effect since January 1, 2023, are as follows (products with ≥ 2% fat).

Table 3. Action thresholds for dioxins and PCB-DLs (WHO, 2018).

Food stuffs	Maximum content	Intervention threshold
Meat and meat products (excluding edible offal) derived from the following animals:		
cattle and sheep	1.75 pg/g of fat	1.75pg/g of fat
poultry	1.25 pg/g of fat	0.75pg/g of fat
pigs	0.75 pg/g of fat	0.50pg/g of fat
Mixed fats	1.00 pg/g of fat	0.75pg/g of fat

Food stuffs	Maximum content	Intervention threshold
Muscle tissue from farmed fish and aquaculture fishery products	1.50 pg/g fresh weight	2.50 pg/g fresh weight
Raw milk and dairy products , including butterfat	1.75 pg/g of fat	2.00pg/g of fat
Chicken eggs and egg products	1.75 pg/g of fat	1.75 pg/g of fat
Clays as a dietary supplement	0.50 pg/g fresh weight	0.50 pg/g fresh weight
Cereals and oil seeds	0.30 pg/g fresh weight	0.35 pg/g fresh weight
Fruit, vegetables (including fresh herbs)	0.30 pg/g fresh weight	0.10 pg/g fresh weight

These maximum levels and action thresholds are regularly reviewed, taking into account, amongst other things, new findings on the presence of dioxins, DL-PCBs and NDL-PCBs in the food chain and the extent to which concentrations of these substances have already been reduced in animal feed and food stuffs (CE,2010). Given the downward revision of the tolerable intake by EFSA in 2026, a further update to the European maximum levels is expected in the coming years.

5.6. Regulations on animal feed

Further up the food chain, maximum levels are also set for raw materials intended for animal feed (Directive 2002/32/EC and its amendments), in order to limit the transfer of dioxins to milk and meat at the source.

CONCLUSION

Dioxins are a prime example of the challenges posed by persistent organic pollutants: environmental persistence, bioaccumulation, a wide range of toxic effects, and exposure of the general population that is predominantly dietary and unintentional. Whilst major acute poisoning incidents are now a matter of industrial history and documented accidents, the real contemporary concern centres on chronic exposure at low doses, the carcinogenic, endocrine-disrupting and developmental effects of which continue to be clarified by research. The recent tightening of safety thresholds by EFSA reflects ongoing scientific and regulatory vigilance, and points to further developments in the European regulatory framework in the coming years.

REFERENCES

- Ae, R., Nakamura, Y., Tada, H., Kono, Y., Matsui, E., Itabashi, K., . . . Kojo, T. (2018). An 18-year follow-up survey of dioxin levels in human milk in Japan. *Journal of Epidemiology*, 28(6), 300–306.
- Aldeli, N., Murphy, D., & Hanano, A. (2024). Impact of dioxins on reproductive health in female mammals. *Frontiers in toxicology*, 6, 1392257.
- Arinaitwe, K., Muir, D. C., Kiremire, B. T., Fellin, P., Li, H., Teixeira, C., & Mubiru, D. N. (2018). Prevalence and sources of polychlorinated biphenyls in the atmospheric environment of Lake Victoria, East Africa. *Chemosphere*, 193, 343–350.
- Barouki, R. (2010). Linking long-term toxicity of xeno-chemicals with short-term biological adaptation. *Biochimie*, 92(9), 1222–1226.
- Bensadi, L., & Azzoug, M. (2026). Levels, Sources, Ecological, and Health Risk Assessment of Heavy Metals in River Sediments in Former and Future River Basin Mining Region, Soummam River, Algeria. *Environmental Forensics*, 27(1), 116–133.
- Bensadi, L., Azzoug, M., & Benlaribi, R. (2024). Occurrence, sources and risk assessment of 12 dioxin-like polychlorinated biphenyls (DL-PCBs) in sediments from the Soummam River protected area, Algeria: A potential threat to the Mediterranean Sea. *Marine Pollution Bulletin*, 208, 117003.
- Bogdal, C., Scheringer, M., Abad, E., Abalos, M., Van Bavel, B., Hagberg, J., & Fiedler, H. (2013). Worldwide distribution of persistent organic pollutants in air, including results of air monitoring by passive air sampling in five continents. *TrAC Trends in Analytical Chemistry*, 46, 150–161.
- Bramwell, L., Mortimer, D., Rose, M., Fernandes, A., Harrad, S., & Pless-Mulloli, T. (2017). UK dietary exposure to PCDD/Fs, PCBs, PBDD/Fs, PBBs and PBDEs: comparison of results from 24-h duplicate diets and total diet studies. *Food Additives & Contaminants: Part A*, 34(1), 65–77.

- Cancer, I. A. f. R. o. (1997). Polychlorinated dibenzo-para-dioxins and polychlorinated dibenzofurans. IARC monographs on the evaluation of carcinogenic risks to humans Lyon. In: France: IARC Press.
- Castro-Jiménez, J., Mariani, G., Vives, I., Skejo, H., Umlauf, G., Zaldívar, J., . . . Laugier, T. (2011). Atmospheric concentrations, occurrence and deposition of persistent organic pollutants (POPs) in a Mediterranean coastal site (Etang de Thau, France). *Environmental Pollution*, 159(7), 1948–1956.
- Chen, T., Yan, J., Lu, S., Li, X., Gu, Y., Dai, H., . . . Cen, K. (2008). Characteristic of polychlorinated dibenzo-p-dioxins and dibenzofurans in fly ash from incinerators in China. *Journal of hazardous materials*, 150(3), 510–514.
- Chmielewski, J., Szpringer, M., Łuszczki, J. J., Czarny-Działak, M., Dutkiewicz, E., Zięba, E., . . . Nowak-Starz, G. (2020). Occupational and environmental exposure to substances and chemical mixtures that are toxic to human reproduction. *Przemysł Chemiczny*, 99(6).
- Chmielewski, J., Zeber-Dzikowska, I., Kosecka, J., Wojtowicz, B., Działak, M., Osuch, M., . . . Czarny-Działak, M. (2020). Exposure to chemicals as an etiological agent of occupational skin diseases and related health education. *Przemysł Chemiczny*, 99(8), 1254–1260.
- Cui, L., Wang, S., Yang, X., Gao, L., Zheng, M., Wang, R., . . . Xu, C. (2018). Fatty acids, polychlorinated dibenzo-p-dioxins and dibenzofurans, and dioxin-like polychlorinated biphenyls in paired muscle and skin from fish from the Bohai coast, China: Benefits and risks associated with fish consumption. *Science of the Total Environment*, 639, 952–960.
- Curtean-Bănăduc, A., Burcea, A., & Bănăduc, D. (2016). Impactul Poluanților Organici Persistenți Asupra Ecosistemelor Acvatice Continentale și Sănătății Umane. *Romania*, 95–108.
- Diletti, G., Scortichini, G., Abete, M. C., Binato, G., Candeloro, L., Ceci, R., . . . Esposito, M. (2018). Intake estimates of dioxins and dioxin-like polychlorobiphenyls in the Italian general population from the 2013-2016 results of official monitoring plans in food. *Science of the Total Environment*, 627, 11–19.

- Djien Liem, A., Furst, P., & Rappe, C. (2000). Exposure of populations to dioxins and related compounds. *Food Additives & Contaminants*, 17(4), 241–259.
- Donat-Vargas, C., Moreno-Franco, B., Laclaustra, M., Sandoval-Insausti, H., Jarauta, E., & Guallar-Castillon, P. (2020). Exposure to dietary polychlorinated biphenyls and dioxins, and its relationship with subclinical coronary atherosclerosis: The Aragon Workers' Health Study. *Environment international*, 136, 105433.
- Dopico, M., & Gómez, A. (2015). Review of the current state and main sources of dioxins around the world. *Journal of the Air & Waste Management Association*, 65(9), 1033–1049.
- Eskenazi, B., Warner, M., Brambilla, P., Signorini, S., Ames, J., & Mocarelli, P. (2018). The Seveso accident: A look at 40 years of health research and beyond. *Environment international*, 121, 71–84.
- Estaquier, J., Blanc, É., & Coumoul, X. (2021). Que sait-on de l'action des perturbateurs endocriniens sur le système immunitaire? *La Revue du Praticien Médecine Générale*, 71(7), 729–734.
- Faiad, W., Soukkarieh, C., Murphy, D. J., & Hanano, A. (2022). Effects of dioxins on animal spermatogenesis: A state-of-the-art review. *Frontiers in reproductive health*, 4, 1009090.
- Gioia, R., Akindele, A. J., Adebuseye, S. A., Asante, K. A., Tanabe, S., Buekens, A., & Sasco, A. J. (2014). Polychlorinated biphenyls (PCBs) in Africa: a review of environmental levels. *Environmental Science and Pollution Research*, 21(10), 6278–6289.
- Guo, J., Feng, Q., Zhang, G., Wang, T., Yang, S., Meng, C., . . . Liu, L. (2025). Heterogeneous variations on historical of mercury, dioxins, and CO₂ emissions from medical waste incineration process in China: Emission inventory, driving factors, and the impact of COVID-19. *Journal of hazardous materials*, 490, 137582.
- Guo, K., Huang, A., & Lee, O. (2020). Engineering of a Novel anti-dioxin bacillus subtilis probiotic for poultry feed. *Undergraduate Research in Natural and Clinical Science and Technology Journal*, 4, 1–8.
- Hoogenboom, R., Traag, W., Fernandes, A., & Rose, M. (2015). European developments following incidents with dioxins and PCBs in the food and feed chain. *Food control*, 50, 670–683.

- Howell, N. L., Suarez, M. P., Rifai, H. S., & Koenig, L. (2008). Concentrations of polychlorinated biphenyls (PCBs) in water, sediment, and aquatic biota in the Houston Ship Channel, Texas. *Chemosphere*, 70(4), 593–606.
- Jarosław, C., Kosowska, E., Bąk-Badowska, J., Żeber-Dzikowska, I., Gonczaryk, A., Nowak-Starz, G., . . . Szpringer, M. (2020). Polichlorowane dibenzodioksyny i dibenzofurany jako środowiskowe zagrożenie zdrowia. *Przemysł Chemiczny*, 99.
- Jones, K., Stratford, J., Tidridge, P., Waterhouse, K., & Johnston, A. (1989). Polynuclear aromatic hydrocarbons in an agricultural soil: long-term changes in profile distribution. *Environmental Pollution*, 56(4), 337–351.
- Kalantzi, I., Mylona, K., Sofoulaki, K., Tsapakis, M., & Pergantis, S. A. (2017). Arsenic speciation in fish from Greek coastal areas. *Journal of Environmental Sciences*, 56, 300–312.
- Kehila, Y. (2014). Rapport sur la gestion des déchets solides en Algérie. *sweep net*.
- Khedidji, S., Ladji, R., & Yassaa, N. (2013). A wintertime study of polycyclic aromatic hydrocarbons (PAHs) in indoor and outdoor air in a big student residence in Algiers, Algeria. *Environmental Science and Pollution Research*, 20(7), 4906–4919.
- Kiukkonen, A., Sahlberg, C., Lukinmaa, P.-L., Alaluusua, S., Peltonen, E., & Partanen, A.-M. (2006). 2, 3, 7, 8-tetrachlorodibenzo-p-dioxin specifically reduces mRNA for the mineralization-related dentin sialophosphoprotein in cultured mouse embryonic molar teeth. *Toxicology and applied pharmacology*, 216(3), 399–406.
- Kogevinas, M. (2011). Epidemiological approaches in the investigation of environmental causes of cancer: the case of dioxins and water disinfection by-products. *Environmental Health*, 10(Suppl 1), S3.
- Kołątaj, W., Kołątaj, B., Karwat, D. I., Klatka, M., & Kozyra, K. (2017). Male infertility and human environmental pollution. *Journal of Education, Health and Sport*, 7(4), 127–166.
- Kulkarni, P. S., Crespo, J. G., & Afonso, C. A. (2008). Dioxins sources and current remediation technologies—a review. *Environment international*, 34(1), 139–153.

- L Charest, P. (2024). Implications multigénérationnelles d'une exposition prénatale paternelle à des polluants organiques persistants (POPs) et à une supplémentation en acide folique sur le développement foetal et adulte du rat.
- Makhoukh, M. (2004). Lutte contre la pollution liée aux déchets solides. In.
- Malisch, R., Kypke, K., Kotz, A., Wahl, K., Bitomsky, N., Moy, G., . . . Magulova, K. (2010). WHO/UNEP-coordinated exposure study (2008-2009) on levels of persistent organic pollutants (POPs) in human milk with regard to the Global Monitoring Plan. *Organohalogen Comp*, 72, 1766–1769.
- Matei, M., Zaharia, R., Petrescu, S.-I., Radu-Rusu, C. G., Simeanu, D., Mierliță, D., & Pop, I. M. (2023). Persistent organic pollutants (POPs): a review focused on occurrence and incidence in animal feed and cow milk. *Agriculture*, 13(4), 873.
- Mathew, N., Somanathan, A., Tirpude, A., Pillai, A. M., Mondal, P., & Arfin, T. (2025). Dioxins and their impact: a review of toxicity, persistence, and novel remediation strategies. *Analytical Methods*, 17(8), 1698–1748.
- McKay, G. (2002). Dioxin characterisation, formation and minimisation during municipal solid waste (MSW) incineration. *Chemical engineering journal*, 86(3), 343–368.
- McLachlan, M., & Richter, W. (1998). Uptake and transfer of PCDD/Fs by cattle fed naturally contaminated feedstuffs and feed contaminated as a result of sewage sludge application. 1. Lactating cows. *Journal of Agricultural and Food Chemistry*, 46(3), 1166–1172.
- Mehouel, F., Bouayad, L., Berber, A., Boutaleb, S., Miri, M., & Scippo, M.-L. (2021). Health risk assessment of exposure to polychlorinated dibenzo-p-dioxins/dibenzofurans (PCDD/Fs) and dioxin-like polychlorinated biphenyls (DL-PCBs) in swordfish from the Mediterranean Sea. *Environmental Science and Pollution Research*, 28(20), 26106–26111.
- Moussaoui, Y., Tuduri, L., Kerchich, Y., Meklati, B., & Eppe, G. (2012). Atmospheric concentrations of PCDD/Fs, dl-PCBs and some pesticides in northern Algeria using passive air sampling. *Chemosphere*, 88(3), 270–277.

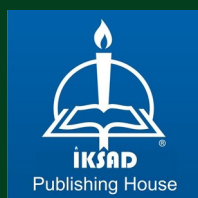
- Nadjiba, B. (2011). *People's Democratic Republic of Algeria*. Badji Mokhtar University,
- Oltramare, C., Mortara, J., Zennegg, M., Buser, A. M., Fumeaux, C. J. F., Berthet, A., & Vernez, D. (2026). Using a physiologically based pharmacokinetic model to evaluate aggregated exposure to PCDD/Fs and PCBs via ingestion in children. *Food and Chemical Toxicology*, 116126.
- Organization, W. H. (2017). Dioxins and their effects on human health; Fact sheet Updated October 2016. In.
- Pan, X., Yan, J., & Xie, Z. (2013). Detoxifying PCDD/Fs and heavy metals in fly ash from medical waste incinerators with a DC double arc plasma torch. *Journal of Environmental Sciences*, 25(7), 1362–1367.
- Pavuk, M., Serio, T. C., Cusack, C., Cave, M., Rosenbaum, P. F., & Birnbaum, L. S. (2019). Hypertension in relation to dioxins and polychlorinated biphenyls from the Anniston Community Health Survey follow-Up. *Environmental health perspectives*, 127(12), 127007.
- Perelló, G., Díaz-Ferrero, J., Llobet, J. M., Castell, V., Vicente, E., Nadal, M., & Domingo, J. L. (2015). Human exposure to PCDD/Fs and PCBs through consumption of fish and seafood in Catalonia (Spain): temporal trend. *Food and Chemical Toxicology*, 81, 28–33.
- Pham, T. D., & Sillanpää, M. (2020). Ultrasonic and electrokinetic remediation of low permeability soil contaminated with persistent organic pollutants. In *Advanced Water Treatment* (pp. 227–310): Elsevier.
- Piskorska-Pliszczyńska, J., Maszewski, S., Mikołajczyk, S., Pajurek, M., Struciński, P., & Olszowy, M. (2017). Elimination of dioxins in milk by dairy cows after the long-term intake of contaminated sugar beet pellets. *Food Additives & Contaminants: Part A*, 34(5), 842–852.
- Pollutants, P. O. (2011). Stockholm Convention on persistent organic pollutants. In: Geneva.
- Quaß, U., Fermann, M., & Bröker, G. (2004). The European dioxin air emission inventory project—final results. *Chemosphere*, 54(9), 1319–1327.

- Quinn, L., Pieters, R., Nieuwoudt, C., Borgen, A. R., Kylin, H., & Bouwman, H. (2009). Distribution profiles of selected organic pollutants in soils and sediments of industrial, residential and agricultural areas of South Africa. *Journal of Environmental Monitoring*, 11(9), 1647–1657.
- Regulation, A. (2010). Setting maximum levels for certain contaminants in foodstuffs as regards aflatoxins. *Officials Journal European Union*, 165, 8–12.
- Rennert, A., Wittsiepe, J., Kasper-Sonnenberg, M., Binder, G., Fürst, P., Cramer, C., . . . Wilhelm, M. (2012). Prenatal and early life exposure to polychlorinated dibenzo-p-dioxins, dibenzofurans and biphenyls may influence dehydroepiandrosterone sulfate levels at prepubertal age: results from the Duisburg birth cohort study. *Journal of Toxicology and Environmental Health, Part A*, 75(19-20), 1232–1240.
- Rose, M. (2016). Dioxins and dioxin-like compounds in food and feed. In *Dioxin and Related Compounds: Special Volume in Honor of Otto Hutzinger* (pp. 253–276): Springer.
- Safe, S. (1990). Polychlorinated biphenyls (PCBs), dibenzo-p-dioxins (PCDDs), dibenzofurans (PCDFs), and related compounds: environmental and mechanistic considerations which support the development of toxic equivalency factors (TEFs). *Critical reviews in toxicology*, 21(1), 51–88.
- Salmela, E., Lukinmaa, P.-L., Partanen, A.-M., Sahlberg, C., & Alaluusua, S. (2011). Combined effect of fluoride and 2, 3, 7, 8-tetrachlorodibenzo-p-dioxin on mouse dental hard tissue formation in vitro. *Archives of toxicology*, 85(8), 953–963.
- Samer, C. F., Gloor, Y., Rollason, V., Guessous, I., Doffey-Lazeyras, F., Saurat, J. H., . . . Daali, Y. (2020). Cytochrome P450 1A2 activity and incidence of thyroid disease and cancer after chronic or acute exposure to dioxins. *Basic & clinical pharmacology & toxicology*, 126(3), 296–303.
- Sanderson, J. T. (2006). The steroid hormone biosynthesis pathway as a target for endocrine-disrupting chemicals. *Toxicological sciences*, 94(1), 3–21.
- Schantz, S. L., Gasior, D. M., Polverejan, E., McCaffrey, R. J., Sweeney, A. M., Humphrey, H., & Gardiner, J. C. (2001). Impairments of memory

- and learning in older adults exposed to polychlorinated biphenyls via consumption of Great Lakes fish. *Environmental health perspectives*, 109(6), 605.
- Sobol, Ł., Długogórski, B. Z., Karczewski, M., Murthy, V., Sabat, D., Styczyńska, M., . . . Dyjakon, A. (2025). Toward dioxin-free chars: comparative toxicity of biomass valorization pathways under CO₂, N₂, and hydrothermal conditions. *Bioresource Technology*, 133855.
- Solomon, G. M., & Weiss, P. M. (2002). Chemical contaminants in breast milk: time trends and regional variability. *Environmental health perspectives*, 110(6), A339.
- Sorg, O., Zennegg, M., Schmid, P., Fedosyuk, R., Valikhnovskyi, R., Gaide, O., . . . Saurat, J. (2009). 2, 3, 7, 8-tetrachlorodibenzo-p-dioxin (TCDD) poisoning in Victor Yushchenko: identification and measurement of TCDD metabolites. *The Lancet*, 374(9696), 1179–1185.
- Ssebugere, P., Sillanpää, M., Matovu, H., & Mubiru, E. (2019). Human and environmental exposure to PCDD/Fs and dioxin-like PCBs in Africa: A review. *Chemosphere*, 223, 483–493.
- Steenland, K., Bertazzi, P., Baccarelli, A., & Kogevinas, M. (2004). Dioxin revisited: developments since the 1997 IARC classification of dioxin as a human carcinogen. *Environmental health perspectives*, 112(13), 1265.
- Stevens, J. B., & Gerbec, E. N. (1988). Dioxin in the agricultural food chain. *Risk analysis*, 8(3), 329–335.
- Suskind, R. R., & Hertzberg, V. S. (1984). Human health effects of 2, 4, 5-T and its toxic contaminants. *Jama*, 251(18), 2372–2380.
- Szajner, J., Czarny-Działak, M., Dziechciaz, M., Pawlas, N., & Walosik, A. (2021). Dioxin-like compounds (DLCs) in the environment and their impact on human health. *Journal of Elementology*, 26(2).
- Takiguchi, T., Vu, H. T., & Nishino, Y. (2022). Effects of polychlorinated dibenzo-p-dioxins, polychlorinated dibenzofurans, and dioxin-like PCBs on teeth and bones in animals and humans. *Toxics*, 11(1), 7.
- Themba, N., Chokwe, T., & Sibali, L. (2023). A review of PCDD/F and dl-PCB contamination in foods and dietary exposure assessment. *Int J Environ Impacts*, 6(1), 7–12.

- Turok, I., & McGranahan, G. (2019). Urbanisation and economic growth: The arguments and evidence for Africa and Asia. *Urbanisation*, 4(2), 109–125.
- Van den Berg, M., Birnbaum, L. S., Denison, M., De Vito, M., Farland, W., Feeley, M., . . . Haws, L. (2006). The 2005 World Health Organization reevaluation of human and mammalian toxic equivalency factors for dioxins and dioxin-like compounds. *Toxicological sciences*, 93(2), 223–241.
- van den Berg, M., Kypke, K., Kotz, A., Tritscher, A., Lee, S. Y., Magulova, K., . . . Malisch, R. (2017). WHO/UNEP global surveys of PCDDs, PCDFs, PCBs and DDTs in human milk and benefit–risk evaluation of breastfeeding. *Archives of toxicology*, 91(1), 83–96.
- Weber, R., Herold, C., Hollert, H., Kamphues, J., Blepp, M., & Ballschmiter, K. (2018). Reviewing the relevance of dioxin and PCB sources for food from animal origin and the need for their inventory, control and management. *Environmental Sciences Europe*, 30(1), 42.
- White, S. S., & Birnbaum, L. S. (2009). An overview of the effects of dioxins and dioxin-like compounds on vertebrates, as documented in human and ecological epidemiology. *Journal of Environmental Science and Health, Part C*, 27(4), 197–211.
- Xie, L., Du, T., Wang, J., Ma, Y., Ni, Y., Liu, Z., . . . Wang, J. (2021). Recent advances on heterojunction-based photocatalysts for the degradation of persistent organic pollutants. *Chemical engineering journal*, 426, 130617.
- Xu, W., & Cai, Z. (2015). Risk assessment of dietary exposure to PCDD/Fs, DL-PCBs and NDL-PCBs of Hong Kong resident. *Science China Chemistry*, 58(6), 1082–1088.
- Yongkai, W., Shuhui, Z., & Li, M. (2025). Effect of 2, 3, 7, 8-tetrachlorodibenzo-p-dioxin (TCDD) on the immune system maternal-fetal interface during palatal development. *Journal of Molecular Histology*, 56(1), 60.
- Zeitler, R. (2020). Stockholm Convention on Persistent Organic Pollutants (POP).

- Zhang, M., Buekens, A., & Li, X. (2016). Brominated flame retardants and the formation of dioxins and furans in fires and combustion. *Journal of hazardous materials*, 304, 26–39.
- Zouboulis, C. C. (2020). Endocrinology and immunology of acne: Two sides of the same coin. *Experimental Dermatology*, 29(9), 840–859.



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